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SOME FUNDAMENTAL ASPECTS OF SLUDGE DEWATERING

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SUMMARY

An overview is given of major fundamental aspects of sludge dewatering. First the presence of water in sludge and filter cakes is treated schematically. Subsequently attention is paid to the changes taking place during filtration and expression, the major changes being those in local porosity inside flocs and between the flocs. For the description of the flow through a bed of permeable flocs a new, simple approximating model is proposed: the "DUAL FLOW model". This allows the estimation of the effective permeability of a bed with permeable particles; from simulation follows that for compressed beds the contribution of the flow through the flocs can be much higher than that of the flow in the small open spaces between the flocs. Simulations of the expression of a floc indicate that during filtration and expression the local floc porosity will very fast reach equilibrium with the local compression pressure. From these considerations it follows that major focussing points for further study are:
- a more detailed insight into the relations between porosity, permeability and pressure distribution during filtration and expression
- theoretical and experimental insight in the size, strength and permeability of flocs, in dependence of structure parameters and pretreatment.

1. INTRODUCTION

1.1. General

In the beginning of 1990 we started a study of some fundamental aspects of sludge dewatering in our laboratory, within the larger Dutch national project "Municipal Waste Water Treatment 2000 (RWZI-2000)". A team of three full-time project members (ir. Arend J.M. Herwijn, ir. Erik J. La Heij, ing. Paul M.H. Janssen) took up the study in cooperation with dr.ir. W. Jan Cournans and myself. Basic aim of the study is the understanding of physical and physico-chemical phenomena occurring on microscale, and how these phenomena manifest themselves on the macroscopic scale. As desired results we see the links between various characterisation methods and physical parameters, and the development of theoretical and simulation models predicting filtration and expression behaviour. These type of models could then be used in the optimisation of dewatering processes and equipment parameters. One of the methods used in our study is the drying of filter cakes or parts, which gives fundamental insights in water transport and binding, but also gives information from which drying processes for sludge can be modelled and optimised.
As will become clear in the following an important element will be the colloid-chemical aspects of floc formation, strength and structure, and the consequences for the engineering aspects.

1.2. The presence of water

In Fig. 1 we present schematically the way that water may be present in sludge and sludge cakes. In a suspension or in a filter cake we may distinguish a water phase and a floc phase. The porosity or volume fraction of the water phase is denoted by $\varepsilon_w$, and so the volume fraction of the flocs is equal to $(1 - \varepsilon_b)$.

We also use the void ratio $e_b$, the volume of water phase per unit of volume of floc phase:

$$e_b = \frac{\varepsilon_w}{(1 - \varepsilon_b)} \quad (1)$$

The flocs in turn consist of a wet skeleton, between which interstitial liquid is present in the floc pores. We have then the internal floc porosity $e_f$, which is the fraction of the floc volume, taken up by the liquid. The volume fraction of the wet skeleton is thus $(1 - e_f)$. The floc void ratio $e_f$ is then given by:

$$e_f = \frac{\varepsilon_f}{(1 - \varepsilon_f)} \quad (2)$$

Looking in more detail into the flocs we have a collection of elementary particles, made up of basic sludge particles and additives. The basic sludge particles stem from the waste water plant itself, and thus will vary with place, time of year, and other conditions. The additives are dependent on the specific sludge treatment given before solid-liquid separations. Now we have water inside the basic particles, like microbial cells, or pieces of wood, etc. Also we may have spots and/or particles of additives, which may contain water. Further we will have hydration layers at the particle surfaces. For a quantitative account of the amount of water in the system, one should theoretically make a detailed mass balance of all substances in a sludge or filter cake. Although this is useful for scientific purposes, and also for a possible drying step, for the processes of filtration and expression we may reasonably approximate the water content of a system by:
\[
X_{w,\text{cake}} = \frac{X_{w,i} + X_{\text{add,1}} X_{w,\text{add}} + \rho_1 \rho_f (1 + \epsilon_b)}{(1 + X_{\text{add,1})}}
\]

In this equation:

- \(X_{w,\text{cake}}\) = water content of cake [kg/kg dry solids]
- \(X_{w,i}\) = internal water content of particles [kg/kg dry solids]
- \(X_{\text{add,1}}\) = amount of dry additives/kg dry sludge, remaining in the sludge flocs [kg/kg ds]
- \(X_{w,\text{add}}\) = water content of additive particles or layers [kg/kg ds]
- \(\rho_f\) = density of water phase [kg/m³]
- \(\epsilon_f\) = floc void ratio [m³ liquid/m³ ds]
- \(\epsilon_b\) = bed void ratio [m³ bed liquid/m³ flocs]
- \(\rho_{sk}\) = density of (wet) floc skeleton [kg/m³]

1.3. Factors influencing dewatering steps

From the above picture we can derive several important factors, all influencing the dewatering process.

