SETTLING AND CONSOLIDATION OF SOFT MUD-SAND LAYERS

by

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Abstract

This paper discusses the settling and consolidation of soft mixtures of mud and sand based on experiments in a set of laboratory settling columns of varying lengths in the range of 0.5 to 3 m. Two types of natural muds with varying percentages of sand have been used in the settling columns. In addition, mud-sand mixtures with relatively high percentages of sand have been tested. The theory of the hindered settling and consolidation processes is briefly explained and a relatively simple simulation model is proposed. The model simulation results are compared to the results of two laboratory tests with reasonably good agreement between measured and computed values. A plot of the dry bulk density as function of the percentage of clay and sand is presented, which can be used to get an estimate of the in-situ density of muddy layers to be dredged from navigation channels and harbour basins. Furthermore, a plot of the time scale of the primary consolidation process is presented.

Keywords: soft mud-sand layers; mud settling; mud consolidation; self weight consolidation

1. Introduction

Deposition and consolidation of mud are basic processes in natural, low-energy environments. Mud is herein defined as a mixture of clay<2μm, silt, sand>63μm and organic and calcareous materials. The composition and structure of the deposited sediment bed is dependent on the input concentrations, clay, silt and sand content supplied by the water system, layer thickness and sedimentological, chemical and biological properties of the sediments involved.

Deposition and consolidation of mud in navigation and harbour basins requires (hopper) dredging operations to remove the sediments and dumping operations at disposal sites. Land disposal may be an attractive alternative to reusing the dredged materials for reclamation works.

Dredging and dumping of muddy sediments require basic knowledge of the settling and self-weight consolidation behaviour of the sediments in order to estimate the time-evolution of the sediment densities involved. Mud which has been dredged by a cutter or a hopper dredger and transported through a pipeline has a relatively low dry density of about 200 to 300 kg/m^3 and is not easily suitable to be used as building material. At mud reclamation sites on land, this type of material is pumped as a mud slurry into small compartments surrounded by sandy dikes. Relatively large consolidation times (years) are required to arrive at a bearing capacity suitable for machinery and construction activities. Often, thick sand layers are placed on top of the soft layers to speed up the consolidation process.

Knowledge of the consolidation of soft muddy layers can be obtained from settling tests in laboratory columns. This type of research work has shown that the consolidation process of soft materials consists of three distinct phases (Migniot 1968 and 1989):

1) hindered settling phase (initial hours) and
2) primary (short-term) consolidation phase accompanied by large strains (weeks to months);
3) secondary (long-term) consolidation phase accompanied by small strains (Terzaghi-type consolidation; years)

The settling and consolidation processes are essentially vertical processes with downward movement of sediments and upward movement of expelled pore water and can therefore be studied in laboratory settling columns. Early work on the self-weight consolidation of mud has been done by Been and Sills (1981), by Lin (1983) using mud with very low sand content and by Torfs et al. (1996) with varying sand contents.

Been and Sill (1981) have described laboratory experiments on the development and consolidation of soft mud with low sand content in settling columns with measurement of density (X-ray technique), total stress, pore pressure and settlement. Their earlier theoretical model was modified to simulate the observed results of the settling columns. Modifications made to the model in the light of observed experimental features allow it to be used to predict the laboratory consolidation results.

Lin (1983) studied the self-weight consolidation of a lake mud with 25% clay, 65% silt and 10% sand (Lake Panora, Iowa, USA) in fresh water using a settling column height of about 2 m. The initial consolidation time of a suspension with a dry density (concentration) of about 225 kg/m^3 was found to be of the order of 1 week to obtain an end density of about 450 to 500 kg/m^3.

Torfs et al. (1996) have done consolidation tests with Scheldt-mud and HongKong-mud in settling columns with various types of mud and varying sand contents (0% to 60%) in saline water. Most of their tests concern the settling and consolidation of relatively thin HongKong-mud layers < 0.2 m with initial concentrations < 50 kg/m^3. Some tests with Scheldt-mud were done in a long settling column of 2 m with an initial concentration of 150 kg/m^3. The settling procedure was varied to study its effect on the bed structure, as follows: (1) almost instantaneous filling of the column, (2) continuous filling by pumping the mixture from a base container and (3) intermittent filling with intervals of days to weeks resulting in layered beds.

Torfs et al. (1996) have found that the filling procedure affects the formation of a matrix structure prior to consolidation. When the bed matrix structure is formed, the sand particles are held within the structure of the bed. In the case of low concentrations << 100 kg/m^3, compact flocs and sand particles can sink through the mixture to form a bottom layer of higher density, and segregation occurs with an almost sand-free upper layer. Segregation occurs at low concentrations (<< 100 kg/m^3) and high sand contents (10% to 30%) resulting in a layered density profile. The degree of segregation is limited to a maximum sand content (about 30%), which is a function of the mud type. The presence of large quantities of sand increases the consolidation rate as small drainage paths are created by sand pockets through which the pore water is expelled during consolidation.

Torfs et al. (1996) have also studied layered beds resulting from sequential events of deposition due to differences in conditions as present during storm and post-storm conditions. Layered beds are most pronounced in conditions with high sand contents and relatively high time intervals between events resulting in a bed of mud and sand layers. A few hours between input events is long enough for the bed to develop a mud layer with gelling structure and support the next layer of sand. Layer thickness decreases with increasing sand content to a limiting value at about 30%. The intermittent deposition of thin mud layers without sand also lead to more rapid consolidation as the pore water path remains relatively small.

Dankers (2006) focused on the effect of fine sand particles on the consolidation behaviour of mud in saline water. The dry density of the top mud layer was about 50 to 100 kg/m^3 on which a suspension of settling sand particles (110 μm and 360 μm) in concentrations < 10 kg/m^3 was poured. The experimental results show the generation of small pockets of sand in the upper layers of the mud. Coarse sand particles move relatively far through the mud layer creating drainage paths for pore water. The consolidation rate of the upper mud layers increased by about 10%.

Fossati et al. (2015) presented several self-weight consolidation tests performed with Río de la Plata sediments (Uruquay). Samples with a relatively small clay/silt ratio (<0.15) showed faster settling and consolidation rates with a stable height during the first day of the experiment. The end density was about 700 kg/m^3 after 1 day for a mixture of 10% clay, 90% silt. The end density increased to about 770 kg/m^3 for a mixture of 10% clay, 70% silt and 20 % sand. A different behaviour is observed for cohesive sediment with a clay/silt ratio of about 0.5 showing a continuous consolidation process during several days with a decreasing rate. The end dry density was about 350 kg/m^3 for a mixture with 35% clay and 65% silt. Their results show a strong effect of the clay-silt ratio. Some of the experimental values of these previous research efforts are used in the present study.

This study is focussed on the following research questions:

- what is the time scale of the primary (short-term) consolidation phase and what are the dry density values involved for various types of mud?;
- what are the effects of the mud layer thickness and percentage of sand on the primary consolidation time and end dry density of the mud layer?;
- what is the effect of a top layer of sand (external load) on the consolidation time and end dry density of the mud layer;
- can the hindered settling and primary consolidation process be simulated by a relatively simple model?

The theory of the hindered settling and consolidation processes is briefly explained and a relatively simple simulation model is presented. Several laboratory tests in settling columns with varying lengths between 0.5 m and 3 m are explained. Two types of natural muds used in the settling tests are described. In addition, mud-sand mixtures with high percentages of sand have been used and are described. The proposed consolidation simulation model is used on two laboratory test results. Finally, a synthesis of all results is presented.

2. Consolidation theory and models

2.1 Processes

The settling and consolidation process of mud-sand suspensions at the bottom of the water column can be divided into various distinct phases:

- hindered settling phase in which the particles and flocs move slowly downward hindered by the return flow of water displaced by the moving sediments; the sediment concentrations (dry density) are approximately 10 to 150 kg/m^3; the time scale is hours to days;
- transitional fluid mud phase in which the particles and flocs make contact with each other resulting in a gel/slurry-type structure and significant decrease of the effective settling velocity; the onset of floc contacts is known as the gel-point and occurs at concentrations of about 100 to 150 kg/m^3; the gel-point concentration is higher ($\cong$200 kg/m^3) for mixtures with a relatively high sand content; the time scale is days;
- primary consolidation phase in which there is a slow building up of contact forces (grain stresses) and pore water is driven out accompanied by relatively large strains; an initial soil-type (buttery-type) matrix structure is formed with small dewatering channels (cracks) through which water can escape; the dry bulk density at the onset of primary consolidation (c_{soil}) is about 300 to 400 kg/m^3; the dry bulk density increases gradually to about 600 to 700 kg/m^3 (weakly consolidated soft soil) at the end of the primary consolidation phase and depends on the percentage of fine sand; the time scale is weeks to months;
- secondary (secular) consolidation stage in which the soil network structure is strengthening to firm soil accompanied by relatively small strains; the dry bulk density values in the range of 1000 to 1200 kg/m^3; the typical time scale is months to years.

