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Large-scale Dewatering of Fine-grained Dredged Material

Abstract

The disposal of fine-grained material from maintenance dredging activities is an increasing problem for most industrialised areas. Rapid dewatering of dredged material is a major item to optimise the use of the available storage volume. This article describes the large-scale pilot tests for the treatment and storage of the dredged material as well as the monitoring and experimental tests such as settlement columns and mathematical consolidation tests.

The laboratory experiments discussed here were carried out at the Catholic University (Katholieke Universiteit) Leuven, Belgium by Lut Van den Bosch and Heidi Huysentruyt. Some of this work has been undertaken as part of the MAST-2 G8 Coastal Morphodynamics Programme, funded partly by the Commission of European Communities, Directorate General for Science, Research and Development, under contract MAS2 CT92-0027. The pilot project was realised by a joint venture of Dredging International NV, Ondernemingen J. De Nul NV and Baggerwerken De Cloedt & Zoon NV on behalf of the Flemish Government, Department of Environment and Infrastructure (DOLSO).
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Introduction

The disposal of fine-grained dredged material from the maritime navigation channels becomes increasingly difficult and necessitates authorities to take a global approach. Such an approach is outlined in a companion paper (Smits *et al.*, 1997) dealing with the optimisation of dredging and disposal equipment for fine-grained sediments and the beneficial use of dredged material. Because in most industrialised areas only limited surfaces and volumes can be made available for the

Figure 1. Layout of the dewatering fields.

storage of dredged material it is very important that these volumes will be used as efficiently as possible. Especially for fine-grained material it is important that the material is stored with a low water content, for the following reasons:
– to reduce the volume; and
– to improve the geotechnical characteristics of the disposal site.

In order to attain these goals a large-scale testing and study programme has been executed in Belgium since 1990. This programme aimed to increase the natural settling and consolidation phenomena as much as possible in specially designed dewatering fields until a stable clay-like material has been obtained which can be used for beneficial applications such as landscape projects.
In order to optimise the compaction of dredged material, a good understanding of its consolidation behaviour is necessary.
This paper focusses on the in-situ and laboratory consolidation measurements used to evaluate a different drainage system for prototype dewatering fields with a surface of approximately 25 ha. Because the deposition and consolidation process in the field occurs essentially in the vertical direction, these processes in the sediment-water mixture have been modelled under one-dimensional conditions in the laboratory.
This involves laboratory tests under controlled conditions where measurements can be carried out without disturbing the weak soil structure. Computer models are required to extrapolate the laboratory experiments and to predict the field situation.
Several parameters influence the consolidation behaviour: temperature, light, initial concentrations and thickness, filling rate, sediment composition (particle size fractions, organic matter), ions in the pore water (e.g. dissolved salt) and meteorological conditions.
There is also a significant difference in the consolidation behaviour in underwater disposal sites and disposal on land, because the initial density under water is reduced owing to mixing with water, which allows the coarser material to segregate.

Dewatering Fields: In-situ Consolidation

A pilot plant for the dewatering of fine-grained dredged material was installed on the Left Bank harbour area of Antwerp, consisting of five dewatering fields of approximately 4.5 ha each (Figure 1). The dewatering fields were filled in successive layers with dredged material from the river Scheldt (between 11/04 and 29/06/1990): approximately 286,000 m^3 equivalent to 157,000 tonne dry solids (TDS) were dredged with a small cutter dredger. The dredging procedure was as follows:
1. filling the basin without evacuation of the process water;
2. initial settlement of dredged material;
3. withdrawing the surface water from the field;
4. refill the basin with an extra amount of material;
5. repeat step (2).

Detailed filling characteristics are listed in Table I.
A general view of the silt level variations in a dewatering field is given on Figure 2. Further details are given by Van Mieghem *et al.* (1991). In each field a different combination of drainage and surface dewatering systems has been applied to enhance the natural consolidation process (Table II and Figure 3).

