CHAPTER 226

CONSOLIDATION OF SOFT MARINE SOILS: UNIFYING THEORIES, NUMERICAL MODELLING AND *IN SITU* EXPERIMENTS

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ABSTRACT

This paper first presents a literature review of consolidation theories. A link between sedimentation and consolidation models is pointed out and a more general formulation is suggested. The constitutive relationships between the void ratio and the effective stress or the permeability are discussed from experimental data available in literature. Then a numerical modelling is used to simulate settling column tests. At last field measurements of mud characteristics are presented.

1 INTRODUCTION

Cohesive sediments are often at the core of coastal problems, either by their undesirable accumulation in estuaries and sheltered areas as harbours, or by their active pollutant role as a carrier of heavy metals or radionucleides. Thus, various numerical models have been developed over the past decade to reproduce cohesive sediment transport, through the well known advection-diffusion equation, with deposition and erosion acting as sink and source terms. But few industrial models do take into account consolidation. Its representation, when it exists, is often empirical and loosely linked with

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consolidation theories (HAYTER, 1986; TEISSON and LATTEUX, 1986; LE HIR *et al.*, 1989). Recent approaches try to take into account consolidation by including effective stress as a parameter of the settling velocity (TOORMAN, 1992). However, consolidation is a very important parameter which governs sediment dynamics at a fornight tidal scale: part of the sediment, which deposits during neap conditions, will have time to consolidate and will not be resuspended during spring conditions, because of its higher critical shear stress. A good prediction of the amount of resuspended sediment and consequently definitive deposit therefore depends on a good simulation of consolidation.

2 LITERATURE REVIEW

As soft soils are at the boundary between water and soil, consolidation has been investigated by hydraulicians and geotechnicians, with separate approaches. We use an original tree method, shown in fig.1, to analyse the historical background and study the convergence of the different points of view.

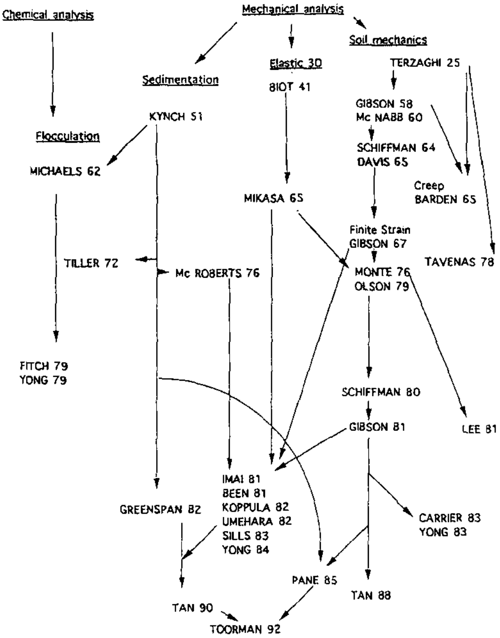

Fig.1: Soft soil consolidation historical tree of theoretical studies.

During the past ten years, some theories have been brought closer, but there is still no real inclusive approach, notably concerning the link between sedimentation and consolidation.

The study of previous theoretical works show that TERZAGHI (1925), KYNCH (1952) and GIBSON *et al.*. (1967) have been the key papers of this theoretical background. As TERZAGHI's formulation is only valid with small deformations and KYNCH's formulation does not take into account the effective stress, they reveal to be too restrictive. GIBSON's model is more general, but is limited to constitutive relationship only depending on the void ratio, and to incompressible phases.

In order to simulate the behaviour of a very soft marine soil, a relevant model should take into account large deformations, increasing or decreasing effective stresses due to the load history (deposition and erosion), variable or cyclical pore pressure (waves, tide), compressible fluid and grains (unsaturated, organic matter) and long term deformations (creeping).

3 TOWARDS A UNIFYING THEORY

As they appear different, models of consolidation have been rewritten using a unique notation system which allows their comparison.

