CHAPTER 227

EFFECTIVE STRESSES AND PERMEABILITY IN CONSOLIDATING MUD

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Abstract

Measurements of density and pore pressures for consolidation experiments on estuarine mud are analyzed. Results for bulk permeability, local permeability and effective stress are presented and simple relationships between each of these parameters and the density are proposed. The problems associated with the accuracy of the measurements and their consequences on the determination of closure equations for consolidation models are discussed.

1. Introduction

The study of erosion, deposition and transport of sediments is of major importance for the operation of harbours, the planning of maintenance dredging, the spreading of pollutants and the stability of coastal structures. Therefore, many efforts have been devoted during the past few years to develop mathematical models for simulating the movement and deposition of sediments in coastal regions and estuaries. Although various commercially available models are capable of predicting fairly well the behaviour of non-cohesive material (sand), they do hardly better than producing qualitative results when cohesive sediments (mud) are involved. This, unfortunately, is very often the case in harbours and estuaries. The reason is that the basic physical processes involved are not yet fully understood, and thus cannot be modelled adequately.

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The actual erosion rates and whether or not a muddy bed will be eroded by currents or wave action depend on the degree of consolidation of the bed. Each cohesive sediment transport model should therefore include the modelling of the time history of the bed and its consolidation. A review of consolidation models can be found in (*Shiffman et al.*, 1985) and (*Alexis*, 1991). More recent approaches, taking into account hindered settling as well, are due to (*Tan et al.*, 1990) and (*Toorman*, 1992).

The consolidation of a cohesive sediment bed depends on: (1) the expulsion of water through the pores between the solid particles, i.e. on the permeability k of the mud layer; (2) the deformation of the card-house-like structure of mud flocs, i.e. on the effective stresses $\sigma' = \sigma - p$, in which σ is the total stress and p is the pore water pressure. Therefore, there is a great need for general constitutive equations for the effective stress and for the permeability of a mud layer. Both are still largely unknown.

In the first part of this paper the results of experiments in settling columns will be described and discussed. Experiments were carried out both with drained and undrained mud layers. In the second part an attempt is made to determine permeability and effective stress as a function of bulk density.

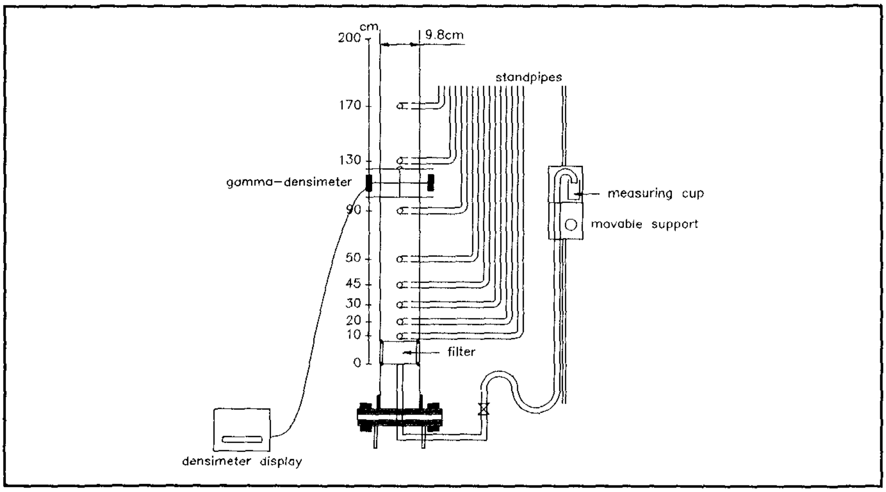


Fig.1: Settling column: experimental set-up.

2. Settling column experiments

In the Hydraulics Laboratory of the K.U.Leuven several series of consolidation experiments on drained and undrained mud layers were carried out in order to investigate the effect of drainage on the consolidation rate.

2.1 Experimental set-up.

Figure 1 shows the experimental set-up of the settling column. The transparent column has a diameter of 0.10 m and is equipped with water pressure gauges. Where the piezometers are connected to the column, a cigarette filter is inserted to prevent mud particles from entering the tubes. The bottom of the column is closed for undrained experiments. In the case of drainage it is replaced by a filter, about 10 cm thick, consisting of a gradation of sand and gravel. The bottom of the filter is connected to a small reservoir of which the level can be changed in order to allow a variation of the imposed head difference over the mud layer. The percolating discharge is measured by regular weighing of the measuring cup. Density profiles can be measured with a nuclear density probe with an accuracy of 10 kg/m^3 (*MAST-G6M* Report, 1992).