**Floc formation**

The flocs are formed from the basic sludge particles, in many cases with the addition of additives. Thus the nature of the basic sludge particles is one of the prime factors. This will depend on the treatment plant, the waste water stream fed, the conditions changing over time. The amount and nature of additives, combined with the way the process is carried out, is for a given set of basic sludge particles, at a given concentration determining for the floc formation process. This implies the way the floc skeleton is built up, the floc size, the initial floc porosity, the chain length of aggregates, the number of links per volume of floc, and the bond strength between the elementary floc particles. Thus the floc formation process determines the initial floc porosity, size and strength.

Examples of floc size distributions as measured in our lab by means of a Malvern Mastersizer are given in Figs. 2 and 3, with FeCl₃/Ca(OH)₂ and polyelectrolyte as additives. We see that with increasing addition of FeCl₃ up to a certain point the distribution tends to go to increasing size; for the polyelectrolyte this effect is much more markedly. Also interesting is the amounts of both additives needed to obtain an effect; for polyelectrolytes this is roughly 1/100 of that for the iron compound. It is clear that other mechanisms will be operating in both cases, and also that in the case of iron addition the iron hydroxide will form a considerable part of the sludge flocs.
Fig. 2. Floc size distribution by flocculation with FeCl₃

Fig. 3. Floc size distribution in case of polyelectrolyte addition
Dewatering

In general after a sedimentation step dewatering is performed by means of filtration, expression and in many cases drying. In filtration and expression the water phase moves relative to the solids under the influence of a gradient in liquid pressure. This can be represented by the following equations:

\[ u_i = \frac{K}{\eta} \frac{\partial p_i}{\partial z} = -\frac{1}{\eta R} \frac{\partial p_i}{\partial (z/L)} \]  

in which:
- \( u_i \) = superficial liquid velocity [m/s]
- \( K \) = permeability [m²]
- \( \eta \) = dynamic viscosity [Pa.s]
- \( p_i \) = liquid pressure [Pa]
- \( z \) = distance coordinate [m]
- \( R \) = filtration resistance of cake (\( = L/K \)) [m⁻¹]
- \( L \) = cake thickness [m]

Often is also used the specific filtration resistance \( \alpha \):

\[ \alpha = \frac{R}{w} \]  

with:
- \( \alpha \) = specific filtration resistance [m/kg]
- \( w \) = mass of cake per m² area [kg/m²]

We may write the relation between \( \alpha \) and \( K \) by:

\[ \alpha = \frac{1}{\rho_s (1 - \varepsilon)^3 K} \]  

with:
- \( \rho_s \) = density of "bed particles" [kg/m³]
- \( \varepsilon \) = porosity [-]

For the permeability we may write the Blake - Kozeny equation:

\[ K = \frac{\varepsilon^3 d_p^2}{150 (1 - \varepsilon)^2} \]  

with:
- \( d_p \) = effective particle diameter [m]

The conditions chosen in practice with regard to additives and filter aids reflect the search for a compromise: the material should filter well, which would mean a low...
degree of deformation of flocs and beds, but on the other hand the final water content should be as low as possible, which means a considerable lowering of the porosity upon expression. This can be seen from Eq.(3), in which for a low deformable filter cake the main term in the numerator is that containing the void ratios: the major part of the water is present in the pores of the bed and in the interstitial pores inside the flocs.