Table I. Filling characteristics in the fields

Field nr.	Surface [m2]	# of fill operations	Total height [m]	Height after settlement [m]
L1	42.612	7	4.0	1.64
L2	42.612	6	3.6	1.75
L3	40.216	6	4.8	2.09
L4	64.056	6	4.0	1.93
L5	44.160	7	4.0	1.74

Table II. Applied drainage techniques in dewatering fields

Field nr.	Underdrainage	Evaporation enhancement
L1	gravitational	no
L2	drains and vacuum	vegetation (after 3 months)
L3	no	vegetation (after 3 months)
L4	no	amphirol and discuswheel (after 4 months)
L5	gravitational	amphirol and discuswheel (after 4 months)

A monitoring programme was set up to evaluate the behaviour of the consolidating material and to identify the physical characteristics of the material in the borrow area by means of eight corings, vane-tests and an accompanying laboratory investigations .

Geo-technical characteristics

The average geo-technical characteristics of the material in the borrow area are:

- in situ density: r_n = 1.34 t/m3
- water content: w = 149 %
- specific weight of the grains: r_s = 2.695 t/m3
- organic matter: 8.6 %
- void ratio: e = 4.05
- grain size distribution:
  d_{50} = 7Mm
  sand (d> 63Mm) : 3.3%
  silt (63Mm >d> 2Mm) : 64.9%
  clay (d< 2Mm) : 31.5%

Consolidation process

A continuous follow-up of the silt in the dewatering fields was executed during the consolidation process including the following items:

- regular control of water of the silt level in the dewatering fields;
- periodic detailed campaigns of in-situ density measurements during the first four months;
- periodic measurements of the in-situ shear strength during eight months;
- periodic inspection of the fields; and
- chemical analysis of the silt.

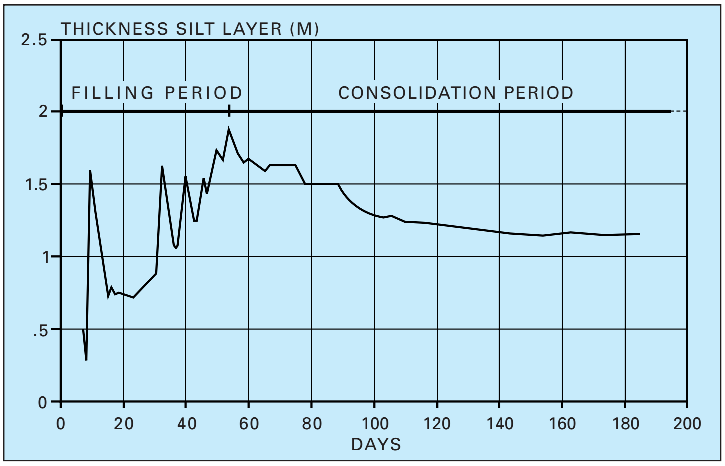


Figure 2. Layer thickness in a dewatering field.

Figure 3. Surface drainage: creation of a ring ditch.

Boundary conditions

A follow-up of the boundary conditions was conducted:
- a self-registering meteo station (rain, wind, temperature, sunshine, and so on, are continuously registered); and
- daily control of the groundwater levels around the dewatering fields.

Furthermore the physico-chemical characteristics of the material as well as the geo-hydrological behaviour of the test site have been measured during the preparatory phase of the project and monitored throughout the pilot test execution (IMDC, 1992).

Results of the Consolidation Monitoring

The consolidation of the material in the deposit was monitored daily during the dredging operations and afterwards on a weekly basis. The results (Table III) illustrate the quicker consolidation in fields L1, L2 and L5 where underdrainage techniques were applied: During the first four months the thickness in the drained fields was reduced with 35%, whereas the reduction was limited to 25% in the undrained fields.

Using the results of the density profiles combined with the evolution of the mud thickness, the total amount of dry solids in the fields was checked for each survey, resulting on average in 155,000 TDS to be compared to the estimated initial dredged quantity of 157.000 TDS. The variation of the average density in the fields is shown inTable IV and Figure 4.

After four months mechanical techniques were applied to further enhance the dewatering process. First an amphirol was deployed with poor results. Later ditches were dug with traditional earth-moving equipment to generate horizontal pressure gradients which enhance the drainage. The improvement of the evaporation by vegetation was obtained by sawing a mixture of grass species in fields L2 and L3. This operation was done after three months of consolidation (beginning of autumn). During the first (winter) months the effect was limited but in spring, owing to the natural plant growth on the consolidating mud, the vegetation improved drastically.

