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Consolidation of high water content soils in an estuarine environment

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ABSTRACT

The constant silting up of ports and estuaries makes it necessary to carry out dredging operations to ensure free access to port infrastructure. The dredged materials are disposed of at sea, with the creation of a maritime deposit, or stored on land in decantation pools. In each case, this leads to the creation of high water content soil. This paper presents a geotechnical laboratory approach to the formation of high water content soils on an experimental sedimentation/consolidation test bench. The original feature of this test bench is that it is possible to carry out highly accurate pressure and density measurements in a time very close to the beginning of the test. These measurements are used to analyse the changes in the total stress, the pore pressure, and the effective stress. On a diagram showing the void ratio/effective stress, we have highlighted the changes in the intermediate phases of the formation of a natural soil which consolidates under its own weight.

INTRODUCTION

High water content soils are often at the centre of delicate industrial and environmental problems, particularly concerning the behaviour of port or estuary mud, and deposits at sea.

In soil mechanics, an understanding of the behaviour of soils is based upon the concept of effective stress proposed by Terzaghi (1936) and defined by the difference between the total stress and the pore pressure. Theoretical studies (Alexis et al. 1992) highlight the effective stress as the main constitutive law for the numerical modelling of soil sedimentation/consolidation.

However, the behaviour of high water content soils may be influenced by creep flow, flocculation, and segregation phenomena. Good knowledge of the behaviour of the soils is gained through carrying out suitable tests under well-controlled laboratory conditions.

The overall pace of soil formation through deposition is shown in Fig. 1 (Kynch 1952). Initially, the upper part behaves like a suspension, the settling of which is determined by the concentration alone (Kynch 1952). Later, a soil skeleton develops, characterised by a difference between the total stress and the pore pressure. It is the appearance of the effective stress, which marks the beginning of the consolidation phase. After a certain concentration is reached, when the particles interact with neighbouring particles, a continuous structure forms which can support part of its own weight. The consolidation phase begins. Flexible junctions between the particles allow for the slow deformation of the structure under the effect of its own weight.

The structure slowly settles under the effect of its own weight, expelling water contained in its pores. The interstitial water is subjected to major losses due to hydraulic friction as it rises to the free surface above the mud deposit. As long as the system is not in equilibrium, the pore pressure is higher than the hydrostatic stress, the difference being referred to as the pore overpressure (u).

The consolidation continues till there are overpressure gradients creating a rising flow leading to the expulsion of the water from the pores. The final equilibrium is reached when the overpressures totally dissipate.

EXPERIMENTAL TEST BENCH

The study of the behaviour of high water content soils in consolidation requires special instruments. Been (1981), Toorman (1992), and Berlamont et al. (1992) introduced specially adapted experimental devices based on density measurements using X or gamma rays, but the devices are not able to produce profiles during the first phase of the

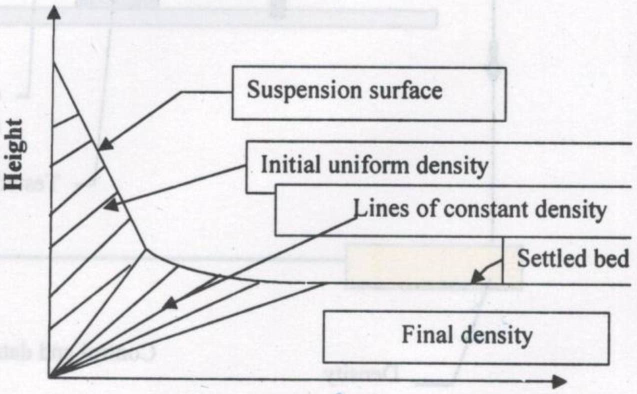

Fig. 1: Typical Kynch plot of constant concentration lines

tests. Our experimental test bench (Fig. 2) can measure pore pressures and densities within the material during formation under its own weight.