During filtration there is a build-up of the cake, causing a conversion of liquid pressure into solid pressure, which tends to compress the cake. This compression can be viewed as a combination of simultaneous phenomena:
- expression and volume change of flocs
- bed compaction associated with floc deformation
- bed compaction associated with shear induced relative floc displacement

Next to the material properties of the flocs, also the choice of process conditions is determining the way the pressure profiles are built up. A higher filtration rate tends to increase the pressure gradients, thereby increasing the solid pressure on the particles, which in turn leads to a decrease in porosity and thus permeability $K$, which increases the pressure drop even more. At constant pressure filtration or expression, the resistance of the filter medium determines the initial flow rate and thereby also the steepness of pressure gradients in the initial phase of the process.

It is important to realise that it is the combined effect of floc properties and process conditions, which determines the filtration rate and/or pressure, and the final water content.

Although the description of filtration and expression requires a more detailed analysis, interesting observations for practice can be obtained from laboratory tests, such as filtration of a sample under constant pressure. By fitting the curve of filtrate volume over time, we find an average value of the specific cake resistance $a_{av}$. In Figs. 4 and 5 we see the influence of additives on this average resistance, again for the addition of FeCl₃, and for polyelectrolyte (Rohm KF-945), both at a filtration pressure of 2 bar.

![Specific cake resistance $a_{av}$ in case of addition of FeCl₃](image)
It is clear that the resistance decreases upon addition up to a certain amount. The decrease is quite strong; comparison with the particle size data shows that there is no quantitative correspondence between the average particle size and the resistance. For FeCl₃ the effect is larger than expected from Eqs. (5) to (7), for polyelectrolyte it is lower. Apparently the deformation of the flocs and the bed under shear are also determining factors.

In Fig. 6 we have plotted the average specific cake resistance in dependence on the filtration pressure, which shows a typical power dependence with a power 0.8.

Although this and analogous tests give a practical insight into filtration and expression resistances, for treatment of more difficult situations, development of new
equipment and optimization, more detailed knowledge is required of the distribution of pressure and permeability over the material and of the development in the course of time.

2. SOME HYDRODYNAMIC CONSIDERATIONS

2.1. Flow through a bed of permeable flocs: the DUAL - FLOW model

In considering the modelling of the filtration process we were faced with the problem that the Blake - Kozeny equation for a bed was in principle derived for particles with a closed surface, and is based on the concept of the hydraulic radius of the pores in a bed, connected with the "wetted particle surface" [1]. Now it is known that flocs may have a quite open structure, and so an extension was sought of the theory. The basic assumption is that water flows both through the pores between flocs and through the flocs themselves. This has two effects for a given liquid pressure gradient:

- the liquid between the flocs is less decelerated at the floc surface
- liquid flows through the flocs themselves

From a simple approximation starting with laminar flow through a pore of which the walls are formed by porous flocs we can derive:

\[ u_l = u_{l,\text{bed}} + u_{l,\text{floc}} \]

\[ = \frac{1}{\eta} \left( - \frac{\partial p_l}{\partial z} \right) \left[ ( K_{b,\text{sol}} + \epsilon_b K_f ) - (1 - \epsilon_b) K_f \right] \]

\[ = \frac{1}{\eta} \left( - \frac{\partial p_l}{\partial z} \right) \left[ K_{b,\text{sol}} + K_f \right] \]  

(8)

Herein \( K_{b,\text{sol}} \) is the permeability of a bed consisting of particles of the same size as the flocs, but with a closed surface, and \( K_f \) is the permeability of the flocs. The K's are given by:

\[ K_{b,\text{sol}} = \frac{\epsilon_b^3 d_f^2}{150 (1 - \epsilon_b)^2} \]  

\[ K_f = \frac{\epsilon_f^3 d_e^2}{150 (1 - \epsilon_f)^2} \]  

(9)

with \( d_f = \text{floc diameter} \) \quad [m]  
\( d_e = \text{effective diameter of elementary floc particles} \) \quad [m]

For the effective permeability of the floc bed in relation to that of a similar bed consisting of closed particles we obtain:
In order to estimate the importance of this effect we plotted in Fig. 7 this ratio vs. the bed porosity, for a floc porosity of 0.80, with the ratio of floc size to elementary particle size as parameter. We can see that for very high bed porosity there is hardly any influence, the bed behaves the same as for closed particles. For lower bed porosity, especially for \( \epsilon_b < 0.1 \) we see that the flow through the flocs causes a large increase of the bed permeability, especially at decreasing floc size.

