EFFECTIVE STRESSES AND PERMEABILITY IN CONSOLIDATING MUD

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The study of erosion, deposition and transport of sediments are 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.

Whether or not a muddy bed will be eroded by currents or wave action as well as the actual erosion rates depend on the degree of consolidation of the bed. Each cohesive sediment transport model should therefore include the modelling of the 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).

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 a mud layer; (2) the deformation of the card-house-like structure, 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.

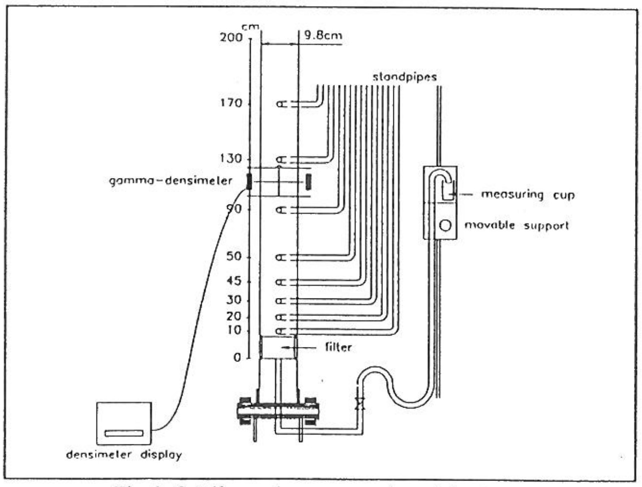

Fig.1: Settling column: experimental set-up.

In the Hydraulics Laboratory of the K.U.Leuven, an attempt was made to determine both permeability and effective stress in mud by conducting consolidation tests in drained and undrained consolidation columns, equipped with water pressure gauges and a nuclear density probe (fig.1). The columns were filled with mud from the river Scheldt. The initial density was 1095 kg/m^3 and the initial height of the mud layer was 1.6 m. One column was closed at the bottom. The other one had a filter at the bottom and a variable head difference was imposed (fig.2). The percolating discharge was measured by regular weighing of the measuring cup (fig.1). With regular time intervals interface levels, pore pressures and density profiles were recorded.

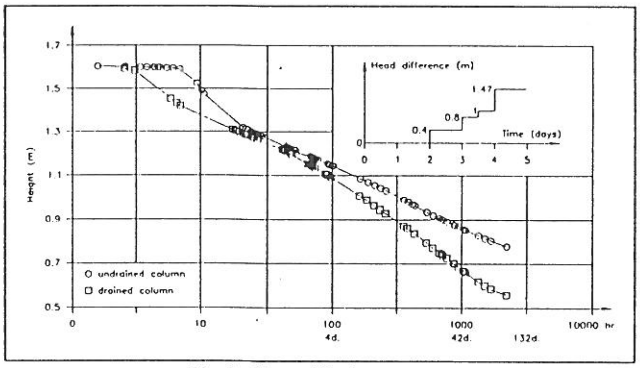

Fig.2: Consolidation curves.

Fig.2 shows the consolidation curves for both experiments. During the first 2 days the consolidation rate for the drained column is greater than for the closed one, although the head difference was zero. This phenomenon was already observed in other experiments in drained columns (*Mengé et al.*, 1991). After 3 months the compaction in the drained column is 23% higher than that of the undrained mud layer. Comparison of the density profiles shows that the zone of high density is larger for the drained column (fig.3).

Observing the density profiles for the drained column at different time steps it can be seen that there is a zone of constant density and a lower zone of increasing density. An inflexion point is observed in the density profiles, which was found to correspond with the point where the water head above hydrostatic reaches its maximum value (fig.4). Hence, it can be concluded that the pore water flows downward through the filter for the zone under the inflexion point and upward for the zone above it.

The global permeability of the layer is calculated as a function of the average bulk density ρ for the closed column by Darcy's law (fig.5):

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

where: Δh = head difference above hydrostatic at the bottom of the column; L_i = mud layer thickness at time i; A = cross sectional area of the column; $Q = A\ (L_i - L_{i+1})/2\Delta t$; $L = (L_{i+1}+L_i)/2$. The relation between k and ρ can be approximated by:

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

where: a and b are empirical constants. Eq.[2] is valid for $1130 < \rho < 1210$ kg/m^3 for the actual data. For the drained column the permeabilities of the upper and the bottom zone of the mud layer are obtained also by using Darcy's law and the percolated discharge

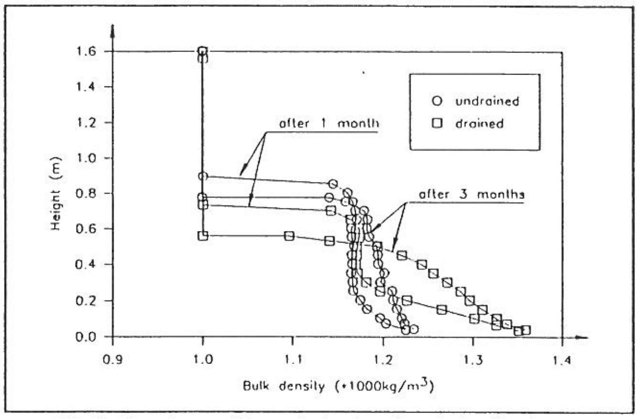

Fig.3: Density profiles : drained and undrained column.