In our laboratory, we used transparent columns of 90 mm in internal diameter with a usable height of 1500 mm. These columns are placed in a room maintained at a constant temperature of 10° C in order to avoid the formation of gas through the decomposition of the organic matter contained in the material. The mixture is introduced into the column through the top open extremity and may be maintained in a homogeneous state through manual movement using an agitator. The density and pore pressure profiles are automatically produced by the Data and Control Unit (Fig. 2).

DENSITY MEASUREMENTS

The density measurements were carried out using gamma densitometry. The calibration of the gamma densitometer was carried out using two products of known density (demineralised water and consolidated silt). The measurement accuracy of the gamma densitometer used was 5/1000.

PRESSURE MEASUREMENTS

Ten equally spaced pressure measurement intakes were fitted to a generative line of the column. Particular care was given to the mounting of these intakes to ensure that they were situated at very precise points (absolute location error less than 0.01 mm). They were connected to a rotary distributor allowing for the selection of one of the intakes in order to connect it automatically to a single pressure measurement sensor. Filters (of the cigarette filter variety) made it possible to measure only the water pressure. These filters avoid the problems of clogging during tests. The accuracy of the pressure measurement sensor is theoretically +/- Pa. In practice, the accuracy of our pressure measurement was about +/- 3 Pa.