![Fig. 7. Relative permeability of porous floc bed compared to closed particles, as function of bed porosity with relative floc size as parameter](image)

Suppose that we can approximate the equilibrium void ratio of the flocs by:

\[
e_f^* = e_{f0} (1 + a \ p_s) - \gamma_f (\epsilon_f - e_{f0})
\]  \( (11) \)

with

- \( e_{f0} \) = initial floc void ratio \([-]\)
- \( p_s \) = solid pressure \([\text{Pa}]\)
- \( a \) = coefficient \([\text{Pa}^{-1}]\)
- \( \gamma_f \) = floc compression coefficient \([-]\)

In this hypothetical relationship is reflected that a more open floc will be weaker. Now for a bed we may assume that a small deformation and displacement of flocs causes a much larger change in bed porosity than in floc porosity:
In Fig. 8 the simulated effects of the compression pressure on the porosity of the flocs and of the bed is shown.

\[
\frac{e_b}{e_{b,0}} = \left( \frac{e_f}{e_{f,0}} \right) ^\beta
\]

with \( \beta = \) bed compression exponent \((>1)\.

In Fig. 8, the simulated effect of local solid pressure on porosity of flocs and of bed is shown.

In Fig. 9, the permeability of the bed with porous flocs is now compared with the initial permeability, for different local (uniform) solid pressures. The dotted lines represent the change in permeability of the spaces between the flocs, the drawn lines show the permeability through the whole bed. It is again clear that for the small flocs considered in this simulation a considerable amount of the total flow goes through the flocs. Also a considerable decrease is seen of the bed permeability with increasing pressure.

In Fig. 10 again the relative permeability is plotted vs. the compression pressure, but now for larger flocs. We now see that the difference between a bed of flocs and a bed of closed particles is considerably less; the contribution of floc flow is here relatively low. This leads however to a much stronger decrease in overall permeability than in the case of smaller flocs.
Fig. 9. Simulated effect of solid pressure on permeability of a bed of porous flocs. Small floc size.

Fig. 10. Influence of the solid pressure on permeability of a floc bed. Larger flocs.

In conclusion we may state that this model is a good base for further refinement and experimental study. It will be especially of interest to investigate the separate deformations and porosity changes of flocs and beds, and the changes this brings
2.2. Dynamic flow through compressible beds: application to floc expression

2.2.1. Description of theory

The theory of dynamic changes in pressure and porosity profiles during filtration and expression has been reported by several authors [2-4]. The basic equation for the porosity change in one-dimensional flow reads:

\[ \frac{\partial \varepsilon}{\partial t} = - \frac{\partial}{\partial r} (\varepsilon u_1) \]  

(13)

Herein \( r \) is the distance coordinate with respect to a fixed coordinate system. We assume a modified version of D'Arcy's law:

\[ v_l - v_s = - \frac{K_l}{\eta \varepsilon} \left( \frac{\partial p_l}{\partial r} \right) \]  

(14)

with

- \( v_l \) = linear liquid velocity [m/s]
- \( v_s \) = linear velocity of solids [m/s]

The relation between the linear and superficial velocities reads:

\[ v_l = \frac{u_l}{\varepsilon} \]  

(15)

\[ v_s = \frac{u_s}{(1 - \varepsilon)} \]

Assuming no net volume production we have:

\[ u_l + u_s = u_t \cdot f(r) \]  

(16)

Herein \( u_t \) is the total net convective flow per m², which for filtration is equal to the filtrate flow per m², and for expression is equal to 0.

Neglecting gravity terms we have for the force balance:

\[ p_l + p_s = \rho_l \]  

(17)

\[ \frac{\partial p_l}{\partial r} = - \frac{\partial p_s}{\partial r} \]

Combination of Eqs. (13) - (17) leads to the differential equation:
in which it is assumed that there is a unique relation between $\varepsilon$ and $p_s$.