2.2 Basic equations

The most general model for self-weight consolidation of soft soils is the Gibson model, which can be derived from the vertical continuity equation of sediments, as follows (Gibson et al. 1967, 1981; Winterwerp and Van Kesteren, 2004; Merckelbach, 1996):

$$\partial\phi/\partial t - \partial(w_s\phi)/\partial z = 0 \quad (1)$$

$$\partial e/\partial t + (1+e)^2\, \partial(w_s/(1+e))/\partial z = 0 \quad (2)$$

Using the following expressions:

continuity equation: $\eta w_{pore} + (1-\eta) w_s = 0$;

law of Darcy: $w_{Darcy} = \eta(w_{pore} - w_s) = -w_s = -(k/\rho_w\, g))\, \partial p_E/\partial z$;

excess pore pressure: $\sigma = p + \sigma_s = p_{static} + p_E + \sigma_s = \rho_w g(h-z) + p_E + \sigma_s$ and thus $\partial p_E/\partial z = \rho_w g + \partial\sigma/\partial z - \partial\sigma_s/\partial z$;

soil stress: $\sigma = \rho_{soil}\, g\, z = \eta\, \rho_w + (1-\eta)\rho_s = e/(1+e)\, \rho_w + (1/(1+e))\rho_s$;

$\partial\sigma/\partial z = \partial[e/(1+e)\, \rho_w + (1/(1+e))\rho_s]/\partial z$;

Darcy velocity: $w_{Darcy} = -\, [k/(\rho_w\, g)]\, [\partial p_E/\partial z] = -(k/\rho_w\, g))\, [\rho_w g + \partial\sigma/\partial z - \partial\sigma_s/\partial z]$;

settling velocity: $w_s = -w_{Darcy}$;

Based on this, the following equation can be derived:

$$\partial e/\partial t + (1+e)^2\, ((\rho_s-\rho_w)/\rho_w)\, \partial[k/(1+e)^2]/\partial z + [(1+e)^2/(\rho_w g)]\, \partial[(k/(1+e))\, \partial\sigma_s/\partial z]/\partial z = 0 \quad (3)$$

with: ϕ = volume concentration= $c/\rho_s = 1/(1+e)$; $\phi = 1-\eta$; c = mass concentration (=ρ_{dry}= dry bulk density)); z= vertical coordinate; t=time; e = void ratio= $\eta/(1-\eta) = (\rho_s-c)/c$; η = porosity factor=$e/(1+e)=1-c/\rho_s=1-\phi$; w_s = settling velocity of mud particles/flocs relative to fixed datum (negative value in downward direction); w_{pore} = pore water velocity relative to fixed datum; σ = soil stress; σ_s= grain stress; p= pore water pressure; p_E= excess pore water pressure.

Equation (3) is known as the Gibson-equation. The variables k, e and σ_s are three unknown functions of the vertical coordinate (z) and time (t). Numerical solution can be simplified by assuming that the variables e and k are known power functions (with calibration/fit coefficients) of the grain stress (σ_s). However, the numerical solution is difficult because of the moving upper interface. Therefore, Equation (3) is often rewritten in a moving reference system (see Winterwerp and Van Kesteren, 2004; Merckelbach, 1996).

In the early phase of the consolidation process, the grain stresses are relatively small ($\partial\sigma_s/\partial z \cong 0$) and can be neglected resulting in:

$$\partial e/\partial t + (1+e)^2\, ((\rho_s-\rho_w)/\rho_w)\, \partial[k/(1+e)^2]/\partial z = 0 \quad (4)$$

which is known as the Kynch-equation.

In the end phase of the consolidation process, the vertical gradient of the deformations are small ($\partial e/\partial z \cong 0$) and the permeability is almost constant resulting in:

$$\partial e/\partial t + [k(1+e)/(\rho_w g)]\, \partial[\partial\sigma_s/\partial z]/\partial z = 0 \quad (5)$$

Using: $\Delta\varepsilon = \Delta e/(1+e) = -m_v\, \Delta\sigma_s$ or $1/m_v = -\, (1+e)\, \partial\sigma_s/\partial e$, Equation (5) can be described as:

$$\partial e/\partial t - [c_v\, \partial e/\sigma_s]\, \partial^2\sigma_s/\partial z^2 = 0 \text{ or } \partial\sigma_{s,E}/\partial t - c_v\, \partial^2\sigma_{s,E}/\partial z^2 = 0 \quad (6)$$

with: $\Delta\varepsilon$ = infinitesimal compaction; $\sigma_s = \sigma_{s,o} + \sigma_{s,E}$= grain stress; $\sigma_{s,o}$= grain stress before loading (constant); $\sigma_{s,E}$= excess grain stress; $c_v = k/(\rho_w g\, m_v) = -[(1+e)k/(\rho_w g)]\, \partial\sigma_s/\partial e$= consolidation coefficient, m_v= compressibility coefficient.

Equation (6) is known as the classical Terzaghi consolidation equation (in terms of the grain stress) for firm soils and can be soved analytically. The solution gives an end settlement value of: $s_{end} \cong -q\, h\, m_v$, with q= upper load ($N/m^2$), h= layer thickness (m) and m_v=compressibility coeficient (m^2/N). The latter coefficient follows from a compressibility test. These tests were done for both the N-mud and D-mud (see **Table 3**).

2.3 Self-weight consolidation of soft mud soils

Given the difficulties in solving the Gibson-equation for soft soils, a more simple semi-empirical model for the primary consolidation behaviour of soft soils is herein proposed following the work of Winterwerp (1999). He has proposed a numerical model for self-weight consolidation based on the one-dimensional continuity equation for sediments.

Based on this work, the self-weight consolidation can be described by the one-dimensional continuity equation for the fine sediments (< 63 μm):

$$\partial\phi/\partial t - \partial(w_{s,eff}\, \phi)/\partial z - \partial(D\partial\phi/\partial z)/\partial z = 0 \quad (7)$$

with: ϕ=volume mud concentration, $w_{s,eff}$= effective settling velocity, D= diffusion coefficient, z= vertical coordinate, t=time. The second term is the vertical settling term. The third term is the diffusion term. Hereafter, the effective settling velocity is discussed in more detail. This solution is different from that of Winterwerp (1999).

In low-concentration flows (< 10 kg/m^3), the most dominant process is flocculation (forming of flocs) resulting in an increase of the effective settling velocity. In high-concentration flows with concentrations of 10 to 150 kg/m^3, the suspended sediment particles/flocs cannot settle freely due to the presence of the surrounding particles/flocs. This process is known as hindered settling and consists of various effects: flow and wake formation around the particles and the increase of density and viscosity of the suspension. The hindered settling effect was studied experimentally by Richardson and Zaki (1954) and Richardson and Meikle (1961) using glass-type particles (ballotini) with particle sizes in the range of 35 to 1000 μm and alumina powder with a particle size of about 5 μm. They found that the hindered settling velocity can be represented as: $w_{s,eff}= w_{s,max}(1-\phi)^n$ with ϕ= volume concentration, $w_{s,max}$= maximum settling velocity (input value). The n-coefficient varies in the range of n= 2 to 4.

At the end of the hindered settling process, the mud particles and flocs are in direct contact with each other and a primary stage of consolidation is initiated with seepage flows of water through the pores between the particle-floc skeleton structure. The mud concentration at the onset of the primary consolidation process is herein defined as the soil concentration (ϕ_{soil}). The consolidation proces will go on until the end concentration of the primary consolidation process is reached, which is the start of the secondary (Terzaghi) consolidation stage.The primary consolidation process is accompanied by relatively large strains in contrast to the secondary consolidation stage with relatively small strains.

The settlement rate of the mud interface during the primary consolidation process can be determined by using a macro-scale approach for the total mud height, see **Figure 1 (left)**.

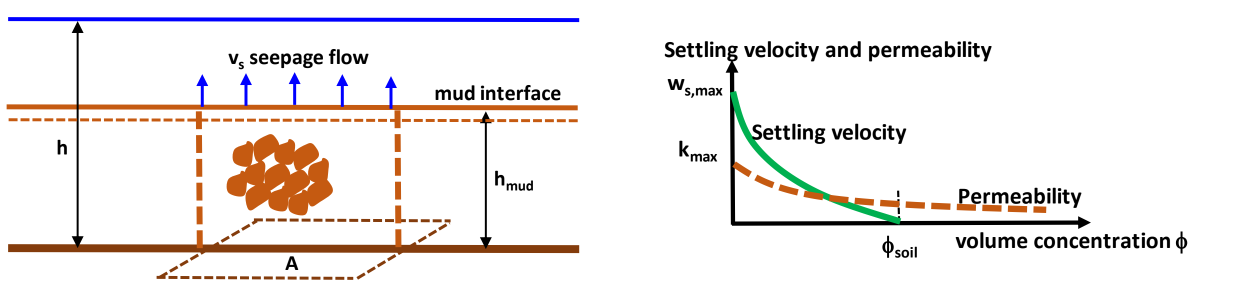


Figure 1 *Hindered settling and primary consolidation process*

The volume of the mud suspension with area A and height h_{mud} is:

$$V_{mud} = V_{sediment} + V_{water} = A\,(1-\eta)\,h_{mud} + \eta\,A\,h_{mud} = A\,h_{mud} \quad (8)$$

There is a volume change in time due to the outflow of seepage water through the pores, which yields:

$$dV_{mud}/dt = d(Ah_{mud})/dt = v_s\,A \quad (9)$$

$$dh_{mud}/dt = v_s = w_{s,eff} = \alpha_2\,k \quad (10)$$

with: $v_s= k\,(\rho_w g)^{-1}\,dp_E/dx = \alpha_2\,k$ = Darcy seepage velocity (m/s);
$\alpha_2 =(\rho_w g)^{-1}\,dp_E/dx$= pressure gradient coefficient (range of 0.1 to 0.5), p_E= water overpressure (N/m^2);
k = permeability coefficient (m/s); η = porosity coefficient; t= time; h_{mud}= mud height.

Equation (10) states that the settlement rate of the mud interface is related to the permeability of the soft soil. The α_2-coefficient representing the effect of the water overpressure gradient will gradually decrease to zero due to dewatering processes. The α_2-coefficient is not explicitly considered herein, but is included in the k-coefficient which is assumed to a function of the mud concentration. The k-coefficient is assumed to decrease gradually to a small value for increasing mud concentration, see **Figure 1 (right)**.

Summarizing, the effective settling velocity of Equations (7) and (10) is described by:

$$w_{s,eff}= w_{s,max}\,(1-\phi_{mean}/\phi_{soil})^2 + k \quad \text{for } \phi_{mean} < \phi_{soil} \qquad (11)$$
$$w_{s,eff}= k \quad \text{for } \phi_{mean} > \phi_{soil}$$

with: $k=k_{max}(1- \phi_{mean})^n$=permeability coefficient, $w_{s,max}$=maximum settling velocity (10^{-4} to 10^{-3} m/s), k_{max}= maximum permeability ($\cong$ 10^{-6} to 10^{-7} m/s), n=coefficient (range of 5 to 10), ϕ_{mean}= depth-mean volume concentration of the lower layer with concentrations > ϕ_o; $\phi_{soil}= c_{soil}/\rho_s$= volume concentration at onset of primary consolidation phase (-); c_{soil}= soil mass concentration in range of 300 to 400 kg/m^3 (kg/m^3); ϕ_o= initial volume concentration at t= 0; h= thickness of mud layer (-).