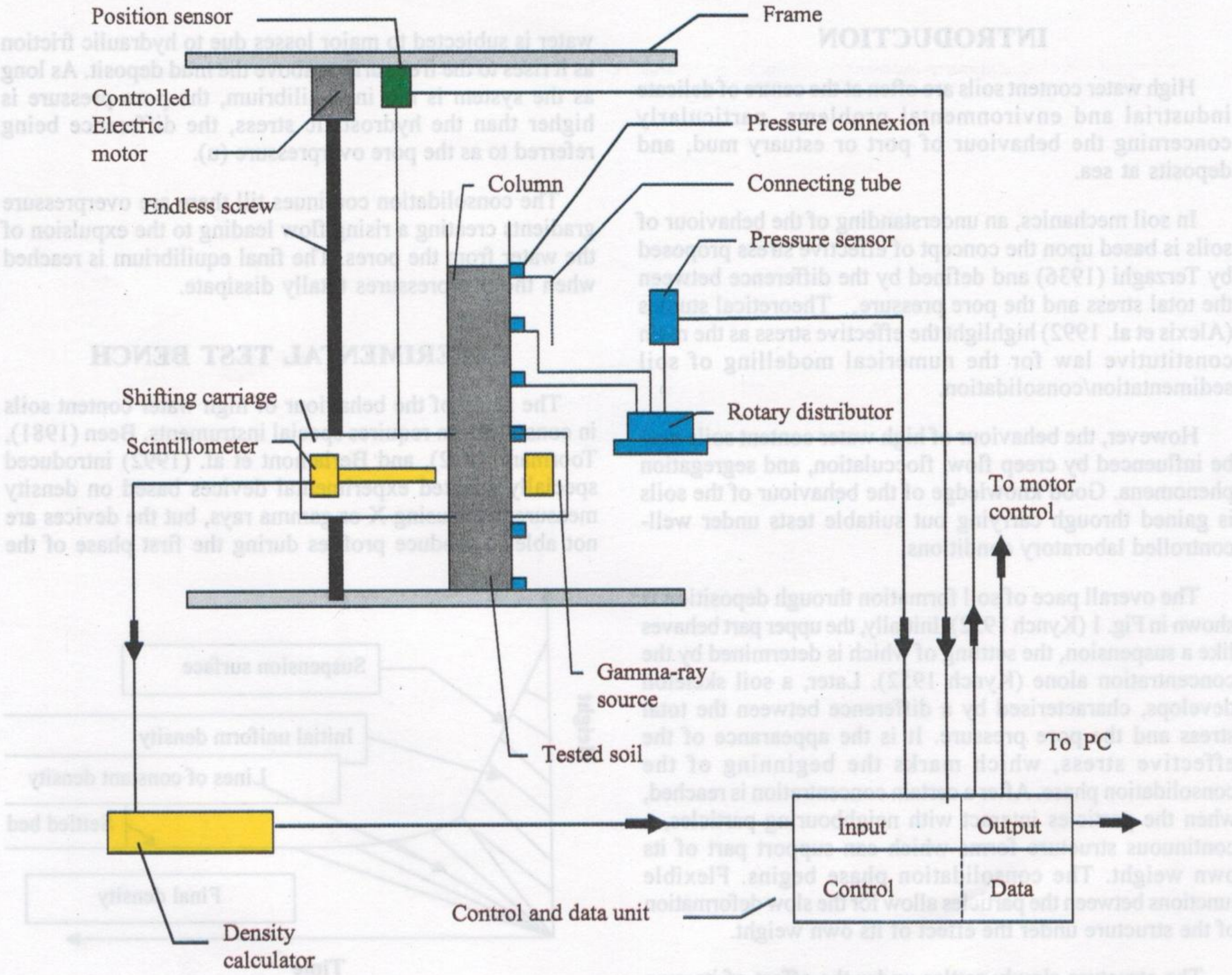

Fig. 2: Sketch of the gamma-densimeter bench

CALCULATION OF EFFECTIVE STRESS

The total stress (at all points) is obtained through the integration of the density profile measured on the column. The effective stress is obtained through the difference between the total stress and the pore pressure measured.

The effective stress represents the portion of the total stress supported by the grains. It is zero in pure sedimentation and progressively increases with the consolidation of the material (dissipation of the pore overpressures).

EXPERIMENTAL RESULTS

The standard sedimentation/consolidation test involves the introduction of a mixture of natural seawater and a high water content soil into the column. This is prepared at a given concentration and allowed to develop freely under the effect of its own weight.

We present the results obtained in our laboratory on a natural soil taken from the Loire estuary (France) with an initial density of 1.12 (corresponding to a concentration of 200 g/l). Within the soil, 82% of particles were smaller than 63 µm and 18% smaller than 2 µm.

Density

The experimental device allowed us to obtain the first density profile at 1.33 minutes while the first profiles presented in the bibliography were obtained, depending on the authors, between 10 and 45 minutes. For the test presented here (Fig. 3), we noted that the first 8 density profiles (up to t = 1 hour 30 minutes) were virtually vertical, except at the top and bottom of the column.

The profile at t = 3 hours marks the true beginning of the deposition process of the material and shows a clear increase in density in the upper part of the column. It was necessary to wait for the profile for 8 days in order for the density to be virtually constant once again. At 45 minutes the density of the seawater was reached at the top of the column (clear water). Gradually, a mud deposit formed with a final height of 686 mm at the end of the test at 32 days, representing a settling ratio of approximately 54% of the initial height.

Pore over pressure

The pore overpressure is obtained through the difference between the measured pressure and the hydrostatic pressure. Fig. 4 shows the changes in pore pressure over the 32 days of the test. The initial distribution is virtually triangular. The pore overpressure then gradually dissipates with the evacuation of the water contained in the pores. At the end of the test, the pore overpressure at the base of the column had only dissipated by 50 per cent compared to its initial value.

Effective stress profile

Fig. 5 shows the changes in the effective stress across the column height according to time. We note that, from the very first profiles (1.33 minutes to 1.5 hours), the effective