The consolidation tests in the pilot fields were finalised in approximately one year, but owing to difficulties in obtaining the necessary permits and credits the consolidated material remained in the testfield for a period of approximately three years. Once the permits were acquired, the consolidated mud was used for a large-scale landscaping test to create green buffer hills between the industrial port area and the agricultural area in the surroundings (see Figure 5). The in-situ density of the mud had further increased by self-weight consolidation to an average value of 1.48 t/m^3, with small differences between the different fields. Over the total height of 0.82 m, the density increased gradually with 0.14 t/m^3. In the landscaping project an average density of 1.62 t/m^3 was obtained after compactions which corresponds to the density of soft clay.

Laboratory Tests

The consolidation behaviour of many mud samples from the river Scheldt has been studied in the Hydraulics

Table III. Evolution of the mud thickness

Field nr.	Initial height [m]	Height [m] after n days				Reduction
		30	75	90	120	[%]
L1	1.64	1.33	1.10	1.07	1.07	65
L2	1.75	1.33	1.18	1.16	1.15	65
L3	2.09	1.86	1.61	1.58	1.58	76
L4	1.93	1.66	1.47	1.47	1.45	75
L5	1.74	1.30	1.11	1.10	1.09	64

Table IV. Evolution of the mud density

Field	Initial density[t/m^3]	Density [t/m^3] after n days			
		30	75	90	120
Average	1.223	1.272	1.314	1.318	1.318
Drainage	1.223	1.285	1.333	1.345	1.345
No drainage	1.223	1.255	1.290	1.293	1.295

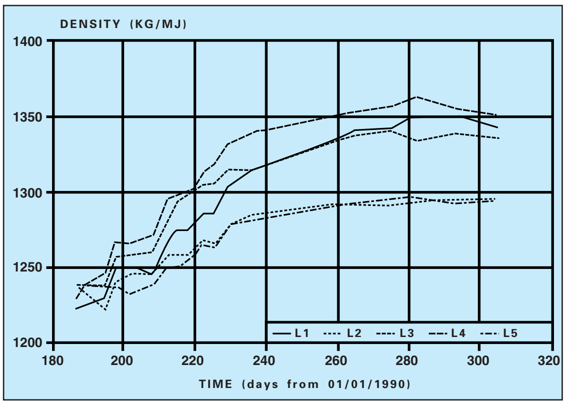


Figure 4. Density profile evolution in field L2.

Laboratory of the Katholieke Universiteit (Catholic University) Leuven, Belgium. The aims of these tests are:

1. the determination of the relevant consolidation parameters and calibration of the constitutive equations; and
2. the evaluations of different dumping schemes and drainage systems. Tests are carried out in transparent columns.

Density and pore-water profiles and the mud-water interface level are recorded at regular time intervals.

During a preliminary test service, the influence of the columns diameter on the consolidation test results was studied. Owing to wall friction the consolidation rate may reduce with decreasing column diameter and/or layer thickness and with increasing wall roughness (Huysentruyt and Berlamont, 1993). These tests showed that a minimal diameter of 100 mm (for smooth column walls) is recommended.

Drainage tests

The laboratory set-up used for most of the consolidation tests under drainage conditions is presented schematically in Figure 6. The density is measured at increasing intervals with a gamma-transmission probe. Pore pressures are measured with standpipe piezometers, which are not more problematic to work with than electronic ones (same accuracy, no electronic drift, but capillary effect). The drainage pressure is regulated by adjusting the level of the recipient reservoir.

The tests have been conducted during approximately four months. Further details on the test installation can be found in Mengé *et al.* (1991) and Berlamont *et al.* (1993).

The settling columns are placed in a dark, temperature-controlled room and tests are performed at 10°C, which corresponds roughly with the temperature of the sediment on the bottom of the river Scheldt. In this way fermentation is reduced which allowed a considerable prolongation of the test period without disturbance by natural gas production

Figure 5. Test site for landscaping (hill in the middle of the photo).

Figure 6. Consolidation column set-up in laboratory.