GIBSON's law (1967) appears to be the most general of the previous studies. This formulation needs the use of a Lagrangian coordinate, the material coordinate z, which is constant for a given slice of sediment and corresponds to the height of solids above the slice. Stresses acting on sediment are studied separately, as effective stress on grains on the one hand, and pore pressure on fluid on the other:

$$\sigma = \sigma' + u_w$$

Mass balance,

$$\frac{\partial v_m}{\partial z} + \frac{\partial e}{\partial t} = 0$$

stresses equilibrium,

$$\frac{\partial \sigma}{\partial z} = \gamma\,(1+e) \qquad \frac{\partial u_0}{\partial z} = \gamma_w\,(1+e)$$

extended Darcy's law,

$$v_m = -\frac{k_r}{\gamma_w}\frac{\partial u}{\partial z}$$

and constitutive relationships,

$$\sigma' = \sigma'(e) \qquad k = k(e)$$

are written to get the Gibson's equation:

$$\frac{\partial e}{\partial t} - \frac{\gamma'_s}{\gamma_w}\frac{dk_r}{de}\frac{\partial e}{\partial z} + \frac{1}{\gamma_w}\frac{\partial}{\partial z}\left(k_r\frac{d\sigma'}{de}\frac{\partial e}{\partial z}\right) = 0 \qquad (1)$$

where: e void ratio, k_r reduced permeability (k/(1+e)), γ_w and γ'_s unit weights of water and of immersed solids.

When self weight is ignored and small deformations are considered, it follows:

$$\frac{\partial e}{\partial t}=\frac{k\,E'}{\gamma_w(1+e_0)}\frac{\partial^2 e}{\partial z^2} \qquad (2)$$

When effective stress is ignored, it follows:

$$\frac{\partial e}{\partial t}-\frac{\gamma'_s}{\gamma_w}\frac{dk_r}{de}\frac{\partial e}{\partial z}=0 \qquad (3)$$

SCHIFFMAN *et al.* (1985) have shown that the GIBSON's equation (1) includes TERZAGHI's equation (1925) (2) used in geotechnics for terrestrial soil and KYNCH's equation (1952) (3) used in sedimentation as simplified and particular cases, when they are written in the same system of notations.

Moreover, the relation with the two-phase flow approach (TEISSON et *al.*,1992) can be pointed out.

The usual condition of zero effective stress during the sedimentation phase induces the existence of a boundary void ratio. But a slightly decreasing effective stress down to very small but non zero values, with increasing void ratio, could allow to link sedimentation and consolidation as a continuous process.

We propose a new and extended formulation to take into account the compressibility of fluid and grains and non pure Darcinian flow:

$$\frac{\partial}{\partial z}\left(\gamma_f\, v_m\left(e,\frac{1}{1+e}\left(\gamma'_s-\frac{\partial\sigma'}{\partial z}\right)\right)\right)=\gamma_s\frac{\partial}{\partial t}\left(e\frac{\gamma_f}{\gamma_s}\right) \qquad (4)$$

where the mean relative flow velocity v_m depends on e and the excess pore pressure gradient, but not necessarily according to the Darcy's law. It can be easily shown that the simultaneous use of the assumption of incompressibility for solid and fluid phases and of Darcy's law will make Gibson's equation 1 a restrictive case of equation 4.

Let us notice that the grain size distribution remains uniform, because of the use a material coordinate, but that creeping and the history of loading could be taken into account using a relevant effective stress evolution.

4 CONSTITUTIVE RELATIONSHIPS

In order to solve (1) or (4) the representative constitutive laws σ'(e) and k(e) are definitely needed, which is the most difficult part of the task as these parameters can only be obtained through experimental ways for a given mud.This is all the most difficult as we deal with cohesive sediment and a very large range of concentration (BERLAMONT, 1992).

These two specificities also put the stress upon the necessary link between hydraulics and soil mechanics with a mutual benefit.

We have brought together experimental data issued from a hundred tests available in litterature. Our will was to mix the results of available experiments, in order to point out common trends although the experimental conditions and the soil composition were different in these various tests.