The parameters: $w_{s,max}$, k_{max}, c_{soil}, and n are input parameters; the α_2-coefficient is assumed to be 1; the parameter ϕ_{mean} is the computed layer-averaged volume mud concentration as function of time. These parameters can be estimated from a simple laboratory consolidation experiment (initial mud height $\cong$ 1 m).

Equation (7) can be discretized as (programme MUDCONSOL.xls):

$$\phi_{i,t+\Delta t}=\phi_{i,t} + (\Delta t/\Delta z)\, w_{seff,t}[\phi_{i+1,t} - \phi_{i,t}] + D\, (\Delta t/\Delta z^2)[\phi_{i+1,t} - 2\phi_{i,t} + \phi_{i-1,t}] \qquad (12)$$

with: $\phi_{i,t} = c/\rho_s$ = volume concentration in point i at time t (-); c = mass concentration (=ρ_{dry}= dry bulk density), (kg/m^3); ρ_w= water density (kg/m^3); ρ_s= sediment density (=2650 kg/m^3); $w_{s,effective}$ = effective settling velocity of mud particles (m/s) based on Equation (11); D= diffusion coefficient (m^2/s); z= vertical coordinate (m).

Boundary conditions: $\phi= \phi_o$ at time t= 0 for all z (initial uniform concentration; input value)
Boundary condition at bottom z=0: $\phi_{z=0,t+\Delta t}=\phi_{z=0,t} + (\Delta t/\Delta z)\, w_{seff,t}[\phi_{z=0+\Delta z,t} - \phi_{z=0,t}]$
Boundary condition at surface z=h: $\phi_{z=h,t+\Delta t}=\phi_{z=h,t} + (\Delta t/\Delta z)\, w_{seff,t}[- \phi_{z=h,t}]$
Another boundary condition at z=0 is: $w_{s,eff}\, \phi_{z=0}+ D\, \partial\phi_{z=0}/\partial z$ or $c_{z=0}=c_{z=0+\Delta z}/[1-(w_{s,eff}/D)\, \Delta z]$.

This latter condition means that the downward settling term is equal to the upward diffusive term (local equilibrium at the bottom without deposition). Numerical solution requires very small grid sizes near the bed to get a stable solution and is, therefore, not used herein.
The total sediment mass (kg/m^2) in the water column is: $M_s = {}_o\int^h c\, dz$.
Using an equidistant grid (Δz= 0.01h; 101 grid points over thickness h), it follows that:

$$M_{s,t} = \sum c_{i,t}\, \Delta z = 0.5c_{1,t} + 0.5c_{N,t} + {}_{i=2}\sum^{i=N-1} c_{i,t} \qquad (13)$$

Deposition: $\Delta M_{s,t}= M_{s,t=o} - M_{s,t}$
with: $M_{s,t=0}$= sediment mass at t=0, c_1= mass concentration in point 1 at bottom, c_N= mass concentration in point N at surface. It is assumed that the potential deposition quantity $\Delta M_{s,t}$ remains in suspension in the lower layer. The potential deposition is redistributed as a uniform concentration over the lower mud layer. This effect reduces the effective settling rate of the mud interface.

Column		Type of mud	Initial concen tration	Initial height of mud suspen sion	Duration	Additional sand load (d_{50}=145 μm) on top of mud layer		Settling height at end of test	Density at end of test
No	Len gth (m)		(kg/m³)	(mm)	(days)	Thickness (mm)	At time (days)	(mm)	(kg/m³)
1A	1	N	50 (ps=40%)	900	19	none	-	76	590 (19 d)
1B	1	N	100 (ps=40%)	900	19	none	-	147	610 (19 d)
1C	1	N	200 (ps=40%)	900	19	none	-	302	595 (19 d)
1D	1	N	300 (ps=40%)	900	19	none	-	392	690 (19 d)
2A	2	N	50 (ps=40%)	1850	39	none	-	129	715 (39 d)
2B	2	N	100 (ps=40%)	1850	30	none	-	293	630 (30 d)
2C	2	N	200 (ps=40%)	1850	37	185 (10% of i.h)	11	602	615 (37d)
2D	2	N	300 (ps=40%)	1850	116	370 (20% of i.h.) 555 (30% of i.h.)	11 60	778	715 (116 d)
3A	3	N	300 (ps=40%)	2800	102	560 (20% of i.h.)	22	1213	692 (102 d)
3C	3	N	300 (ps=57%)	2800	69	none	-	1212	693 (69 d)
3D	3	N	300 (ps=73%)	2800	69	none	-	956	878 (69 d)
1E	1	D	50 (ps=20%)	900	83	none	-	114	395 (83 d)
1F	1	D	100 (ps=20%)	900	83	none	-	225	400 (83 d)
1G	1	D	200 (ps=20%)	900	83	none	-	422	426 (83 d)
1H	1	D	300 (ps=20%)	900	83	none	-	596	453 (83 d)
2E	2	D	300 (ps=20%)	1850	76	none	-	1202	462 (76d)
2F	2	D	300 (ps=20%)	1850	76	185 (10%)	13	1156	480 (76 d)
2G	2	D	300 (ps=20%)	1850	76	370 (20%)	13	1156	480 (76 d)

N= mud from Noordpolderzijl; D= mud from Delfzijl-harbour
ps= percentage sand; d= days; i.h.= initial height of mud

Table 1 *Test programme of columns 1 m, 2 m and 3 m; Noordpolderzijl-mud and Delfzijl-mud*

3. Laboratory test setup, test programme and mud properties

3.1 Test setup and programme

Several consolidation tests have been carried out in transparent perspex columns with lengths of 0.5 m (inner diameter of 60 mm); 1 m (60 mm); 2 m (80 mm) and 3 m (90 mm).
The consolidation tests consisted of:

- preparation of the mud suspension in a bucket (saline seawater);
- transfer of the mud suspension into the column;
- mixing of the mud suspension to make a uniform suspension (using a mechanical mixing rod with perforated plate at the bottom);
- start of test at the time that the mixing rod is removed from the column;
- reading of mud surface at various times;
- placement of a sand layer (d_{10}=95 μm, d_{50}=145 μm and d_{90}=210 μm) at a certain time (in some tests) to speed up the consolidation process.

Various types of mud have been used in the consolidation columns:

- mud from the harbour basin of Noordpolderzijl (N-mud); wet bulk density of 1470 $\pm$ 10 kg/m^3 (dry bulk density of 755 kg/m^3); 17% calcareous materials; 7% organic materials;
- mud from the harbour basin of Delfzijl (D-mud); wet bulk density of 1315 $\pm$ 10 kg/m^3 (dry bulk density of 505 kg/m^3); 18% calcareous materials; 10% organic materials;
- artificial mud-sand mixtures by adding fine sand to the base N-mud to obtain mixtures with relatively high percentages of sand (57%) and (73%).

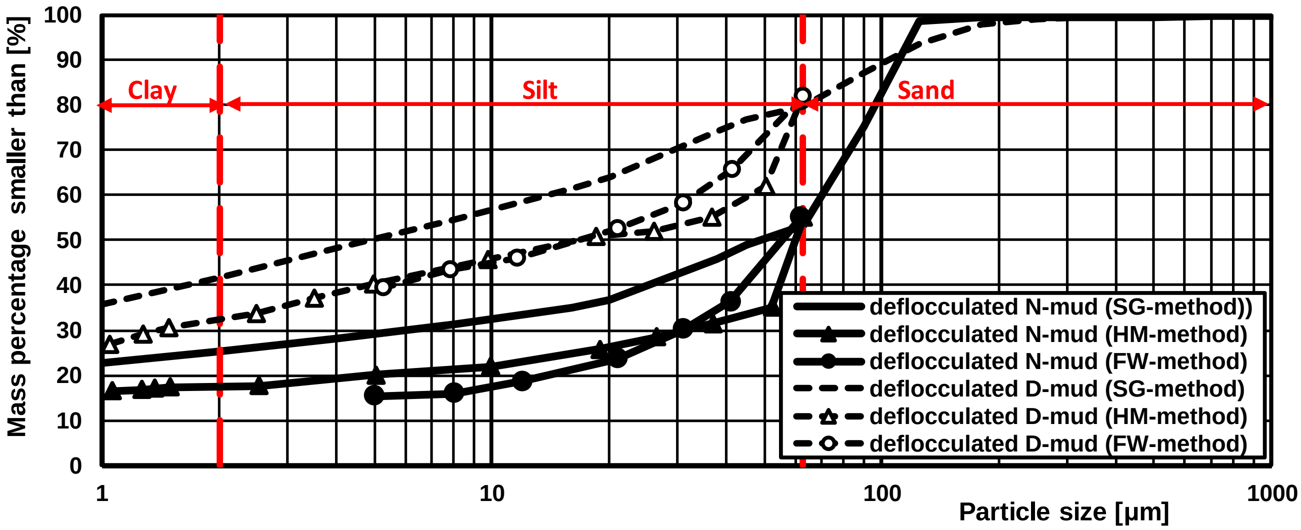
The test programme of the consolidation tests using native saline water is given in **Table 1**.
In some tests, a layer of sand was placed on top of the mud layer at a certain time to study whether this helps to speed up the consolidation process. Various repetition tests have been done to study the reproducibility with fairly good results. Details are given by Van Rijn 2018.