2.2 Experiments

In this paper three sets of experiments are discussed. Table 1 gives an overview of test conditions. In all cases mud from the River Scheldt was used.

Exper. nr.	H_o (m)	ρ_o (kg/m^3)	Drainage	Δh (m)	Duration (days)
KO1	1.600	1095	drained	0.0	119
KO2	1.600	1095	undrained	-	97
KO3	1.602	1095	drained	0.8	126
KO4	1.600	1095	drained	1.6	119
KO5	1.604	1095	undrained	-	92
KO6	1.602	1095	drained	variable	92
KO7	1.983	1060	undrained	-	41
KO8	1.993	1095	undrained	-	22
KO9	1.983	1098	undrained	-	26

Table 1: Experimental conditions

The first set of experiments (KO1, KO2, KO3, KO4) were ordered by IMDC (International Marine & Dredging Consultants) and fit within the study program for the design and optimization of a mud basin and capture reservoir (*Mengé et al.*, 1991). Afterwards, a second series of experiments (KO5 and KO6) were carried out to investigate optimal compaction through controlled drainage. The initial density in each case was 1095 kg/m^3. Interface level, pore pressures, density profiles and percolating discharge were measured. The columns were filled from the top. The columns were cooled at the surface with tap-water to keep them at a constant temperature ($\pm 13\,°C$) in order to reduce gas production by organic matter.

In order to evaluate the results of permeability and effective stress values as a function of density, a third set of undrained consolidation experiments has been carried out. The general set-up for the settling columns was the same as for the previous ones except for a larger number of piezometers, which allows better estimation of local permeabilities. Cooling was now obtained by placing the columns in a constant temperature room. Tests are carried out at a temperature of $8\,°C$, which is a more realistic value for in-situ conditions of underwater disposals and almost eliminates gas production. The columns were now filled by sucking up the slurry into the column by creating vacuum, which has the additional advantage of de-airing the mud.

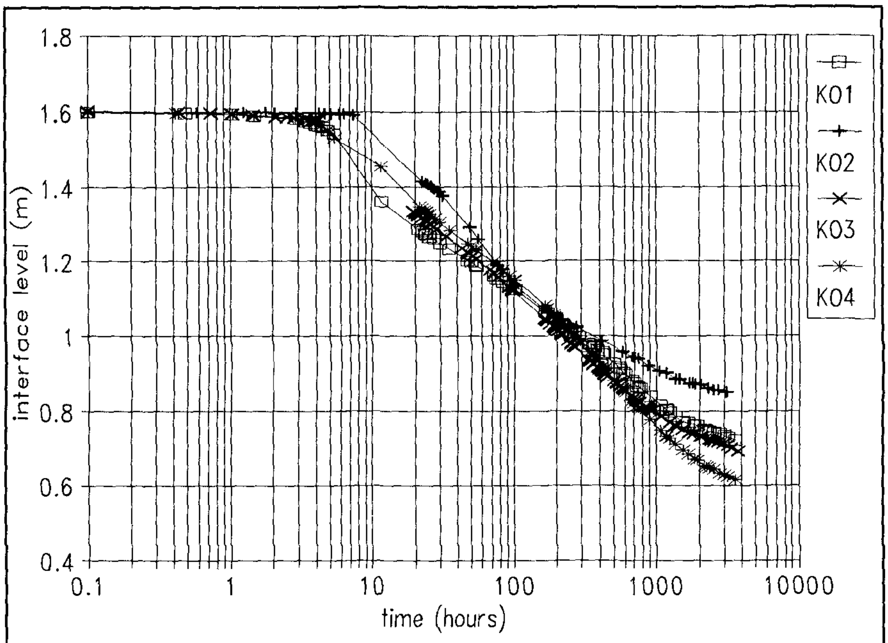


Fig.2: Settling curves for experiments KO1-KO4.

2.3 Discussion of observations

From the settling curves of KO1-KO4 it can be concluded that the descend of the water-mud interface starts earlier when the column is drained. During the first hours the consolidation rate of the undrained column KO2 is much lower than that of the drained column (Fig.2). The consolidation rate of KO1 (head difference $\Delta h = 0.0$ m) is even larger than that of KO4 ($\Delta h = 1.6$ m). After 100 hours the mud-water interface of both columns has reached the same level. This means that consolidation rate of the drained column with head difference 0.0 m has decreased.