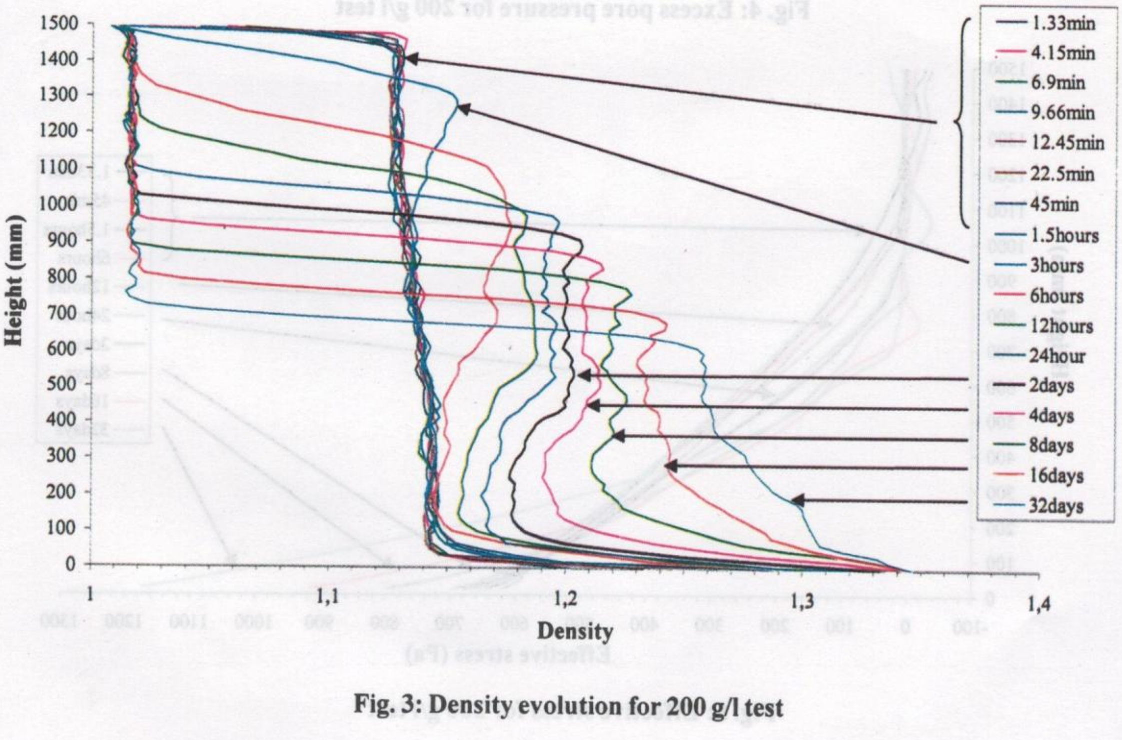

Fig. 3: Density evolution for 200 g/l test

stress shows a triangular distribution pattern with a major value at the base of the column. Therefore in this test there is no phase comparable to hindered settling where the effective stress will be zero. The first phase is a consolidation phase.

During the settling process, the effective stress gradually disappears at the top of the column (clear water). At the base of the column, the effective stress increases regularly until reaching the value double that measured at the beginning of the test.

Particle trajectory

Net total stress

By subtracting the value of the hydrostatic pressure due to natural water from the total stress we obtain the values of the net total stress. This stress is constant at the base of the column and represents the weight of the dry material introduced into the column. This stress decreases over time for a given value, expressing the reduction of the quantity of material above this value under the effect of the descent of the material (Fig. 6).