3.2 Mud composition

Various basic mud tests have been done to determine the mud particle sizes**.** As the determination of the fine mud particle sizes is not a straightforward process, three methods have been used: (i) SediGraph-method (SG); (ii) Hydrometer-method (HM) and (iii) Filtration-Wased method (FW-method). All methods basically measure the settling velocities of the particles, which are converted to particle diameters using the Stokes settling velocity formula. The tests have been done in fresh water using a peptiser-solution for deflocculation. The sand fraction was separated using wet sieving. The calcareous and organic materials were removed chemically to obtain samples with minerals only.
The SediGraph III-instrument (Micromeritics) measures the decrease of the mud concentrations in a small-scale settling cell. The mud concentrations are determined by direct (precalibrated) x-ray absorption.
The hydrometer test is based on the measurement of the decreasing sediment mixture density (initial concentration of 30 gr/l) by using a floating body in a column with settling mud particles over a period of 2 days. The sinking of the floating body is minimum at initial time with maximum mud concentration and maximum in clear water at the end of the test.
The filtration-Wased method is based on the settling of suspended sediments in a special settling column (Wased-column) with a height of 0.5 m. Small subsamples are taken at various preset times from the suspension at 70 mm above the bottom of the column. The mud concentration is determined by filtration of mud from the sample using glass-fibre filters with 0.45 μm pore size.
The test results are given in **Table 2** and in **Figure 2**, which shows the particle size distribution of the N-mud and the D-mud based on the three methods. As regards the N-mud, the percentage of fine sand is about 45% based on wet sieving. The SG-method yields a size distribution with smaller values ($d_{50} \cong$ 45 μm) than those of the HM

and FW-methods ($d_{50} \cong$ 60 μm). The percentage of clay < 2 μm is about 25% based on the SG-method and about 15% based on the HM and FW-methods.

The D-mud is much finer than the N-mud. The percentage of fine sand of the D-mud is about 20%. The SG-method yields a size distribution with much smaller values ($d_{50} \cong$ 5 μm) than those of the HM and FW-methods ($d_{50} \cong$ 18 μm). The percentage of clay < 2 μm is about 40% based on the SG-method and about 30% based on the HM and FW-methods.



SG=SediGraph method; HM=Hydrometer method; FW=Filtration-Wased method; S= Sieving method for sand fraction

Figure 2 *Particle size distribution of deflocculated N-mud and D-mud*

Parameter	**Mud Noordpolderzijl (N-mud) (October 2017)**		**Mud Delfzijl (D-mud) (November 2017)**	
	Minerals + calcareous + organic materials	**Minerals only**	**Minerals + calcareous + organic materials**	**Minerals only**
Particle diameter of mud-sand d_{50}; d_{90} (μm)	30; 110	30; 110	4; 100	5; 100
Particle size (μm) of sand fraction > 63 μm	85	85	120	120
Fluid density seawater (kg/m^3)	1010	1010	1007	1007
Sediment density (kg/m^3)	2570	2570	2560	2560
Wet bulk density (kg/m^3)	1470±10	1470±10	1310±10	1310±10
Dry bulk density (kg/m^3)	755±10	755±10	505±10	505±10
Percentage organic material	7%	0%	10%	0%
Percentage calcareous materials	17%	0%	18%	0%
Percentage sediment > 63 μm	40%	45%	20%	20%
Percentage silt 2 to 63 μm	35%-40%	30%-35%	40%-50%	40-50%
Percentage clay < 2 μm	20%-25%	20%-25%	30%-40%	30%-40%
Plasticity index (difference in water content to go from semi-solid state to liquid state)	33%	n.m.	35%	n.m.

n.m.= not measured; SG= SediGraph-method yields largest percentage clay < 2 μm

Table 2 *Mud data of Noordpolderzijl and Delfzijl*

4. Consolidation results

4.1 Laboratory experiments

A quick scan analysis of the data of Table 1 shows that: (i) the end density increases for increasing percentage of sand, (ii) the consolidation time increases for increasing mud layer thickness and (iii) the end density of D-mud is much smaller than that of N-mud because D-mud has a smaller percentage of sand and a larger percentage of clay. A more detailed analysis is given in Section 5.

Some examples of the increase of the dry density as function of time are given in **Figures 3** to **8**, showing the typical behaviour of the settling and consolidation processes. Three distinct phases are present: (1) hindered settling phase with a time scale of 3 to 4 hours for concentrations of 50 to 100 kg/m^3, (2) primary (short-term) consolidation phase of 10 to 30 days depending on the layer thickness and (3) secular (long-term) consolidation phase.

N-mud in Column 1 m (Figure 3): N-mud with ps=40% and initial concentrations of 50 to 100 kg/m^3 can settle to a dry density of about 150 to 200 kg/m^3 during a period of 3 hours. N-mud with initial concentrations of 200 to 300 kg/m^3 can reach a dry density of 400 to 450 kg/m^3 after 1 day.

The primary (short-term) consolidation process proceeds fairly quickly. After about 20 to 30 days, the concentration (dry density) of N-mud is in the range of 600 to 700 kg/m^3. The largest initial concentration of 300 kg/m^3 yields the largest density of about 700 kg/m^3 at the end of the primary consolidation phase. The in-situ dry density based on samples from the field site is about 755 kg/m^3. Hence, the end dry density of the primary consolidation phase in laboratory conditions is about 10% smaller than the in-situ dry density.

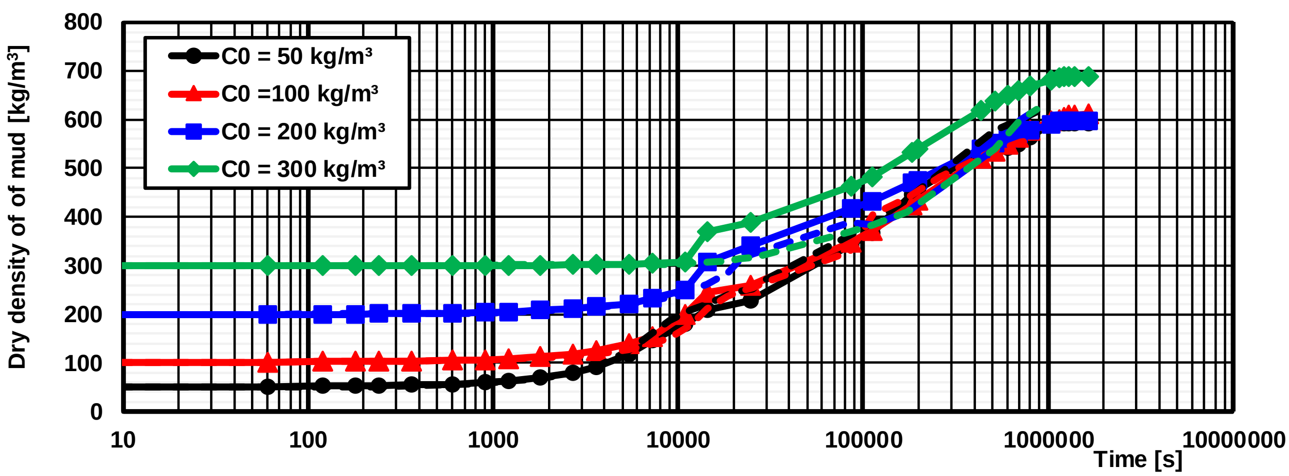
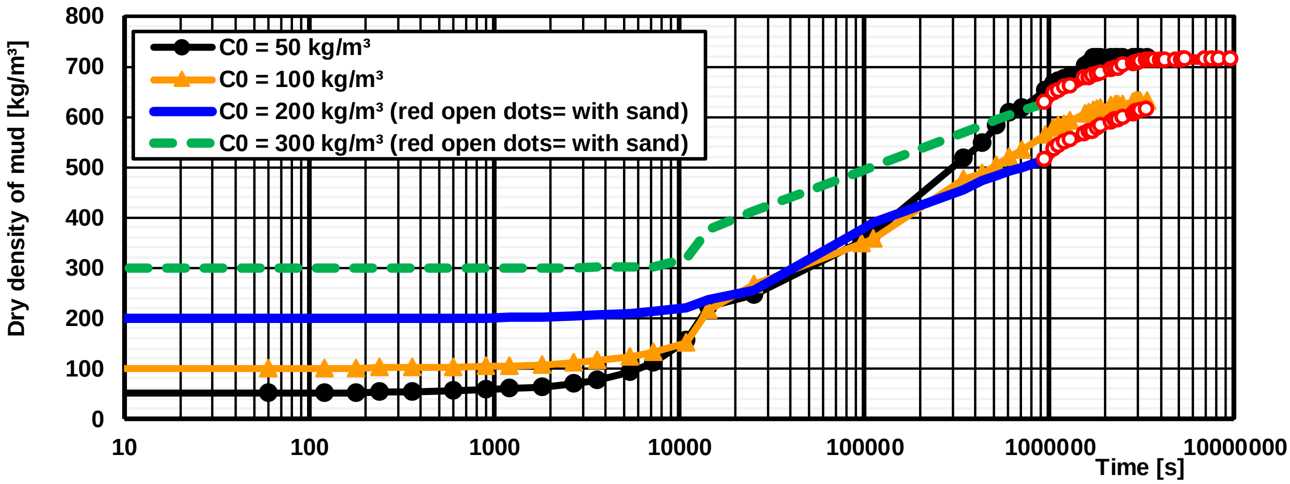


Figure 3 *Dry bulk density as function of time for settling column of 1 m; Noordpolderzijl-mud (40% sand) (Test 1=solid; Test 2 repetition=dashed)*