Void ratio was chosen as the main parameter, consistently with geotechnicians' habit. Bibliographic data were harmonized by transforming the other parameters (water content, density, dry density, weight concentration, volumetric concentration).When needed,the average value of 2,65 was taken for the density of solid particules.

For the effective stress, 48 experimental curves from IMAI (1981), UMEHARA and ZEN (1982), PANE *et al.*(1982), YONG *et al.*(1983), TAN *et al.*(1988) have been used.

A random distribution could have been expected, but in spite of the scattered dots, fig.2 shows a trend of the effective stress. This trend is in agreement with the effective stress shape introduced to link sedimentation and consolidation in part 3.

The next stage will consist of separating dots in different families by taking into account their plasticity as the main parameter of their nature.

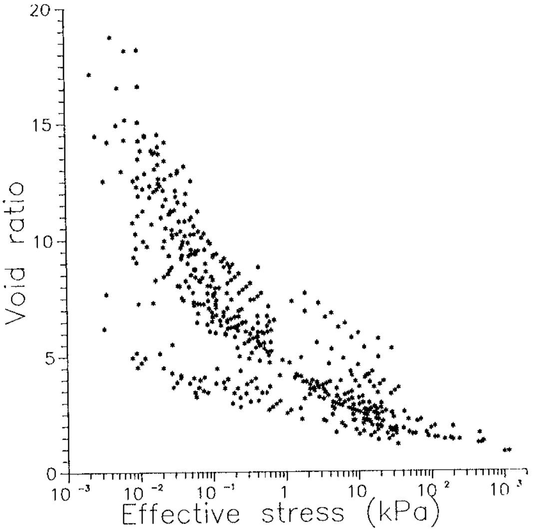

Fig.2: Gathering of effective stress literature experimental data.

A similar diagram has been drawn for the relationship between void ratio and permeability.We have used here 10 experimental curves from PANE *et al.*(1982),YONG *et al.*(1983), TAN *et al.*(1988), TAN *et al.*(1990) and TOORMAN (1992). Permeability or consolidation tests data are shown in fig.3a, down to a concentration of 300 g/l.In order to represent (fig.3b) very low concentration data, down to 50 g/l, settling velocity data (white squares in fig.3b) were transformed in permeability, using the correspondence:

$$v_s = \frac{k}{\gamma_w}(\gamma' - \frac{\partial \sigma'}{\partial x})$$

with a zero effective stress.

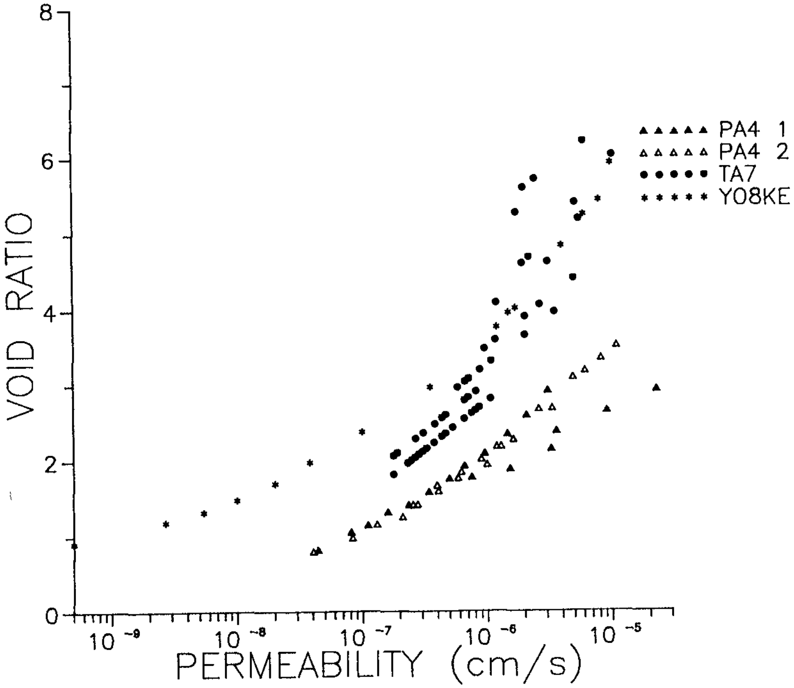

Fig.3a: Gathering of permeability literature experimental data (without settling velocity data).