The smaller the head difference during the first hours the higher the consolidation rate at that moment. Afterwards the consolidation rate of the columns with a lower head difference decreases. At the end of the experiments (after 3 months) drainage gives a better compaction. The compaction increases for greater head difference. The compaction of KO1 and KO3 after 3 months is more or less the same. The compaction of KO4 is much higher than the others (i.e. 21 % better than for the undrained column KO2).

Density profiles for drained columns show that there is an upper layer of approximately constant density and a lower zone where the density increases with depth (Fig.3), which is clearly indicated by a distinct inflection point. The zone of constant density is similar to an undrained mud layer. Comparison of the density profiles of KO1-KO4 shows that the height of the zone with high densities increases with the imposed head difference (Fig.3).

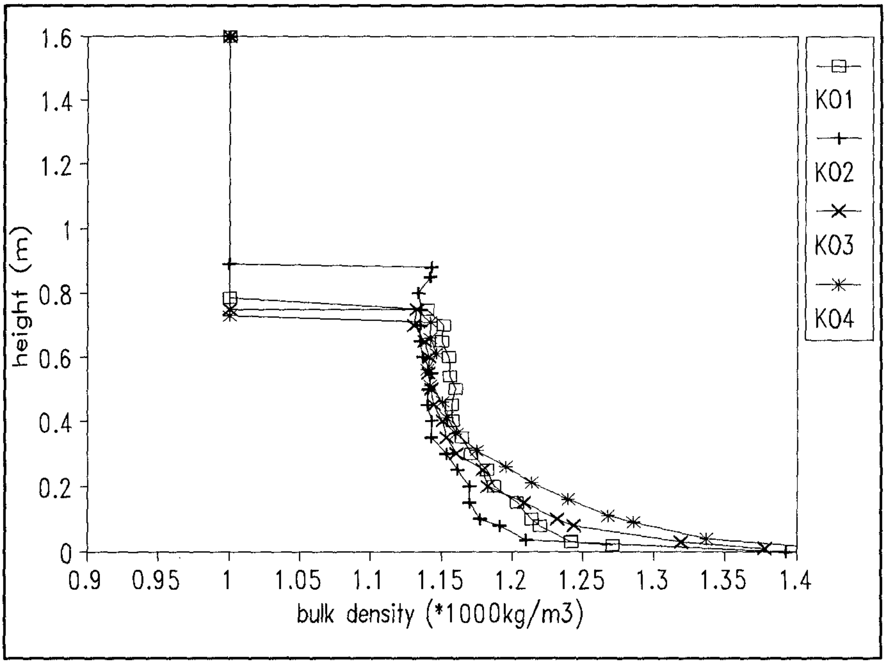


Fig.3: Density profiles for experiments KO1-KO4 after two months.

In order to combine both effects to maximize compaction, two new experiments (KO5 and KO6) were started. In experiment KO6 the imposed head difference was stepwise varied during the experiment from 0 to nearly the initial column height (Fig.4). The experiment KO5 (undrained) was used as reference.

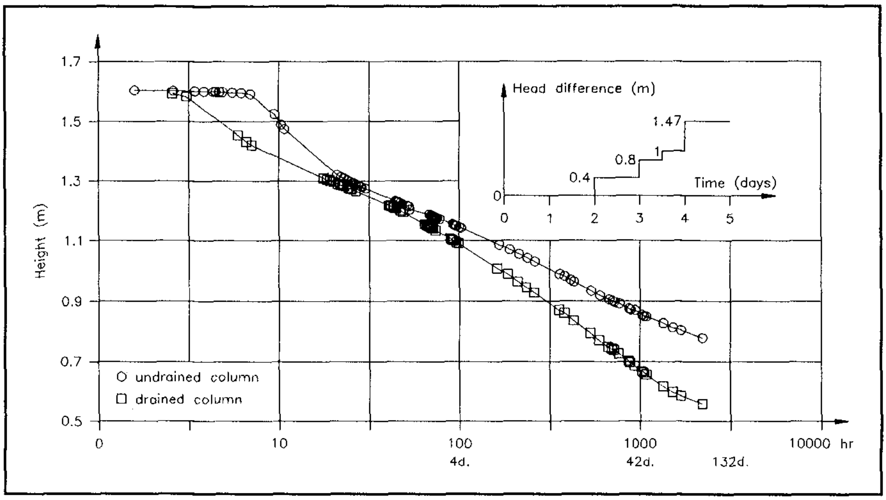


Fig.4: Consolidation curves for columns KO5 (undrained) and KO6 (drained).