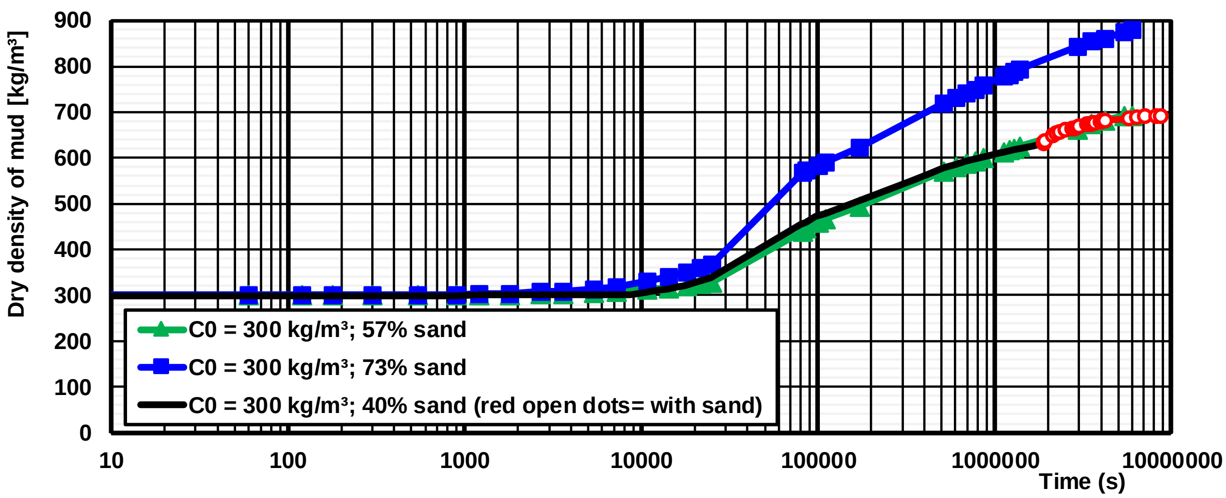
N-mud in Column 2 m (Figure 4): After about 30 days, the concentration or dry density of N-mud with ps=40% is in the range of 600 to 700 kg/m^3. The smallest initial concentration of 50 kg/m^3 yields the largest end density of about 720 kg/m^3 after about 30 days, which is about 10% smaller than the in-situ density of about 755 kg/m^3. The placement of sand layers on top of the mud surface has a very small effect on the dry density (about 5%). After about 35 days (≅3 10^6 s), the primary consolidation process is almost completed.



c_o=200 kg/m^3 (sand layer of 0.185 m after 11 days (≅10^6 s) placed on mud surface)
c_o=300 kg/m^3 (sand layer of 0.37 m after 11 days; sand layer of 0.56 m after 60 days placed on mud surface)

Figure 4 *Dry bulk density as function of time for settling column of 2 m; Noordpolderzijl-mud (40% sand)*

N-mud in Column 3 m (Figure 5): After about 20 days, the dry density of the Noordpolderzijl-mud with ps=40% and ps=57% is about 630 kg/m³. The placement of a sand layer on the mud surface after 11 days only yields a small increase of the dry density (about 5% to 10%). The dry density increases to about 800 kg/m³ after 30 days and to almost 900 kg/m³ after 70 days in the case of Noordpolderzijl-mud with ps=73%.
The time scale of the primary consolidation phase of N-mud with ps=40% and 57% is about 40 days and about 40 to 60 days for ps=73%.



Black line: c_o=300 kg/m^3 with sand percentage ps=40%; sand layer of 0.56 m on mud surface after 22 days
Green triangles: c_o=300 kg/m^3 with increased sand percentage ps=57%; no top layer of sand;
Blue squares: c_o=300 kg/m^3 with increased sand percentage ps=73%; no top layer of sand

Figure 5 *Dry bulk density as function of time for settling column of 3 m; Noordpolderzijl-mud (ps=40% to 73%)*

D-mud in Column 1 m (Figure 6): The hindered settling phase of the columns with c_o=50 and 100 kg/m^3 has a duration of about 3 to 4 hours. The duration of the primary (short-term) consolidation phase with c_o=50 and 100 kg/m^3 is about 10 to 15 days. After about 20 days, the concentration (dry density) of D-mud is in the range of 380 to 430 kg/m^3 for all four tests The largest initial concentration of 300 kg/m^3 yields the largest dry density of about 430 kg/m^3. The in-situ dry density based on samples from the field site was about 500 kg/m^3. Hence, the end dry density in laboratory conditions is about 10% smaller than the in-situ dry density.

The primary consolidation tests were ended after about 80 days. Column 1H was cut into pieces of about 0.1 m to determine the vertical distribution of the dry density, see **Figure 7**. The depth-mean dry density is about 450 kg/m^3. The dry density is about 550 kg/m^3 at the bottom and about 380 kg/m^3 near the mud surface.

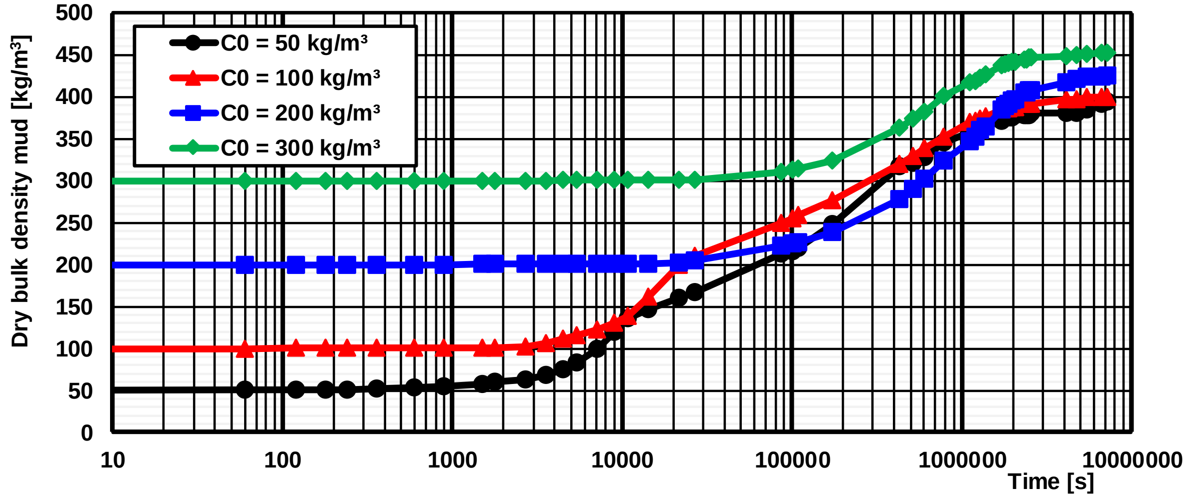


Figure 6 *Dry bulk density as function of time for settling column of 1 m; Delfzijl-mud (20% sand)*

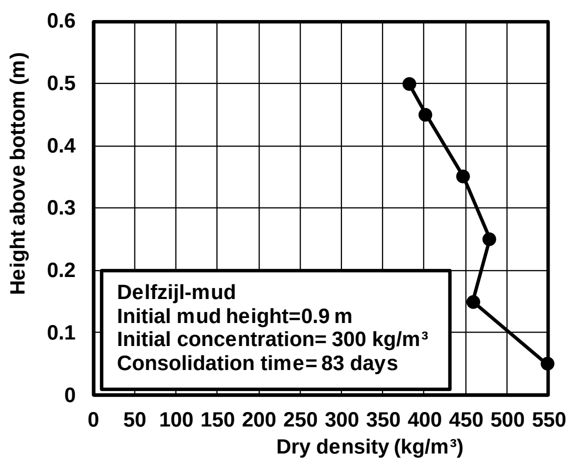


Figure 7 *Vertical distribution of dry bulk density (column 1H of 1 m); Delfzijl-mud (20% sand); initial concentration=300 kg/m³*

D-mud in Column 2 m (Figure 8): The duration of the primary consolidation phase with c_o= 300 kg/m^3 is about 20 to 40 days. After about 20 to 40 days, the concentration (dry density) is about 450 kg/m^3.

After 76 days (end of test), the dry density is about 460 kg/m^3 without a sand layer and about 480 kg/m^3 with a sand layer on top of the mud surface. Hence, the placement of a sand layer on top of the mud yields an increase of the dry density of about 20 kg/m^3 (about 5%). The in-situ-dry density was about 500 kg/m^3. Hence, the end dry density is about 5% to 10% smaller than the in-situ dry density.

The consolidation test was ended after 76 days. Column 2G was cut into pieces of about 0.1 m to determine the vertical distribution of the dry density. The depth-mean dry density is about 480 kg/m^3. The dry density is about 530 kg/m^3 at the bottom and about 480 kg/m^3 near the mud surface. Hence, the vertical variations are quite small within 10% of the mean value. The dry density values near the surface are relatively large due to the presence of a sand layer on top of the mud surface resulting in more compacted upper mud layers. The dry density value is lowest (about 450 kg/m^3) in the middle of the mud layer.

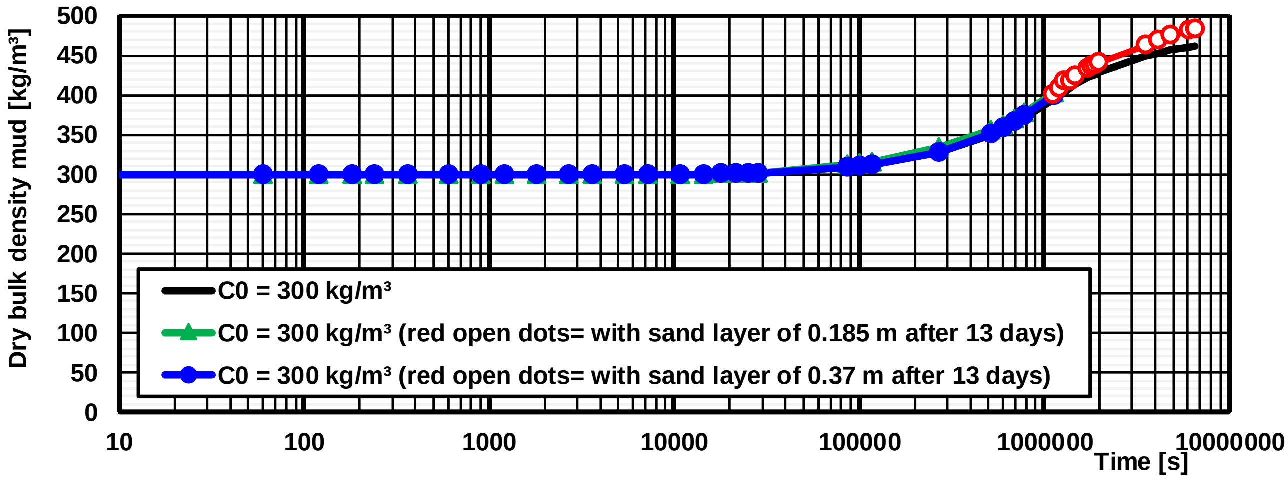


Figure 8 *Dry bulk density as function of time for settling column of 2 m; Delfzijl-mud (20% sand)*

Compressibility tests N-mud and D-mud: mud samples from Noordpolderzijl and Delfzijl with initial dry density values of about 760 and 410 kg/m^3 were used to perform a standard compressibility (Oedometer) test which gives information of the long term consolidation behaviour. Excess water was siphoned off. The base mud had a soft buttery-type of texture after a consolidation period of about 1 month.