The trend seems to be of the same nature on these diagrams, except for the fact that higher effect of the soil composition or structure may lead us to imagine several curves.

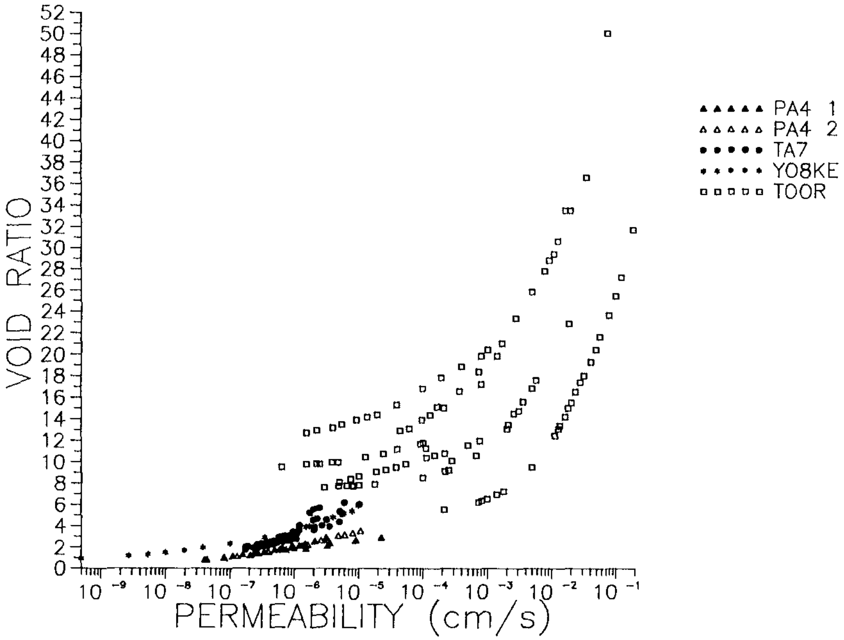

Fig.3b: Gathering of permeability literature experimental data (including settling velocity data).

5 NUMERICAL MODELLING

Gibson's equation expresses time and vertical evolution of the void ratio e, and can be easily modelled as a 1 D vertical advection-diffusion equation, except for the cost of computing due to the required fine vertical discretization. The equation is formulated in finite differences and solved with a semi-implicit numerical scheme. But the main problems lie in the appropriate formulation of the boundary condition at the interface between water and consolidating bed, and in the determination of the constitutive relationships k(e) and $\sigma'(e)$, i.e. permeability and effective stress as a function of the void ratio. Experimental settling tests of BEEN and SILLS (1981) have been satisfactorily reproduced with our model.The simulated height of the sediment column is in good agreement with the experimental one (fig.4). Density at bottom is well represented but little discrepancies appear in the middle of the column (fig.5).They are probably due to the rather high sensitivity of the model to the constitutive relationships.

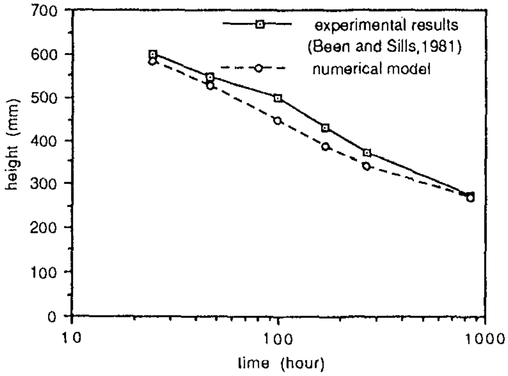

Fig. 4: Time evolution of total height of deposit.