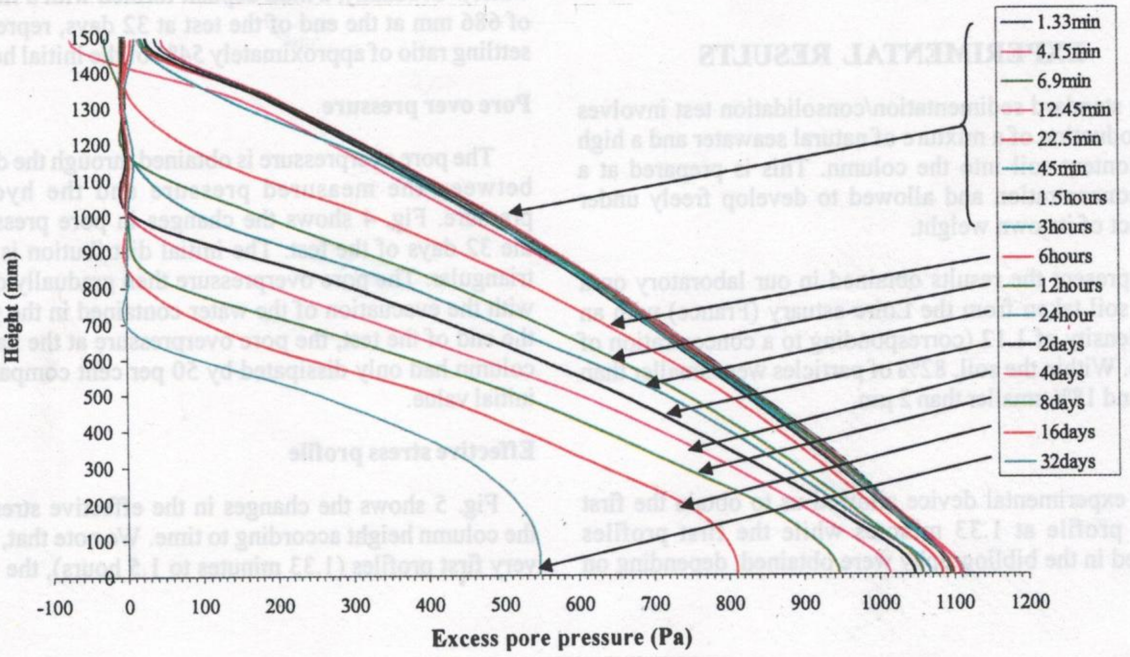

Fig. 4: Excess pore pressure for 200 g/l test

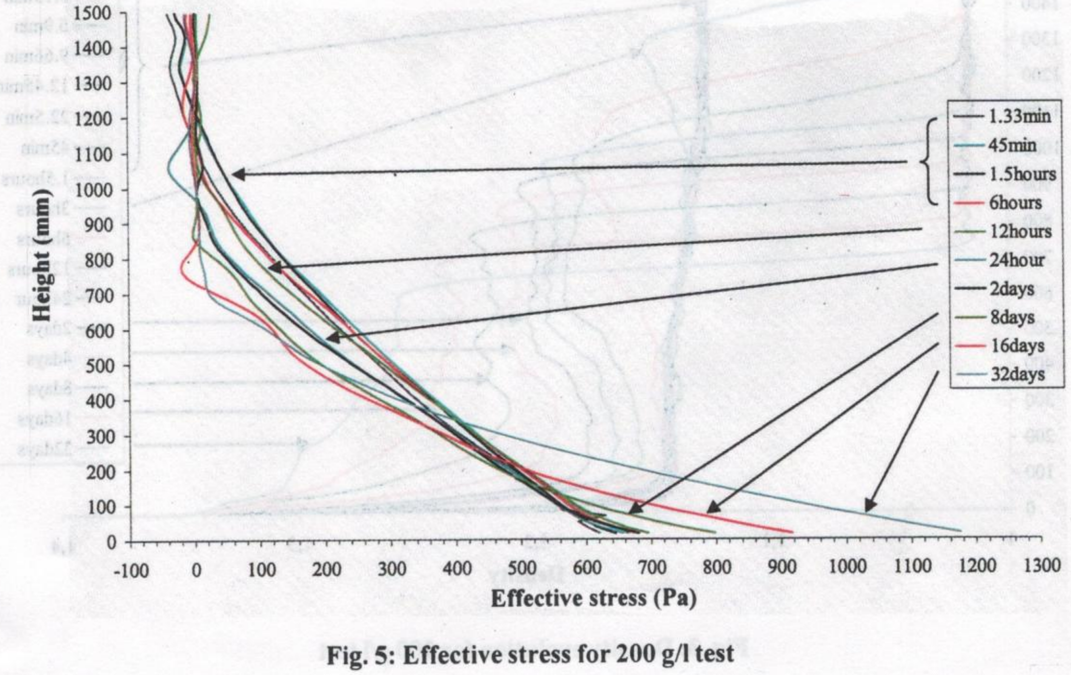

Fig. 5: Effective stress for 200 g/l test

Iso-net total stress

The iso-net total stress value is a Lagrangian coordinate. The iso-net total stress curves make it possible to work out the trajectory of given particles (Fig. 7), assuming an absence of grain migration between the various layers of material.