A ring with thickness of about 20 mm was filled with mud and subjected to an Oedometer test under a series of external loads. The results based on the Terzaghi-analysis method (Equation 6) are given in **Table 3**. The permeability is computed as: $k=\rho_w\, g\, c_v\, m_v$ with ρ_w =1010 kg/m^3.

After 7 steps consisting of 40 hours each with loading up to about 200 kpa (or 2.0 kg/cm^2), the total settlement is about 6 mm which is about 30% of the initial value of 20 mm.

The compressibility m_v-coefficient decreases by a factor of about 50 to 100 between step 1 and step 7.

The k-value also decreases by a factor of 50 to 100 between step 1 and 7. As the sample is more compressed/compacted, the permeability (k-value) increases. The mud from Noordpolderzijl has a slightly larger permeability (in the end phase) as the percentage of sand is larger.

The TERZAGHI-consolidation time scale for the long-term consolidation of a layer of N-mud with a thickness of 1 m under external loading is given by the expression (dewatering in upward direction only): $T_{end} = 0.5\, h^2/c_v = 0.5x1^2/(140\pm50\ 10^{-10}) \cong$ 0.3 to 0.6 10^8 s $\cong$ 1 to 2 years. The consolidation time scale for D-mud is 5 to 10 years, because the c_v-coefficient is much smaller.

Sample	**Maximum loading (N/m^2)**	**Total settlement (mm)**	**Dry and wet density (kg/m^3) and percentage sand (%)**	**c_v-coefficient (m^2/s)**	**m_v-coefficient (m^2/N)**	**k-permeability (m/s)**
N-mud (3)	202 10^3	20.07-13.75= 6.26 (31,3%)	initial=760; 1490 end= 1115; 1525 ps=40%	initial= 200 10^{-10} middle= 90 10^{-10} end= 120 10^{-10}	initial= 22 10^{-6} middle= 2 10^{-6} end= 0.4 10^{-6}	initial= 42 10^{-10} middle= 2 10^{-10} end= 0.5 10^{-10}
D-mud (1)	201 10^3	20.03-13.70=6.33 (31.6%)	initial=410; 1265 end= 940; 1515 ps= 20%	initial= 20 10^{-10} middle= 20 10^{-10} end= 15 10^{-10}	initial= 80 10^{-6} middle= 50 10^{-6} end= 1 10^{-6}	initial= 15 10^{-10} middle= 1 10^{-10} end= 0.2 10^{-10}

Table 3 *Oedometer results of Noordpolderzijl-mud (N-mud) and Delfzijl-mud (D-mud)*

4.2 *Field consolidation results*

The bed of the tidal channel of Noordpolderzijl (Groningen, The Netherlands) is situated between the landward harbour basin and the seaward Wadden Sea and consists of a soft layer of sandy mud with a thickness of 0.5 to 0.7 m on top of a more compacted sandy subsoil. A male person will sink into the mud near the harbour basin over about 0.5 m. The vertical distribution of the wet end dry bulk density of the soft top layer was studied by analyzing field samples. In June 2017, various mud samples were taken at different locations along the tidal channel of Noordpolderzijl (length of about 3 km; width of about 15 m). The channel bed is exposed (almost dry) at low water. Bed samples were taken over the upper 0.5 m in the middle and at the eastern side of the channel bed at low water with exposed bed, see **Figure 9**. The dry bulk density and the percentage of sand (> 63 μm) have been determined in the laboratory. The d_{50} of the sand fraction varies between 95 μm at the landward end to about 120 μm at the seaward end. The ratio of the fraction of clay (< 2 μm) and silt (2-63 μm) is about 1 to 2; ($p_{silt} \cong 2 p_{clay}$).


Figure 9 *Mud sampling at tidal channel Noordpolderzijl, Groningen, The Netherlands*

The results can be summarized, as follows:

- wet bulk density of top layer of 0.1 m is about 1400 kg/m^3 in the harbour basin; wet bulk density of top layer is about constant at about 1500 kg/m^3 in the landward part (length of 1.5 km) of the channel; wet bulk density increases to about 1900 kg/m^3 in the most seaward sandy part (1 km) of the channel;
- wet bulk density is larger in deeper layers; the wet bulk density is about 1600 kg/m^3 in the layer 0.1-0.4 m in the landward part; wet bulk density is about constant at 1900 kg/m^3 in vertical direction in the sandy seaward channel section.

The dry bulk density of the samples from Noordpolderzijl (shown in **Figure 14**) increases for increasing percentage of sand. The bed composition is muddy at the landward end and sandy at the seaward end. The dry bulk density data can be reasonably represented by:

$$\rho_{dry} = (1-p_{org}/100)[400\,(p_{clay}/100) + 800\,(p_{silt}/100) + 1600(p_{sand}/100)] \quad (14)$$

with: p_{org}= percentage organic materials, p_{clay}=percentage clay, p_{silt}=percentage silt, p_{sand}=percentage sand. Equation 14 is shown in **Figure 15**.

Information of the in-situ consolidation of Delfzijl-mud was obtained from field samples taken at various locations inside the harbour of Delfzijl (Groningen, The Netherlands). This harbour has a long and narrow basin with the entrance at the eastern side and the main quays at the western side. The depth is about 8.5 m below mean sea level in the long, main traffic lane (of about 5 km) and about 3 m along both long side banks. The bulk density of harbour deposits not only depends on the local mud composition but also on the location within the basin. The bulk density is highest near the entrance where the coarsest sediments are deposited. The bulk density is also relatively high at the most quiescent locations far away from ship traffic. Generally, the bulk density is lowest in the deeper shipping channel where the upper mud layers are consistently being stirred by the ship propulsion systems (rudders, propellers, jets) resulting in a fluid mud-like upper mud layer of 1 to 2 m. Ships can sail through this low density layer (Barth et al. 2016).

Figure 10 shows the dry bulk density of the upper mud layer samples at three locations in the shipping channel of Delfzijl-harbour, where the local bed is about 8.5 m below mean sea level. The sample density values were determined from an acoustic densitymeter in combination with samples taken by a long, vertical sludge sampling

tube of 3 m length (calibration samples for densitymeter). The wet bulk density varies between 1100 and 1220 kg/m³ (dry density between 125 and 300 kg/m³). These values are much lower than the wet bulk density of about 1300 kg/m³ (dry density of about 500 kg/m³; see **Table 2**) found near the shallow banks of the harbour basin, where the mud can consolidate in quiescent conditions. The laboratory results shows that the D-mud with a dry density of 200 to 300 kg/m³ can consolidate to 400 kg/m³ in about 10 days in quiescent conditions. The thickness of the low-density mud layer varies between 1 and 2 m. Beneath this layer, the in-situ density increases to much higher values as indicated by the steep gradient of the density profiles (**Figure 10**).
Particle size analysis of the sludge tube samples shows the presence of 15% to 20% sand>63 μm without much variation over the depth of the soft mud layer (Waterbouwkundig laboratorium 2010).

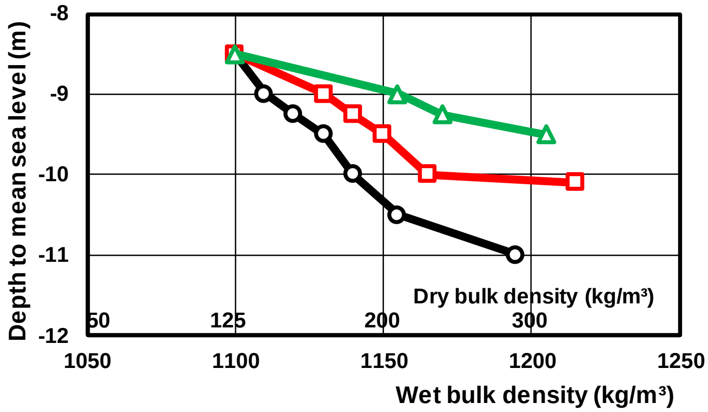


Figure 10 *Bulk density profiles at 3 locations in shipping channel of Delfzijl-harbour, The Netherlands; D-mud*

4.3 Modelling results

The spreadsheet model MUDCONSOL.xls based on Equations (7) to (13) has been used to compute the time development of the mud concentration profiles for two laboratory consolidation experiments with N-mud in a settling column of 0.5 m and D-mud in a settling column of 1.85 m. These two tests represent the wide range of the present laboratory test conditions: short column with sandy N-mud and a long column with clayey D-mud.
N-mud test in Column 0.5 m: initial mud height= 0.36 m; initial concentration= 200 kg/m³. The mud consisted of 65% fines (< 63 μm) and 35% fine sand. The input data are: h_o=0.36 m; $w_{s,max}$=0.001 m/s; k_{max}=1. 10^{-6} m/s; c_o= 200 kg/m³; c_{soil}=400 kg/m³; n=10; D=0 m²/s.
Figure 11 shows the measured and computed values of the relative mud height (h_{mud}/h_o). The parameters $w_{s,max}$, and k_{max} were varied to obtain the best agreement. The concentration at the onset of primary consolidation is set to c_{soil}=400 kg/m³. The test results clearly show the presence of the relatively fast hindered settling process (< 0.1 day) followed by the much slower primary consolidation process between 0.1 and 7 days. The end density is about 650 kg/m³ after about 8 days which is quite well predicted by the model. The primary consolidation time scale is quite short (≅ 1 week) for relatively sandy N-mud with a layer thickness of about 0.35 m.