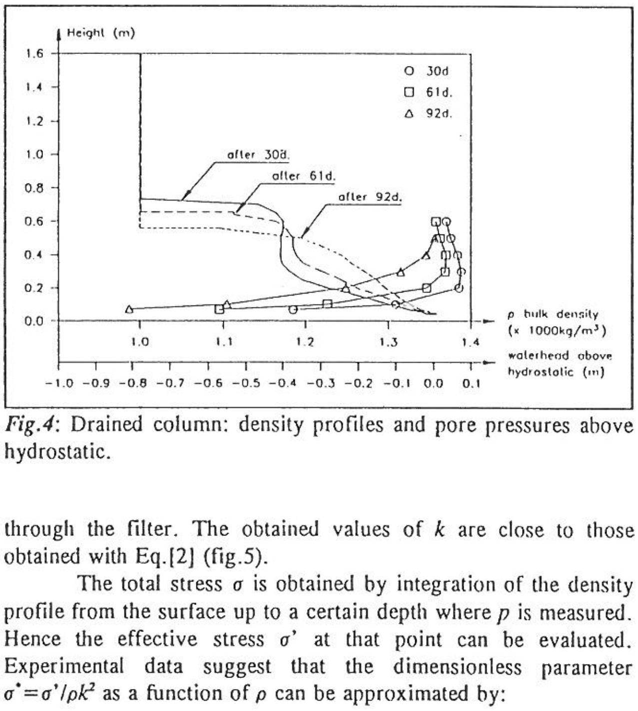

Fig.4: Drained column: density profiles and pore pressures above hydrostatic.

through the filter. The obtained values of k are close to those obtained with Eq.[2] (fig.5).

The total stress σ is obtained by integration of the density profile from the surface up to a certain depth where p is measured. Hence the effective stress σ' at that point can be evaluated. Experimental data suggest that the dimensionless parameter $\sigma^* = \sigma'/\rho k^2$ as a function of ρ can be approximated by:

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

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

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

where: $a'' = a' + 2a$ and $b'' = b' + 2b$ (fig.6). The large scatter for small σ' values is due to the low accuracy for measuring effective stresses, because σ' is obtained as a difference of two parameters (σ and p) which are of the same order of magnitude.

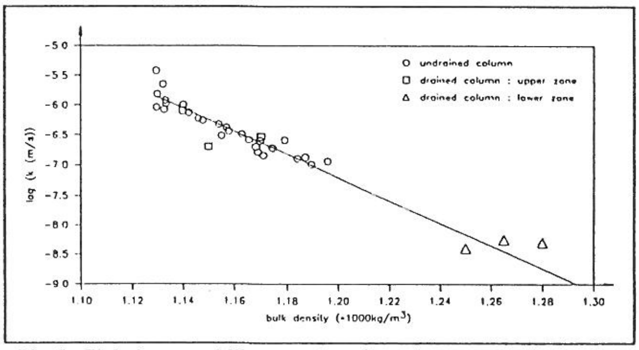

Fig.5: Global permeability as a function of average bulk density.

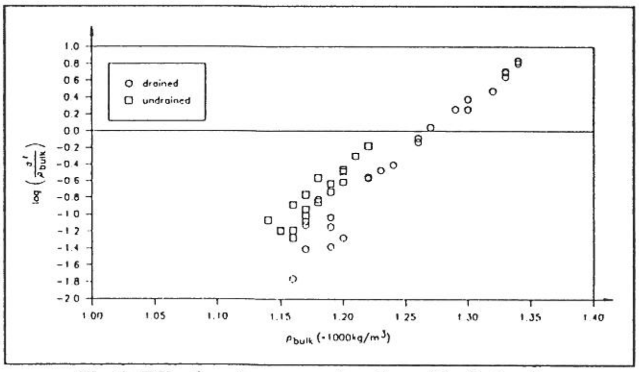

Fig.6: Effective stress as a function of bulk density.

Conclusions

These preliminary results suggest a new relationship between σ' and ρ. However, because of the stratification in the mud layer, it is necessary to obtain values of local instead of global permeabilities in order to find correct closure equations for k and σ'. More experimental work is required to get more accurate information for the ranges of low and high densities, as well as on structural changes at constant density. This is the subject of current research.

Acknowledgements

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References

Alexis, A.(1991): Review of consolidation models. MAST G6-M Project Workshop. Delft.

Mengé, P., L. Van den Bosch, W. Van Impe and J. Berlamont (1991). Mud basin and capture reservoir experimental program.- Laboratory experiments. Report. Soil Mechanics Laboratory, R.U.Gent and Hydraulics Laboratory, K.U.Leuven (in Dutch).

Schiffman, R.L., V. Pane and V. Sunara (1985): Sedimentation and consolidation. Proc. Engineering Foundation Conf. on Flocculation, Sedimentation and Consolidation, pp.57-121.

Tan, T.S., K.Y. Young, E.C. Leong and S.L. Lu (1990): Sedimentation of clayey slurry. ASCE J. Geotechnical Engineering, Vol.116(No.6),885-898.

Toorman, E.A.(1992). Modelling of fluid mud flow and consolidation. PhD thesis. Civil Eng. Dept., K.U.Leuven.