As in the first experiments (KO1-KO4), the lowering of the interface starts earlier for the drained column (KO6) than for the undrained column (KO5) (Fig.4). However, although the geometric head difference during the first 2 days was zero, there is a small head difference over the mud sample caused by a difference in density between the fluid mud (initially the mud has no structure) and the water in the tube connecting the filter with the downstream reservoir. Therefore water can migrate downwards through the filter pushed by a small head difference. After a few hours a structure is formed and the head difference disappears. After 2 days the head difference was increased by lowering the reference reservoir level, resulting in an increased consolidation rate. After 4 days the head difference is 1.47 m. After 3 months the compaction in the drained column is 23 % higher than in the reference undrained column KO5. The density profile of KO6 (Fig.5) shows that the bottom zone of high densities is even thicker than in the tests KO1-KO4.

3. Permeability and effective stress

3.1 Mean bulk permeability

Data of the above discussed experiments have been used to estimate the permeability. For a closed (undrained) column the global permeability of the layer is calculated as a function of the average bulk density ρ using Darcy's law:

$$\frac{Q}{A} = k\frac{\Delta h}{L} \qquad [1]$$

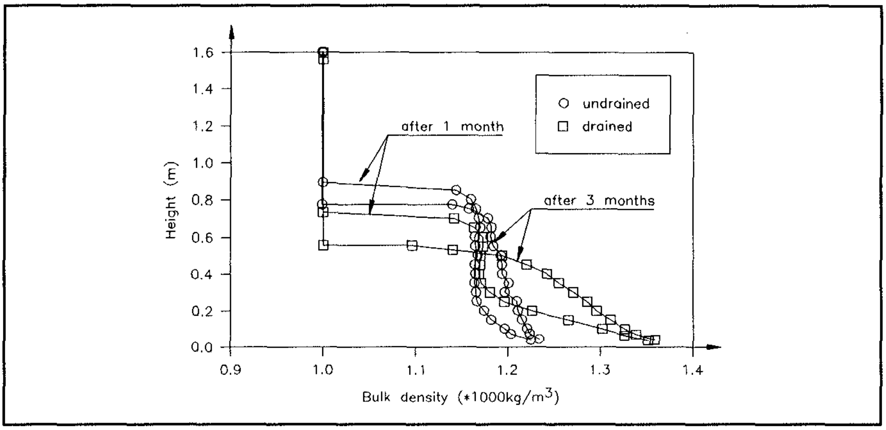


Fig.5: Density profiles for columns KO5 (undrained) and KO6 (drained).

where: Δh = difference over a certain time interval ($\Delta t = t_{i+1} - t_i$) of pressure head above hydrostatic at the bottom of the column; L_i = mud layer thickness at time t_i; A = cross sectional area of the column; $Q = A\ (L_i - L_{i+1})/2\Delta t$ = average pore water flow rate; $L = (L_{i+1}+L_i)/2$ = mean layer thickness.

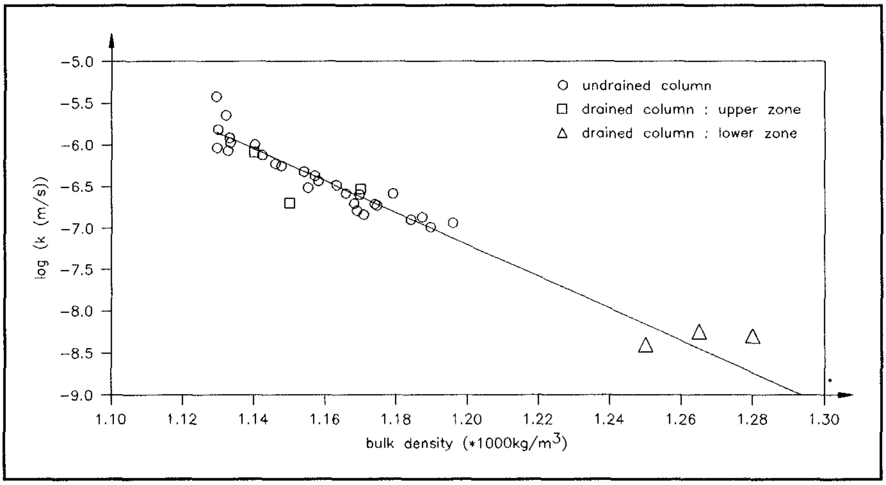


Fig.6: Global permeability as a function of average bulk density for columns KO5 (undrained) and KO6 (drained).