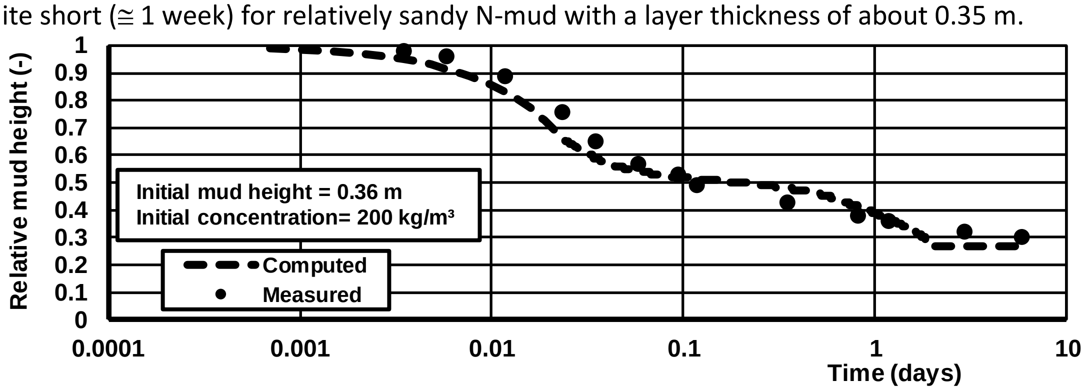


Figure 11 *Relative mud height (h_{mud}/h_o) as function of time; h_o=0.36 m; c_o=200 kg/m³; N-mud*

D-mud test in Column 2 m: initial mud height=1.85 m; initial concentration is c_o=300 kg/m^3. The Delfzijl-mud consists of 80% fines (< 63 μm) and 20% sand. The input data are: h_o=1.85 m; $w_{s,max}$=0.0002 m/s; k_{max}=3.5 10^{-7} m/s; c_o= 300 kg/m^3; c_{soil}=400 kg/m^3; n=10; D=0 m^2/s.
Figure 12 shows the measured and computed values of the dry density as function of time. The parameters $w_{s,max}$, and k_{max} were varied to obtain the best agreement. The soil concentration is set to c_{soil}=400 kg/m^3.
Figure 13 shows the computed density profiles at various times. The effective settling velocity decreases from 10^{-5} m/s to 10^{-7} m/s as function of time, which is caused by the increasing dry density. The permeability decreases from 10^{-7} to 0.3 10^{-7} m/s.

Summarizing, the MUDCONSOL-model can simulate the hindered settling and primary consolidation of soft soils with reasonable accuracy based on the results for thin and thick mud layer experiments. The settling velocity and the permeability of the sandy N-mud were found to be much larger than those of the finer D-mud, which is physically realistic. The input model parameters can be quite simply determined from laboratory settling column tests.

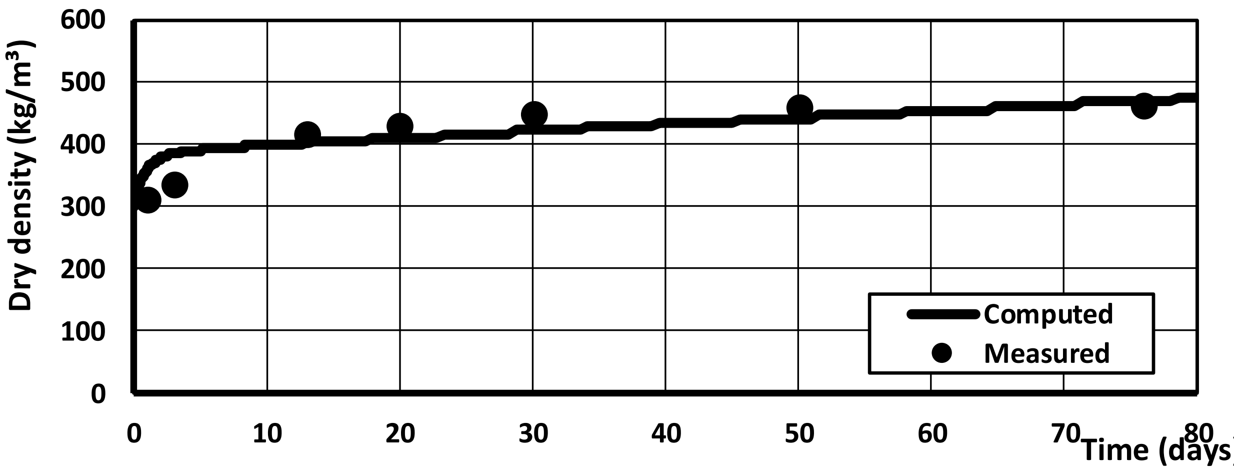


Figure 12 *Measured and computed dry density as function of time; h_o=1.85 m; c_o=300 kg/m^3; D-mud*

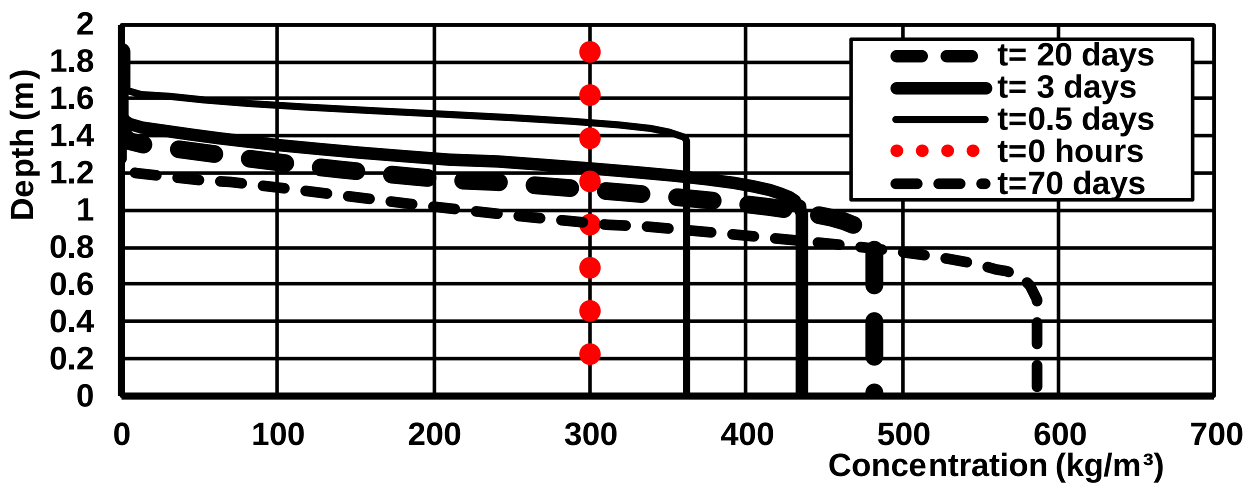


Figure 13 *Mud concentration profiles at various times; h_o=1.85 m; c_o=300 kg/m^3; D-mud*

5. Synthesis and conclusions

The experimental results show that the consolidation process of soft mud-sand mixtures under water consists of three distinct phases: (1) flocculation+hindered settling phase with a duration of a few hours; (2) primary (short-term) consolidation phase with a duration of 2 to 3 weeks and (3) secular (long-term) consolidation phase with a duration of months to years depending on percentage of sand (Terzaghi-type consolidation).

The consolidation process of mud mixtures strongly depends on three parameters: percentage of clay/lutum< 2 to 4 μm, percentage of sand particles > 63 μm and the layer thickness. Other parameters like the type of mud (mineral composition) and the percentage of organic materials are less important. Natural muds may have a percentage of sand in the range of 10% to 50%.
Mud suspensions with initial concentrations of 50 to 100 kg/m^3, as present in near-bed layers of a natural muddy tidal channels, can consolidate to a dry density of about 150 to 200 kg/m^3 during a period of 3 hours, which is a typical value for the tidal slack period when deposition takes place. The hindered settling process is not so much affected by the sand content. The transition from the hindered settling phase to the primary consolidation phase is characterized by the formation of a network structure. The gelling concentrations with some degree of matrix (skeleton) structure are in the range of 100 to 150 kg/m^3.

Natural muds with initial concentrations of 150 to 300 kg/m^3 and a low sand content (< 20%) can reach a dry density of about 350 kg/m^3 after 1 day. Natural muds with high sand content (40%-50%) can reach a dry density of about 450 kg/m^3 after 1 day. Dry density values in this range are the onset of the primary consolidation phase with the gradual buildup of grain stresses in a matrix-type network structure.

The primary (short-term) consolidation process proceeds fairly quickly (10 to 50 days) if the percentage of sand (> 62 μm) is larger than about 30%, as shown in **Figure 14** which is based on the data from the present study and the Literature (**Table 4**). Natural muds with low sand content ($\cong$ 20%) and thickness of 1 to 2 m can consolidate to 400 to 450 kg/m^3 after 20 to 50 days. Natural muds with a high sand content of 40% to 50% and thickness of 1 to 3 m can consolidate to dry density values of 600 to 700 kg/m^3 after 10 to 30 days. The time scale is relatively small (up to 60 days) for a small thickness of 1 m and relatively large (up to 180 days) for a large mud thickness of about 3 m and low sand content. The available data suggests an almost linear relationship between the time scale of the primary consolidation period and the mud layer thickness.

The vertical distribution of the dry density shows relatively high values (15% to 20% larger than depth-mean) in the near-bottom zone and relatively low values (15% to 20% smaller) in the near-surface zone. The end density values of the N-mud and D-mud in the laboratory columns were about 10% smaller than the in-situ density values at the field site where the base mud was taken.

The end dry bulk density of the primary (short-term) consolidation phase of mud mixtures with a layer thickness of 1 to 3 m strongly depends on the percentage of sand (ps), as shown in **Figure 15** with data from the present study and from the Literature. All data used are given in **Table 4**. The end density increases from about 450 kg/m^3 for ps=20% to about 880 kg/m^3 for ps=73%. The end density is higher if the percentage of clay is lower. The dry density values derived from laboratory columns with vertical drainage processes only are somewhat smaller than the values based on field tests. In field conditions, the consolidation processes are also influenced by lateral drainage resulting in larger dry density values (15%).

