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Consolidation and strength development by horizontal drainage of soft mud deposits in lake Markermeer

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Introduction

The behaviour of soft, muddy sediments is becoming increasingly important, as large amounts of mobilised sediments will progressively be used for nature building projects. These fine sediments represent a greater challenge than traditional sandy ones, because of their diverse properties.

In the Netherlands, various building with nature (BwN) projects have already been implemented (De Vriend et al., 2015) with different purposes: from coastal safety (Zand Motor, The Hague) to protection of eroding intertidal shoals with oyster reefs in the Eastern Scheldt (Zeeland).

The MarkerWadden is an example of an ongoing BwN project which aims to improve the ecosystem in lake Markermeer (The Netherlands) by creating islands, marshes and mud flats with sediments partly originating from the fluffy material of the bed of the lake itself. It represents one of the first projects which use fresh unconsolidated mud as a construction material.

Figure 1. Present situation of Markermeer (www.wikipedia.com). The new polders and dikes (from the Zuiderzee works) can be observed in the figure.

Lake Markermeer (Fig.1) is large and shallow: its surface is 680 km^2 (including the IJmeer and the Gouwzee) and its average water depth is 3.6 m (Rozari, 2009; Vijverberg et al., 2011). A thin fluffy layer of silt dominates the lake bed. Already at low wind speeds, wind-induced-waves cause resuspension of this top layer. As a result, the high concentration of suspended particles inhibits light penetration causing the deterioration of the surface water quality. Below this thin fluff layer, a thicker layer of fluvial mud which has been deposited after closure of the Afsluitdijk is observed. Below this layer, a base of marine deposits is present, originating from the period before closure.

Problem analysis

Figure 2 presents a schematic diagram of wetland building with soft mud showing that part of the soil experiences "classical" consolidation with vertical drainage due to self-weight consolidation (column I, Fig. 2). However, higher on the wetland, the soil (water-sediment mixture) rises above the water level, and pore water is more likely to escape also in horizontal direction (column II, Fig. 2) because of the local slope at the water table.

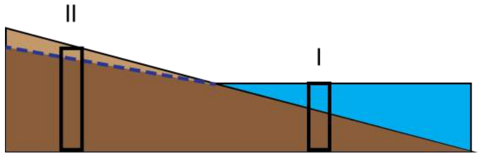

Figure 2. Consolidating soil under and above water – Note the different behaviour of columns I and II

Experimental Methods

A variety of experiments is applied to determine the consolidation and strength development of fresh mud deposits from lake Markermeer. This novel approach mimics land and crust formation with soft soils. The influence of the crust and sediment variability on the consolidation process is studied, as well as the physical-chemical properties. Afterwards, a model is used to upscale the results. This method provides engineering rules for wetland creation and contributes to the understanding of the dominant mechanisms for soil formation from soft sediments.

Previous to the beginning of the horizontal drainage experiments, three small settling columns (each with a volume of 2 litres) with three different concentrations (below the gelling point) are used to determine the sediment properties (i.e., bulk permeability k as a function of void ratio e and void ratio e as a function of and vertical effective stress σ_{zz}^{sk}) by monitoring the settlement of the sediment interface in time. These concentrations must be below the gelling concentration, which represents the concentration at which flocs become space-filling and form a network structure or gel and measurable shear strength builds up (Dankers, 2006).

Once the properties of the soil are known, three types of columns are needed (see fig. 3) in order to perform a horizontal drainage experiment which is properly calibrated. The first one is a control column without any drainage system. In this column, only vertical drainage due to overburden occurs. It gives us the properties of the material. A second column, equipped with a Vyon porous pipe, gives us the effect of the pipe without drainage. Finally, a third column, also equipped with an identical porous pipe, which is now connected to a reference water table by a hose, allows us quantify and observe the effects of horizontal drainage, i.e. an extra difference in head. The length of the porous section of the pipe may be changed from zero to the full column height. In this way, the section of the column experiencing horizontal drainage may be varied.

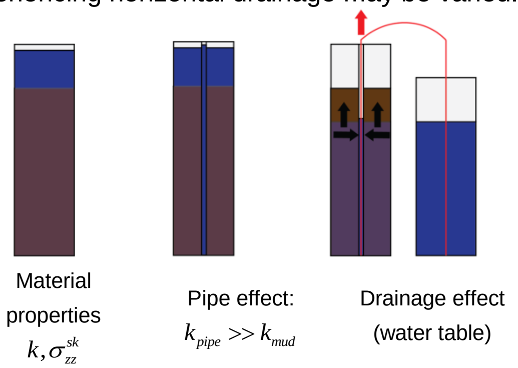

Figure 3.Calibration of the drainage of the columns

Mathematical modelling

An equation for the consolidation of a sloping bed is derived for upscaling the results of the experiments. Note that, for the time being, the equation presented in this abstract does not account for chemico-biological effects and precipitation/ evaporation. However, the influence of these parameters can be experimentally calibrated and included in the formulation.