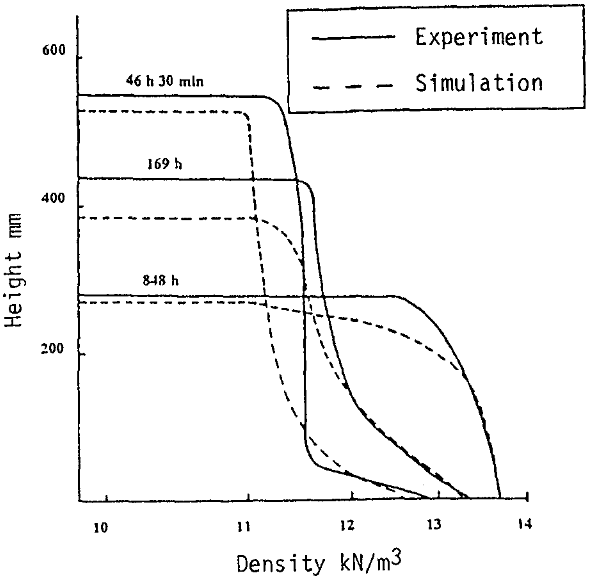

Fig. 5: Comparison of simulation with experiment profiles of BEEN and SILLS (1981).

6 IN SITU EXPERIMENTS

Some specific characterization tests are essential to evaluate fine cohesive sediments properties in muddy intertidal environments, in order to determine the relevant parameters for modelling mud erosion and deposition processes and to confront the results of previous theories and simulations with real situations. The involved parameters are naturally the concentration (or dry density) of the surficial sediment but also its shear strength which is assumed to be correlated with the "rigidity" of the mud.

In a same cross-section of the Elorn estuary (Brittany), small cores have been sampled in three locations of the intertidal area, according to three different mud levels, at several moments of the tidal cycle, during spring or neap tides, in winter and summer (december 1990 - june 1991 - january 1992). From these cores, vertical profiles of water content, dry density and yield stress have been measured every two centimeters, just after sampling. Yield stress mesurements are made with vane testers which are specifically fitted to soft muds. A short synthesis from some of these cores is presented here. The resulting profiles show classical increases of concentration and shear strength over the first ten centimeters. The gradients can vary according to the tidal amplitude, the season and the location along the cross-section.

Tidal variations

The effect of the tidal amplitude is more noticeable in the lower part of the mud bank where large irregular variations of dry density appear on spring tides, probably due either to stronger flows or to drainage processes in the cross-section of the mud.

As for the variation during the tidal amplitude, measurements show larger concentrations as well as higher yield stresses before the covering by the flood than just after the uncovering during the ebb, but the differences are only perceptible for the 2-3 upper centimeters. This phenomenon can lead to a variation of mud erodibility within the tidal cycle.

Seasonal variations

The comparison between winter and summer data, at the same level of the intertidal flat (fig.6 and fig.7), points out more extended gradients in winter, when the surficial mud is less concentrated and less stiff.

These seasonal variations can be attributed to modifications of the deposit rate - due either to erosion elsewhere (L'YAVANC and BASSOULET, 1991) or to temperature effects or more probably to biological processes; several past studies have pointed out the role of biota seasonal variations and, in addition, some positive correlation between the organic content and the shear strength of the mud (see for example MONTAGUE, 1986).

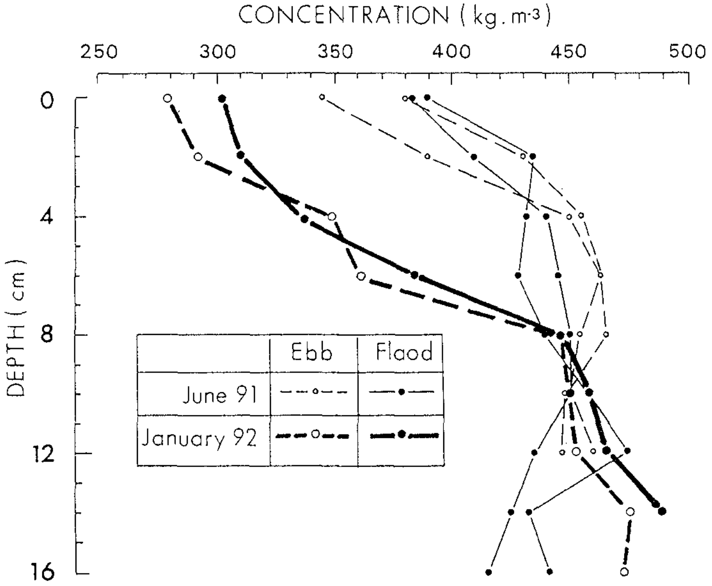

Fig. 6: Concentration profiles at a same location. Winter and summer measurements. Spring tide.