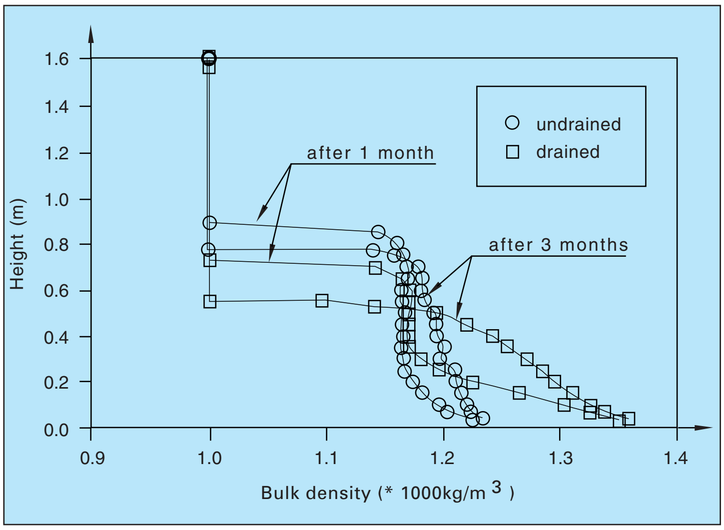
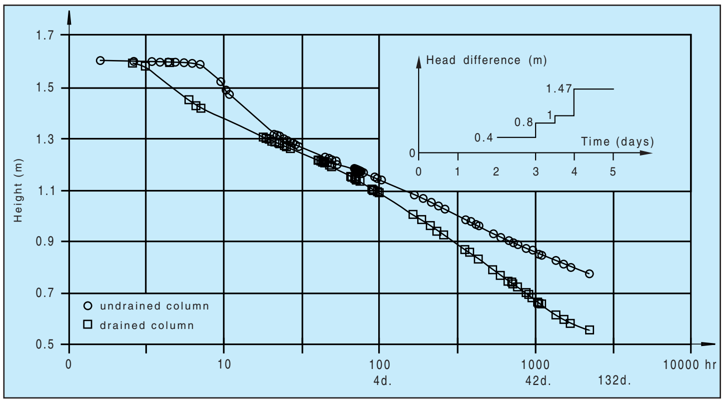


Figure 7. Density profiles for columns KO5 (undrained) and KO6 (drained).

Figure 8. Consolidation curves for columns KO5 (undrained) and KO6 (drained).



Results

As a result of drainage, the hydraulic gradient changes sign and consequently the mud layer can be separated into two layers. The top layer is drained upwards as in batch consolidation tests. The bottom layer is drained downwards. The thickness of the latter layer relative to the total layer thickness increases with time.

The density profile (Figure 7) of the bottom layer has a much steeper density gradient and results in higher densities. Hence, as expected, drainage results in a higher compaction. However, because of the high hydraulic gradient in the bottom layer, the density increases rapidly such that the permeability is decreasing and the dewatering of the silt deposit will be slowed down.

However it is clear that an underdrainage system clearly enhances the dewatering of a mud deposit (Figure 8). The final layer thickness decreases with increasing imposed pressure head difference. The final compaction in the drained columns was about 10-20% higher than in the undrained test. The best result was obtained when the imposed head difference was (stepwise) varied with time, because a too- high initial head difference seems to slow down the upwards dewatering. Unfortunately this would require a very controlled evacuation of the process water which is very difficult to realise in a large-scale dewatering field.

Modelling Consolidation

Mathematical models generally consider only one-dimensional vertical consolidation. Since mud is a soft, often over-saturated soil which allows large deformations, the infinitesimal strain theory of Terzaghi (1923) cannot be applied. Instead one has to use the more general non-linear finite strain model developed by Gibson *et al.* (1967). An excellent review of consolidation models is given by Schiffman et al. (1985). Toorman (1994) proposed to use the sediment concentration as independent variable, rather than the void ratio, used in soil mechanics, because then the behaviour of sediment mixtures can be studied numerically by solving the mass balance of each fraction.