Fig.6 shows the results for columns KO5 and KO6. The relation between k and ρ can be approximated (for $1130 < \rho < 1210$ kg/m^3) by:

$$\log k = a\rho + b \qquad [2]$$

where: a and b are empirical constants.

The inflection point in the density profiles was found to correspond with the level where the water head above hydrostatic reaches its maximum value (Fig.7). Hence, the excess pore water pressure gradient changes sign here, which implies that the pore water flows downward through the filter for the layer under the inflection point and upward for the zone above it. For the drained column the permeability of the upper zone is calculated as above for the undrained columns, whereas for the bottom layer the measured percolated discharge is used in Darcy's law. Hence, in drained columns permeabilities of mud layers of much higher density can be obtained. The obtained values of k are close to those obtained with Eq.[2] (Fig.6).

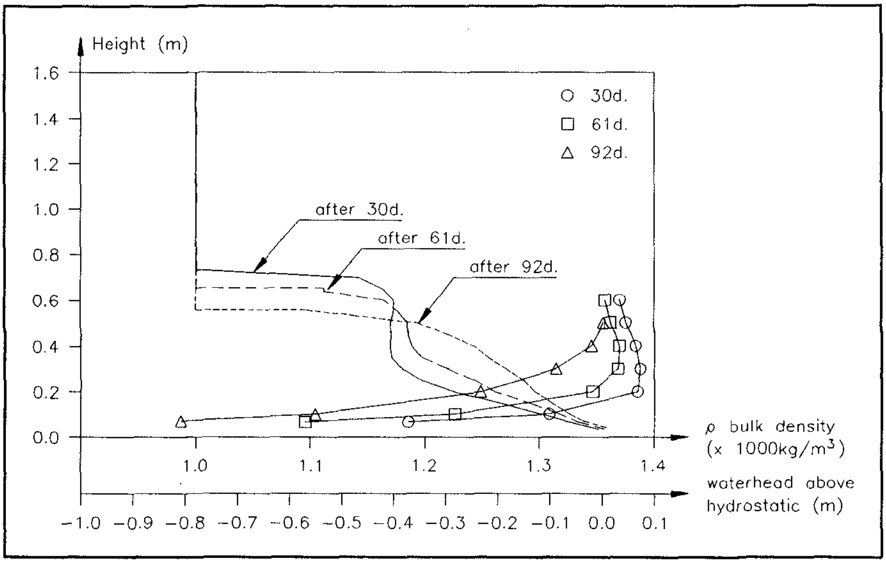


Fig.7: Density profiles and pore pressures above hydrostatic for the drained column KO6.

3.2 Effective stress

The total stress σ at a certain level is obtained by integration of the density profile from the surface down to that level. When the pore pressure p is measured at that point, the local effective stress σ' can be computed as σ - p. Fig.8 shows the total pressure, the pore pressure and the effective stress as a function of the depth for an undrained (KO2) and a drained column (KO4). It can be seen that the effective stresses in the drained mud layer are greater than in the undrained case.