Like the density profiles, these curves show that it is necessary to wait 3 hours before noticing a significant descent of the grains. We also noted that the movement began at the top of the column.

EFFECTIVE STRESS AND VOID RATIO

For a given section of soil (along an iso-net total stress), we have presented its respective void ratio and effective stress values (Fig. 8). We have noted two distinct parts: (i) the one hand an intermediate phase characterised by a strong reduction in the quasi-constant effective stress rating, each curve being dependent on the initial position of the layer in the column (Lagrangian nature of the net total stress) and (ii) a single consolidation phase, upon which the curves of the intermediate phase are added.

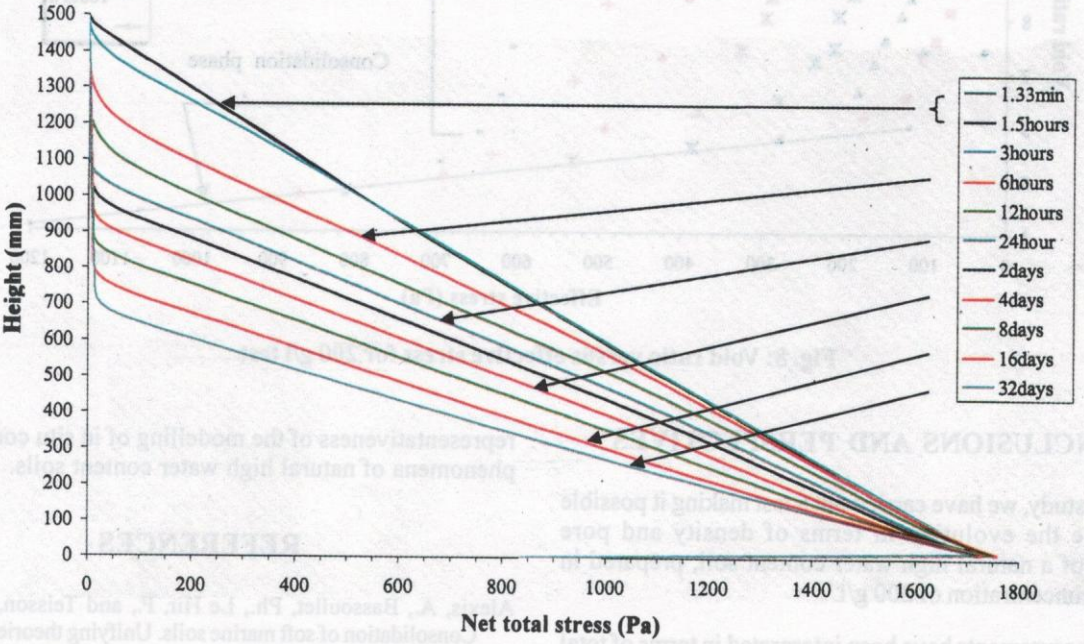

Fig. 6: Net total stress for 200 g/l test

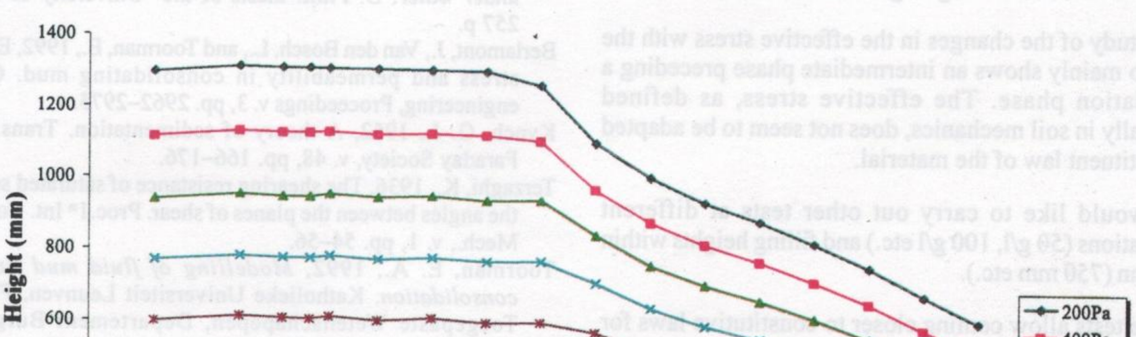

Fig. 7: Particle trajectory for 200 g/l concentration

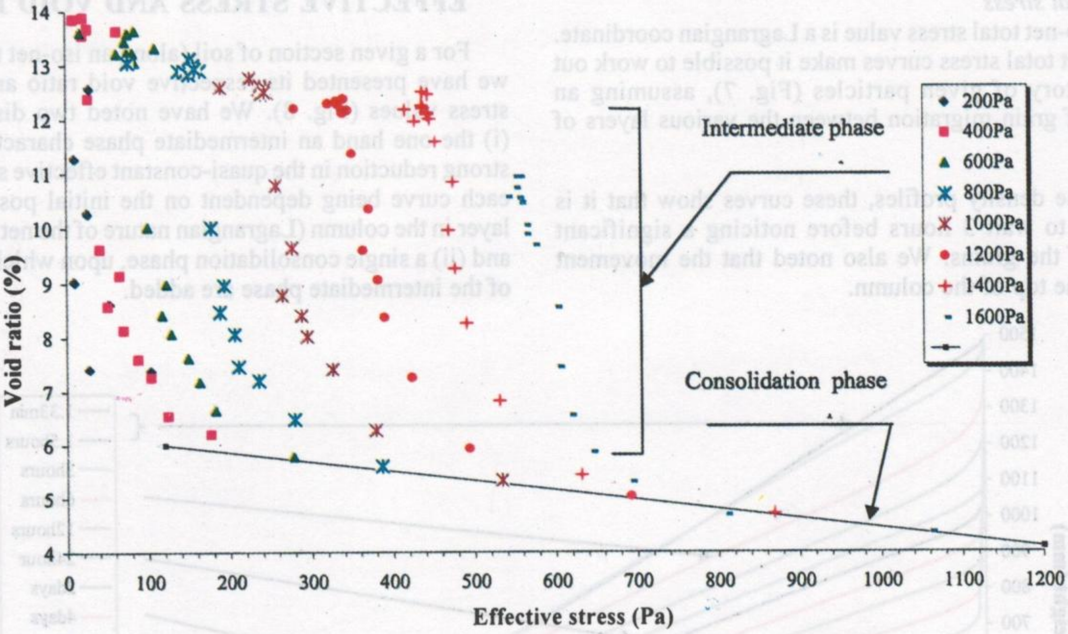

Fig. 8: Void ratio versus effective stress for 200 g/l test

CONCLUSIONS AND PERSPECTIVES

In this study, we have carried out a test making it possible to observe the evolution in terms of density and pore pressures of a natural high water content soil, prepared in an initial concentration of 200 g/l.

The measurements have been interpreted in terms of total stress and pore overpressure. The proposed analysis makes it possible to trace the elementary layer trajectories using the net total stress as a Lagrangian coordinate.

The study of the changes in the effective stress with the void ratio mainly shows an intermediate phase preceding a consolidation phase. The effective stress, as defined traditionally in soil mechanics, does not seem to be adapted as a constituent law of the material.

We would like to carry out other tests at different concentrations (50 g/l, 100 g/l etc.) and filling heights within the column (750 mm etc.).

These tests allow coming closer to constitutive laws for this type of material in order to improve the representativeness of the modelling of in situ consolidation phenomena of natural high water content soils.

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