From all these results, it appears that the state of the surficial mud can change according to various processes which are not presently included in theories and models. On the other hand, a rather good correlation between concentrations and yield stress has been obtained and if we assume an additional correlation between yield stress and erosion processes, the previous direct *in situ* measurements can give information on the erodability of natural mud in an intertidal environment.

7 CONCLUSION

The purpose of our survey was first to make a scanning of previous theories with the attempt to bring the light on the implied assumptions and to classify them.

In order to make a skimming of their most representative qualities we have attempted to develop an original formulation with less restrictive assumptions than before.

Gathering experimental literature data has allowed us to distinguish general trends of effective stress and permeability evolution for a large range of void ratios.

In spite of the usual difficulty to obtain relevant constitutive relationships (effective stress and permeabiblity), we have tried to simulate numerically a sediment settling in a laboratory column with a pair of experimental constitutive laws and have obtained a positive result.

But in situ experiments have shown that our theories still have to be improved, taking into account many other parameters, not considered up to now.

These complementary approaches should lead to a better description, understanding and modelling of consolidation processes, which will benefit to models of cohesive sediment transport.

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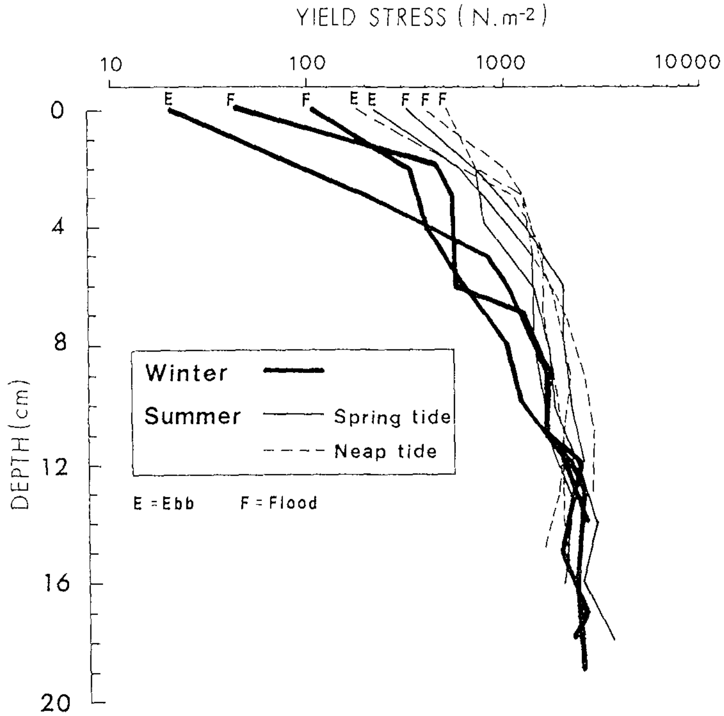

Fig. 7: Yield stress profiles at a same location. Winter and summer measurements.

Symbols

e : void ratio
k : permeability
k_r: reduced permeability
t : time
u : over pore pressure
u_w: pore pressure
u_0: hydrostatic pressure
v_m: mean relative velocity of water
v_s: velocity of solid particules
x : Eulerian coordinate
z : material coordinate

γ : unit weight of soil
γ_f : unit weight of fluid
γ_s : unit weight of solid particules
γ_w : unit weight of water
γ' : unit weight of submerged soil
γ'_s: unit weight of submerged solid particules
σ : total stress
σ' : effective stress

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