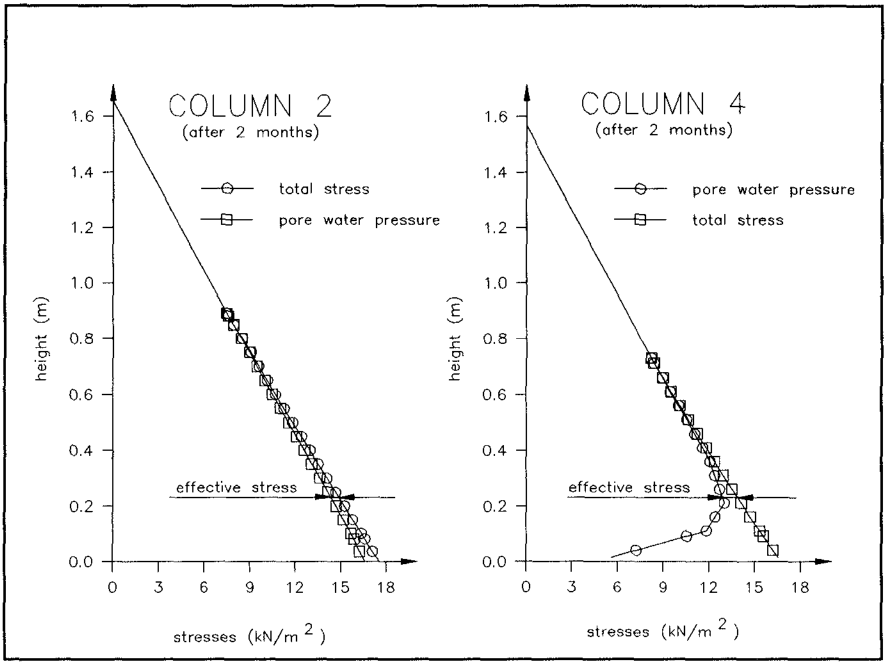


Fig.8: Stresses in the undrained column KO2 and the drained column KO4.

It was found that the dimensionless parameter $\sigma^* = \sigma'/\rho k^2$ (where k is calculated with Eq.[2]) gives a rather good linear correlation with ρ on a semi-logarithmic scale, i.e.:

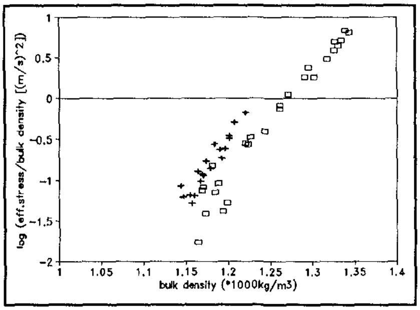
$$\log\sigma^* = a'\rho + b' \qquad [3]$$

Substitution of Eq.[2] in [3] results in:

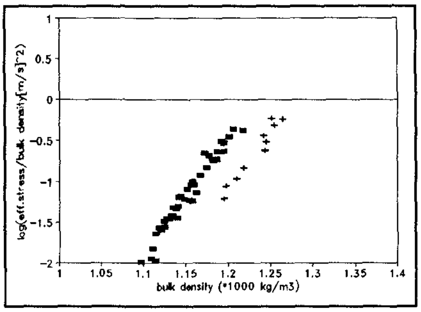
$$\log(\sigma'/\rho) = a''\rho + b'' \qquad [4]$$

where: $a''=a'+2a$ and $b''=b'+2b$. Hence a plot of σ'/ρ as a function of ρ should directly give a linear correlation on a semi-logarithmic scale. The results for an undrained (KO5) and drained (KO6) column can be seen in Fig.9. The large scatter for small σ' values is due to the low accuracy of measuring effective stresses (especially at low ρ), because σ' is obtained as the small difference of two parameters (σ and p) which are of the same order of magnitude (see *MAST-G6M* Report, 1992).

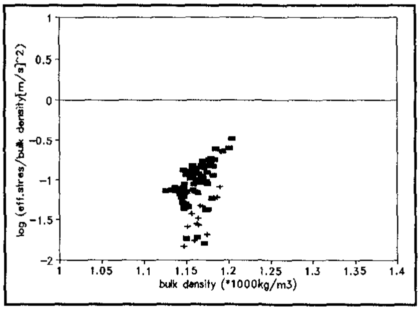
To check the relationship [4] a new set of consolidation tests (KO7-KO9, Table 1) were carried out. The experimental results for the relationship between effective stress and local density are shown in Fig.9. The effective stresses during the first two days are not plotted because of the low accuracy of these values. To extend the relationship for low values of effective stress a more accurate measuring method for effective stress is needed. In general it can be concluded that for the range 1100 $< \rho <$ 1350 kg/m^3 the relationship in a semi-log scale is linear.