The success of this approach has been demonstrated in earlier papers (e.g. Toorman, 1993). The first governing equation is the sediment mass conservation:

$$\frac{\partial \phi}{\partial t} + \frac{\partial (v\phi)}{\partial z} = \frac{\partial \phi}{\partial t} - \frac{\partial S_s}{\partial z} = 0 \qquad 1$$

where: f = sediment volumetric concentration; v = sediment particle velocity; z = vertical co-ordinate, positive in the upward direction; t = time; S_s = -vf = sediment flux. The second equation is the saturated soil stress balance (or Darcy-Gersevanov law), which can be written in its most general form as (Toorman, 1994):

$$\frac{1}{g}\frac{\partial \sigma'}{\partial z} = -(\rho_s - \rho_w)\,\phi + \rho_w \frac{U-v}{k} \qquad 2$$

where: U = averaged velocity = fv + (1-f)u, which is zero when there is no drainage; u = pore water velocity. These equations contain three consolidation parameters, i.e. settling rate (v), permeability (k) and effective stress (s¢). One of these parameters can be eliminated by substitution of equation (2) into (1).

The remaining parameters are obtained experimentally.

Discussion of Results

Comparison between field and laboratory data

In order to evaluate the different results from the field and laboratory experiments, one has to take into account that the conditions in the laboratory tests are not identical to those in the field (Figure 9).

None of the drainage systems in the fields could be fully represented in the laboratory study, because the experimental set-up only allows vertical drainage. Nevertheless, measured density profiles in drained column tests are comparable to those measured in the field (compare Figures 2 and 6). Comparison suggests that the initial density for the column tests was too low, but should have been of the order of 1150 kg/m^3 instead of 1100 kg/m^3 (this to obtain optimal similarity with the in-situ tests).
Another difference between the field and the laboratory is the filling rate. The fields were filled irregularly over a period of nearly two months, while in the laboratory it took only a few minutes. It is known that this can result in very different compaction owing to differences in stress history (Elder and Sills, 1984).
The compaction in the drained column was about twice as large compared to the drained fields. This could be contributed to the more difficult underdrainage systems in the fields and the probably lower relative sediment content.

Model limitations
Results from mathematical models are generally restricted to batch consolidation. In the case of drainage this, requires an additional equation for the average velocity, which equals the flow rate of the percolate, which in its turn is a function of the permeability and the pressure gradient at the bottom. No method is known which is able to solve this problem.

Figure 9. In-situ sampling and density measurement pontoon.

Numerical simulations of batch consolidation tests give good results. However, when used for predictions of the consolidation of a mud layer in different conditions, there can be a significant discrepancy (Toorman and Berlamont, 1991). Similarly, however, laboratory tests on the same mud, but with different initial density or different dumping rate, can also produce significant differences, even in the obtained relationships between the consolidation parameters and concentration. There is a general agreement that this is caused by differences in stress history, and thus structural differences.

These structural effects are controlled by the break-up rate during dredging, the shear flow during hydraulic transport in pipelines and the filling rate of the disposal site, which determines the rate of change of the loading. Research on consolidation of mud should therefore concentrate in the future on these time - dependent effects, which are closely related to rheological time-effects, known as thixotropy.

Conclusions

Both field and laboratory tests illustrate the effectiveness of a well-planned and adequately realised treatment method for the acceleration of the dewatering and consolidation of fine-grained dredged material on a large scale. The volume can be reduced by 35% within four months and by up to 50% in one to two years.

The laboratory tests confirm the assumption that a careful control of the water level in the field especially during the initial period can enhance the consolidation process. Consolidation fields are promising tools for a short-term solution of the problems of ports where a shortage of reclamation areas exists especially for the fine-grained material.

The technique can be used on an industrial scale based on the results.

The application of this technique is an important but an intermediate step towards a global solution as it is only a method to produce a useful product (reft 7). Additionally it is necessary to look for projects where the product (soft clay) can be applied. Different solutions can be suggested. Some of them are actually tested on laboratory or semi-industrial scale:
- utilisation as fill material for landscaping projects
- utilisation to improve poor quality soils
- mixture with night soil for agriculture application
- utilisation as a raw material for the construction industry.

The selection between these alternatives will depend on the level of contaminant content of the dredged material.

It has to be mentioned that the annual production of the consolidated dredged material will be very important. Therefore large-scale utilisation projects will be required.

Another drawback for the utilisation of the dewatered material is the contaminant load of the maintenance dredged material which will be met in almost every port. Although the final solution for the reduction of this contaminant content lies beyond the dredging world with a better implementation of water purification programmes, dredgers will have to cope with this problem in the meantime.

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