For the derivation of this equation, the Eulerian approach by Merckelbach and Kranenburg (2009) is followed, (see also Winterwerp and Van Kesteren, 2004). Figure 4 shows a sketch of a consolidating column of fine sediment, and the various velocities of the particles and pore water. Horizontal drainage is indicated by w_f. It is hypothesized that w_f may change over time and with depth due to consolidation, but remains constant in lateral direction y. Hence, it is assumed that w_f and the permeability k are a function of the vertical coordinate z and time t only. The parameters involved in Fig. 4, as well as the stresses playing a role in the process, are defined in Table 1.

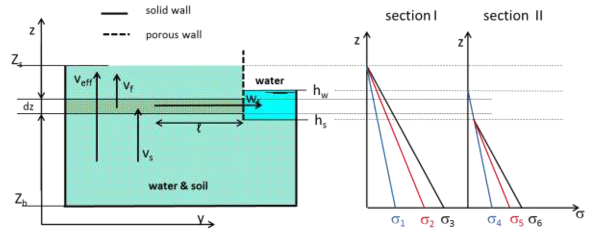

Figure 4. Schematization of consolidating soil and vertical stress distribution

Table 1. Definition of parameters and stresses of Figure 4.

v_f	vertical fluid velocity in Eulerian frame	
v_s	vertical settling velocity of solid particles	
v_{eff}	effective fluid velocity through porous soil	
w_f	horizontal drainage velocity	
ℓ	characteristic length scale for horizontal drainage	
Z_s	level soil-water mixture	
Z_b	bottom level	
h_w	water level	
h_s	level permeable wall	
ρ_b	bulk density	
σ_1	hydrostatic pressure	$\sigma_1 = g\rho_w(Z_s - z)$
σ_2	actual pore water pressure	p_w
$\sigma_2 - \sigma_1$	excess pore pressure	p_e
σ_3	total stress	$\sigma_{zz} = g\int_z^{Z_s} \rho_b \, dz$
$\sigma_3 - \sigma_2$	effective stress	σ_{zz}^{sk}
σ_4	hydrostatic pressure	$\sigma_4 = g\rho_w(h_w - z)$
σ_5	actual pore water pressure	p_w
σ_6	total stress	$\sigma_{zz} = g\int_z^{h_w} \rho_b \, dz$
$\sigma_5 - \sigma_4$	excess pore pressure	p_e
$\sigma_6 - \sigma_5$	effective stress	σ_{zz}^{sk}

Horizontal drainage takes place above level h_s, and it is driven by the head difference between Z_s and h_s.

Elaborating on the 2D continuity equation for the solid fraction ϕ, the momentum equations in y- and z-direction and the vertical gradient stresses, we obtain the consolidation equation (1) for fine sediments with horizontal drainage:

$$\frac{\partial \phi}{\partial t} - \frac{(\rho_s - \rho_w)}{\rho_w}\frac{\partial k\phi^2}{\partial z} - \frac{\partial}{\partial z}\left(\frac{k\phi}{g\rho_w}\frac{\partial \sigma_{zz}^{sk}}{\partial z}\right) = = \frac{\mathrm{d}Z_s}{\mathrm{d}y}\frac{\partial k\phi}{\partial z} \quad (1)$$

where ρ_s is the specific density of the soil.

The left-hand side of equation (1) represents the classical one-dimensional equation for self-weight consolidation and can be used to determine the material properties. The right-hand side defines the effect of the bed slope.

Next, we introduce the fractal descriptions for the mud permeability and effective stress (e.g. Merckelbach and Kranenburg, 2004; Winterwerp and Van Kesteren, 2004):

$$\begin{aligned} k &= K_k \phi^{-2/(3-n_f)} \\ \sigma_{zz}^{sk} &= K_p \phi^{2/(3-n_f)} \\ \Gamma_c &= \frac{2}{3-n_f}\frac{K_k K_p}{g\rho_w} \end{aligned} \quad (2)$$

in which n_f = fractal dimension, K_k [m/s] and K_p [Pa] are coefficients for permeability and effective stress. Γ_c represents a consolidation coefficient, which equals the classical coefficient c_v. Substitution of equation (2) into (1) yields an advection-diffusion equation (3):

$$\frac{\partial \phi}{\partial t} - \Delta_\rho \frac{\partial k\phi^2}{\partial z} - \Gamma_c \frac{\partial^2 \phi}{\partial z^2} = \frac{\mathrm{d}Z_s}{\mathrm{d}y}\frac{\partial k\phi}{\partial z} \quad (3)$$

where $\Delta_\rho = (\rho_s - \rho_w)/\rho_w$

Note that, in order to apply these equations to the explained experimental setup (cylindrical columns), all of them are first rewritten in cylindrical coordinates.

Conclusions

With the described experimental and mathematical methods, the characteristic consolidation parameters of the clayey soil can be obtained. Moreover, the effects of vegetation, evaporation/precipitation and organic geochemistry can be included in the equation (or boundary conditions or material parameters) in the future. Finally, the derived equations for consolidation with horizontal drainage can be implemented in a 2D transport model, such as Delft 3D (Zou et al., 2015).

Thus, this method represents a powerful tool which can be used to develop engineering rules for wetland creation from soft sediment.

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