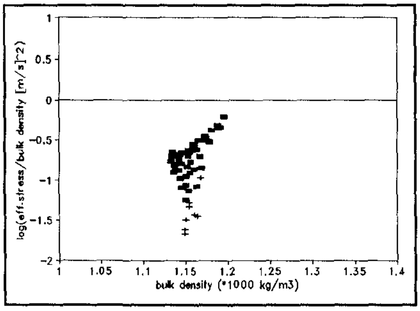
a) + KO5 (undrained)
□ KO6 (drained)



b) KO7 (+ = bottom 5 cm)



c) KO8 (+ = top above ρ_{max})



d) KO9 (+ = top above ρ_{max})

Fig.9: Effective stress as a function of bulk density for columns KO5-KO9.

Looking at the results of the columns KO7-KO9 separately, it can be seen that for KO7 in fact two lines can be distinguished, i.e. for points in the bottom 5 cm of the column and for those above. Possibly, because the initial density (1060 kg/m^3) of this experiment (KO7) was below the gel-point (the critical concentration for structure formation) of this mud, sand may have migrated to the bottom during the first hours of the experiment, causing a difference in composition of the mud for the points of the two lines. Moreover, the density measurements are biased close to the bottom of the column. A comparison of the results of KO7 with those of KO6 and KO5, shows that the data for the bottom layer of KO7 are comparable to those of the drained column KO6, while the values for the top layer of KO7 are on the same line as for the undrained column KO5, even though the mud in both sets of experiments originated from different locations in the Scheldt.

The shape of the density profiles of KO8 is not as expected, showing a large zone of decreasing density with depth (Fig.10). Similar density profiles have also been found by *Bowden* (1988). At first sight, the results of effective stress for KO8 do not show a clear linear correlation (Fig.9c). It can be seen that there are two clouds of points. Possibly the relationship depends on the shape of the density profiles. For KO9 similar observations were made as for KO8.

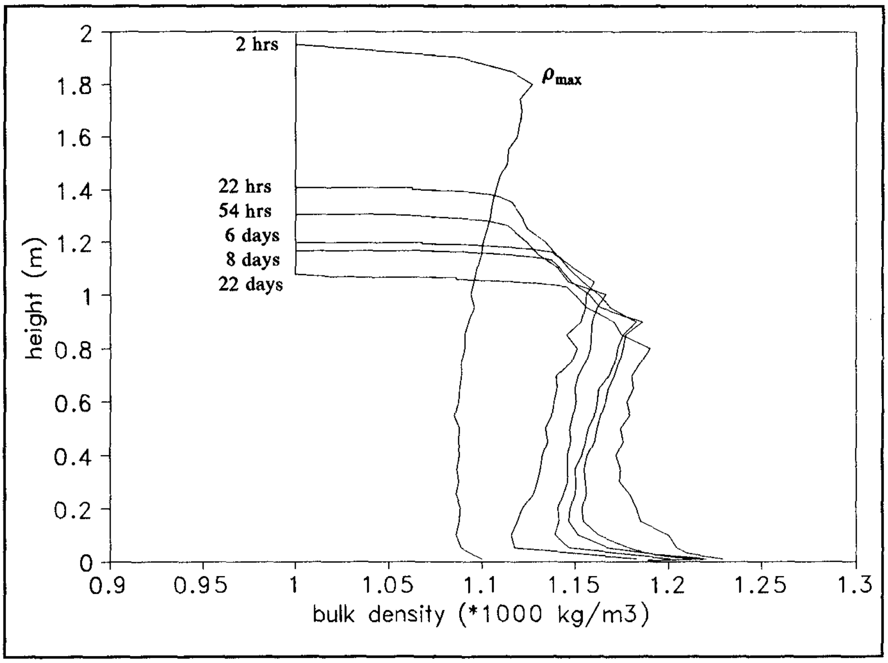


Fig.10: Density profiles for column KO8.

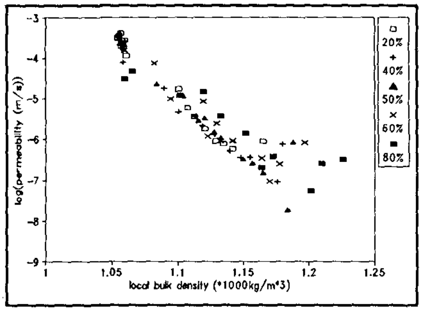
3.3 Local permeability

For the experiments KO7-KO9 an attempt was made to determine the local permeability by using the following form of Darcy's law, which is only valid for undrained tests (*Bowden*, 1988):