The end density can be increased by 5% to 10% by placing a sand layer load on top of the mud surface after about 10 days, once the upper mud layer has developed a network structure. The placement of a top sand load is not very effective as the draining structure of the mud layer itself is not affected except for the upper mud layer in contact with the sand load layer. If sand is available, it is much more effective to mix the available sand through

the mud beforehand than to use the sand as a top load. By mixing of mud and sand, the (end) density at the end of the primary consolidation process can be increased by about 50%.
Equation (14) is also shown in **Figure 15** for realistic values of p_{org}, p_{clay} and p_{silt}.

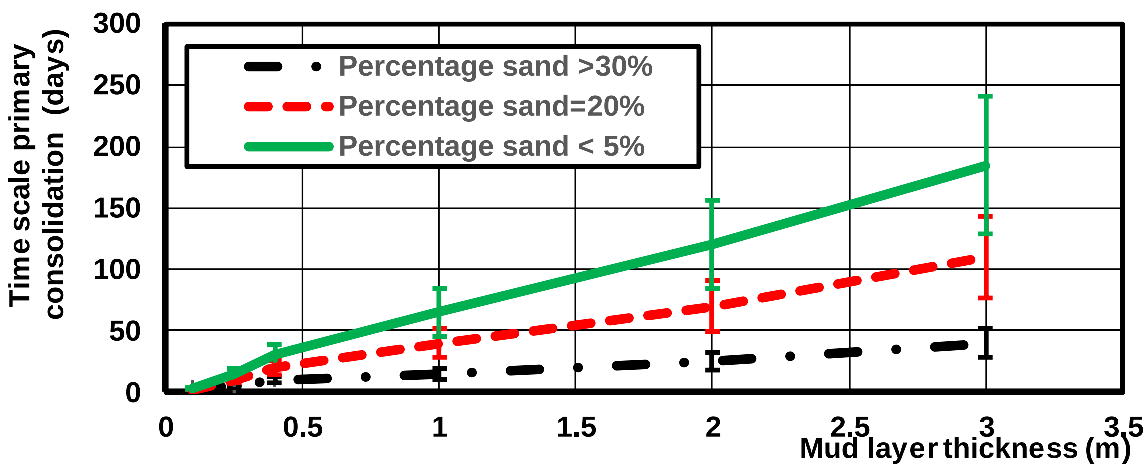


Figure 14 *Time scale of primary consolidation process*

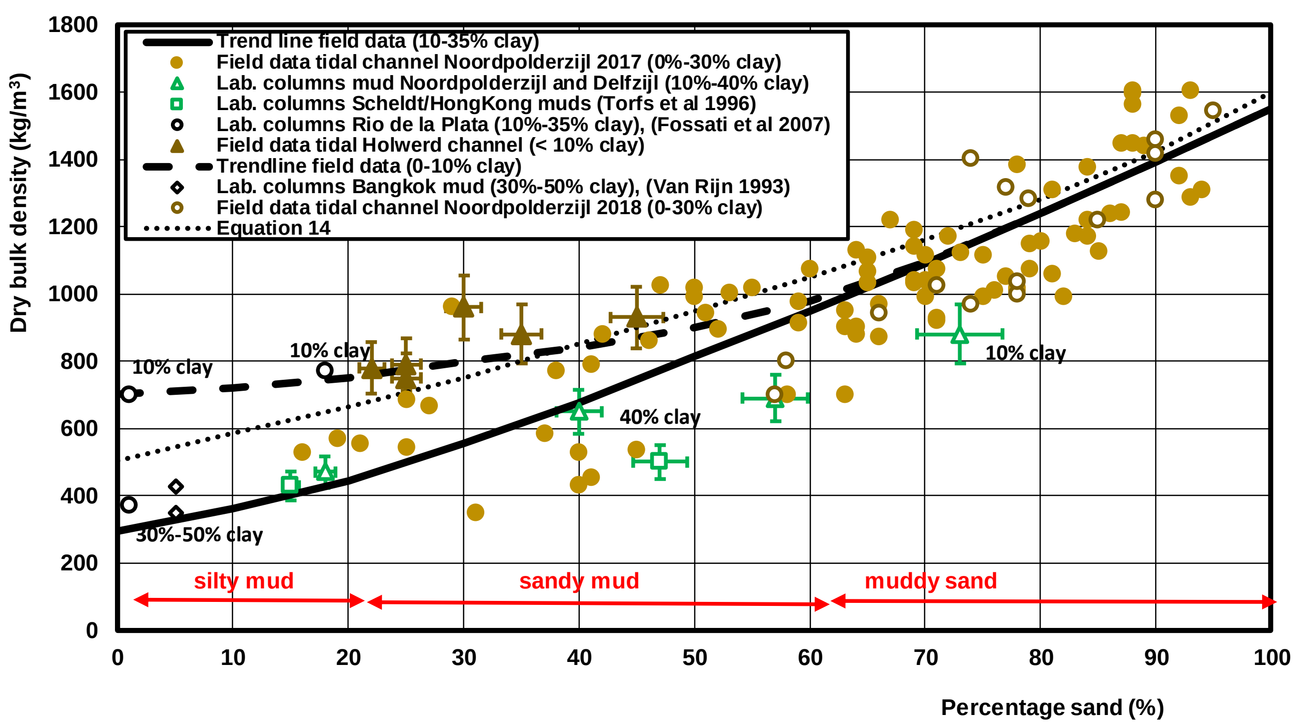


Figure 15 *End dry density of primary consolidation period as function of percentage of sand and clay*

Type of mud	Layer thickness (m)	Percentage clay < 2/4 μm (%)	Percentage sand > 63 μm (%)	Percentage organic materials (%)	Time scale of primary consolidation period (days)	End dry density of primary consolidation (kg/m^3)
Lab. colums: Bangkok mud (Van Rijn 1993)	1	30-50	5	-	90	420
	2	30-50	5	-	180	350
Lab. columns: Scheldt mud (Torfs et al. 1996)		n.m	15	n.m.	60	430
Lab. columns; Hong Kong mud (Torfs et al. 1996)	0.1	40	47	n.m.	<5	500
Lab. columns: Rio de la Plata muds (Fossati et al. 2015)	1	35	1	n.m.	60	370
	1	10	1	n.m.	<1	700
	1	10	18	n.m.	<1	770
Lab. columns: Delfzijl mud (present study)	2	40	18	10	50	470
Lab. columns: Noordpolderzijl mud (present study)	2-3	30-40	40	7	40	650
	2-3	20	57	7	40	690
	2-3	10	73	7	40	880
Field: Holwerd channel (Deltares 2016; Van Rijn 2016)	1-2	<10	22	7	<30	780
	1-2	<10	25	7	<30	750
	1-2	<10	25	7	<30	790
	1-2	<10	30	7	<30	960
	1-2	<10	35	7	<30	880
	1-2	<10	45	7	<30	930
Field: Noordpolderzijl (Van Rijn 2017)	<1	n.m.	20-50	n.m.	<90	400-800
	<1	n.m.	50-60	n.m.	<90	800-1000
	<1	n.m.	60-70	n.m.	<60	800-1200
	<1	n.m.	70-80	n.m.	<30	1000-1400
	<1	n.m.	80-90	n.m.	<30	1000-1600

n.m.= not measured

Table 4 *Laboratory and field data of end dry density values at end of short-term consolidation period*

Figures 14 and **15** can be used to get an estimate of the in-situ density of muddy layers to be dredged from navigation channels and harbour basins. It is most efficient to start dredging when the bulk density of the deposited material is as high as possible. The maximum time scale of the primary consolidation phase is of the order of 6 months for a muddy layer of 3 m, see **Figure 14**. Hence, the dredging interval should not be smaller than about 6 months in a situation with a thick muddy layer with low sand content. Predictions of siltation rates generally yield quantities of sand, silt and clay in tons/year, which can be converted to an in-situ dry bulk density and layer thickness using **Figure 15**. The time scale of primary consolidation follows from **Figure 14**.

When a harbour extension (reclamation) is being made by dredging muddy materials using a hopper dredger with pipe concentrations of about 200 to 300 kg/m^3, it is most efficient to produce mud layers at the reclamation site with a maximum thickness not larger than about 3 m. This layer requires a primary consolidation period of about 3 to 6 months to arrive at a end density of 500 to 600 kg/m^3. At that time, a new mud layer can be poured on the old layer and so on. It would be more efficient, if a mechanical grab dredger can be used to produce a mud layer with a higher initial density, but grab dredging is relative expensive compared to hydraulic dredging. Generally, grab dredging is only economic for relatively small reclamation sites and hydraulic dredging for extensive sites. If sand is abundantly available, it may be considered to apply on-site mixing of mud (30%) and sand (70%) before dumping at the reclamation site.

The long term consolidation process of the reclamation soil can be evaluated from the Terzaghi-equation (6) in addition to the short-term consolidation based on equations (7) to (13).

The most important findings are summarized in the following conclusions:

- The primary (short-term) consolidation process proceeds fairly quickly (10 to 50 days) if the percentage of sand (> 63 μm) is larger than about 30%. Natural muds with low sand content (≅ 20%) and thickness of 1 to 2 m can consolidate to 400 to 450 kg/m^3 after 20 to 50 days. Natural muds with a high sand content of 40% to 50% and thickness of 1 to 3 m can consolidate to dry density values of 600 to 700 kg/m^3 after 10 to 30 days. The time scale is relatively small (up to 60 days) for a small thickness of 1 m and relatively large (up to 180 days) for a large mud thickness of about 3 m and low sand content.
- The dry density can be increased by 5% to 10% by placing a sand layer load on top of the mud surface after about 10 days. The placement of a top sand load is not very effective as the draining structure of the mud layer itself is not affected except for the upper mud layer in contact with the sand load layer. If sand is available, it is much more effective to mix the available sand through the mud beforehand which may result in a density increase of 20% to 50% depending on the amount sand used.
- a fairly simple, semi-empirical model is proposed for the simulation of the settling and primary consolidation processes of soft soils with reasonable accuracy based on the results for thin and thick mud layer experiments. The input model parameters can be quite simply determined from laboratory settling column tests.

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