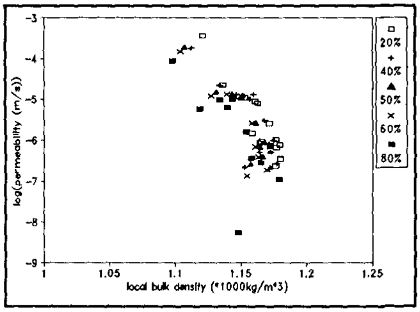
$$k = \frac{w_s'}{i} \qquad [5]$$

where: w_s = local settling rate (average solids velocity), k = permeability, i = local hydraulic gradient. The settling rate can be estimated from successive density profiles, by following levels in the mud layer below which a certain constant fraction of the total mass of the sediment is found. The hydraulic gradient can be estimated by the difference in excess hydraulic head between two neighbouring pressure taps divided by the distance between them.

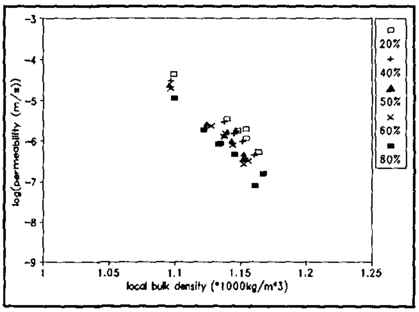
The local permeabilities as a function of local density were calculated for KO7, KO8, KO9 (Fig.11a-c). Again the experimental results can be approximated by a is a linear relationship between log(k) and ρ. For column KO7 the linear approximation is very good in the range from 1050 kg/m^3 < ρ < 1200 kg/m^3. For higher densities there is a lot of scatter. For this range the calculation of k by Eq.[5] is very inaccurate, because the settling rate is determined from two successive density profiles, measured with limited accuracy (§2.1), which hardly change any more at this stage of the consolidation process.



a) KO7



b) KO8



c) KO9

Fig.11: Local permeability as a function of density for columns KO7-KO9.

For KO8 and KO9 a linear relationship between log(k) and ρ is a good approximation. The scatter is larger than for KO7 because the initial density was higher, which reduces the accuracy of the calculation of w_s. The inaccuracy is largest for the 80% mass level, because the density profiles are integrated all the way from the top down. The values of k for KO8 and KO9 are a factor 5 to 10 smaller than the permeabilities of KO7. Because the density profiles are used for calculation of

k, a possible explanation can also here be found in the shape of the density profiles, which is influenced by the initial density of the slurry.

3.4 A theoretical consideration

Darcy's equation for undrained consolidation, Eq.[5], can more explicitly be written as a relationship between effective stress, permeability and settling rate (*Toorman*, 1992):

$$\frac{1}{g}\frac{\partial \sigma'}{\partial z} \approx \rho_w \frac{w_s}{k} - \Delta\rho \qquad [6]$$

where: g = gravity constant; $\Delta\rho = \rho - \rho_{w(ater)}$. When the density is below the critical concentration where no structure exists, hindered settling takes place instead of consolidation and thus there is no effective stress. Hence, Eq.[6] reduces to:

$$k = w_s \frac{\rho_w}{\Delta\rho} \qquad [7]$$

This was first pointed out by *Been* (1980). Therefore, for low densities Eq.[2] can no longer be valid, because in the limit where $\Delta\rho$ goes to zero, the permeability becomes infinite since w_s then equals the (finite) Stokes fall velocity of a sediment particle.

4. Conclusions

The settling curves of the drained and the undrained mud layers show that drainage fastens the settling and the consolidation rates. The compaction can be maximized by applying a variable, i.e. increasing, head difference over the mud sample. Higher densities than in undrained conditions are then obtained in a thick layer above the bottom. Hence it is possible to obtain values of permeability and effective stress at higher densities using drained columns.

The presented results suggest linear correlations between log(k) and ρ and between log(σ'/ρ) and ρ within the range $1100 < \rho < 1200$ kg/m^3. Because there is often significant stratification in the mud layer, it is unlikely that the global permeability can be used to calibrate a closure law for k needed in numerical modelling, since local values are required. Local permeabilities however are harder to measure. Nevertheless, the magnitude of local and bulk permeabilities were found to be comparable. More experimental work is required to get more accurate data for the ranges of low and high densities, as well as to investigate the effect of parameters, such as initial density, structural history, shape of the density profiles, initial height, depth from the interface, etc.

Acknowledgements

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