The boundary conditions depend on the type of operation. For filtration we have:

$$
\begin{align*}
  r = 0 & \quad - u_t - (1 - \varepsilon) \frac{K_t}{\eta} \frac{\partial \varepsilon}{\partial t} \\
  r = R(t) & \quad \varepsilon = \varepsilon_0
\end{align*}
$$

with $R_m$ = resistance of filter medium [m/Pa/s] \\
$r = 0$ = place of filter medium \\
$R(t)$ = coordinate of cake front [m]

For the case of expression we have:

$$
\begin{align*}
  r = 0 & \quad \frac{\partial \varepsilon}{\partial r} = 0 \\
  r = R(t) & \quad \varepsilon = \varepsilon^*
\end{align*}
$$

with $r = 0$ = coordinate of impermeable surface or of symmetry plane \\
$R(t)$ = coordinate of expression front [m] \\
$\varepsilon^*$ = porosity in equilibrium with applied solid pressure [

The latter boundary conditions apply when the resistance of the medium with which pressure is applied is very low. In case there is a considerable resistance, a condition similar to Eq.(19) should be applied.

Solution of the differential equation can only be done numerically. Before doing that however a change of coordinates is necessary, taking the solids volume or mass as measure.

2.2.2. Application to expression of a sludge floc

As follows from the considerations of the DUAL FLOW model, for a theoretical description of a filtration or expression process of a bed one should know the changes both in bed and in floc porosity. Therefore it was thought interesting to model the expression of a floc. The system considered is that of a flat floc, which has a thickness $2R_h$ and is expressed symmetrically in the $r$-direction. The equations of 2.2.1. were transformed to solids volume coordinates, and a modified Crank-Nicholson finite difference scheme was used to solve the equations. For the effect of solid pressure on the equilibrium void ratio Eq.(11) was used. In Fig.11 the calculated porosity profiles for a floc with an initial thickness of 200 $\mu$m are given. Initially there is a very steep gradient at the expression surface, but in progress of
time the porosity profile penetrates into the heart of the floc.

**Fig. 11.** Porosity profiles inside a floc during expression.

In Fig. 12 we see the profiles of the solid pressure as this penetrates into the floc. We see that the pressure profile remains very steep near the floc surface, and only relaxes in the last phase of the expression.

**Fig. 12.** Profiles of solid pressure inside a floc during expression.

In Fig. 13 the average porosity of the floc is given vs the expression time. We see that for this case the largest part of the expression takes place within 1 ms. From this, and other simulations we conclude that within a larger scale filtration or
expression the local floc porosity may be considered to reach equilibrium with the local compression pressure within a very short time.

![Expression of a sludge floc](image)

Fig. 13. Average porosity of a floc during expression in the course of time.

### 3. ELEMENTS OF FURTHER RESEARCH

#### 3.1. Experimental

The general target for further experimental work may be formulated as:

**obtaining insight into the relation between composition, treatment and physical properties of flocs and cakes.**

As follows from the various considerations given above we may see as important physical properties:

1. **Particle size distribution and particle morphology**
   
   These represent the initial conditions of the flocs as they enter the dewatering process. Next to laser-diffraction equipment also analysis of optical images and electron microscopy are important to get impressions of irregularities in shape, and of structural aspects.

2. **Physico-chemical aspects**
   
   It is of great importance to lay the relation between the various factors influencing floc formation and the floc size, strength and structure. This means that measurements should include zeta-potential measurements for various additives, the measurements under 1., and rheological measurements. Important is also to study the properties in relation to different floc preparation methods. Maybe special methods should be devised to measure floc strength directly.

3. **Water binding and transport**
   
   Since water may be present in various ways, it is of interest to determine the
amounts. This may for a part be done by indirect methods. Experiments on freezing curves and the determination of water vapour sorption isotherms may provide information on the amounts of free and bound water. Drying experiments of filter cakes may be analysed in terms of the effective diffusion coefficient, which is related to the pore size distribution [5]. An example of some typical drying curves is given in Fig. 14. The upper curve is for the more open part of a cake, the lower one for a sample near the filter. It is clear that the drying rate is influenced strongly by the differences in compression. Drying experiments thus offer a possibility of obtaining insight into the pore sizes and the liquid flow for cakes with different histories. Of course the information is also needed to design and optimize drying equipment.

4. Macroscopic water transport and filtration properties

A systematic investigation is needed into porosity, permeability and deformation of flocs and beds, as influenced by the initial floc properties and the process variables. One aspect is to carry out standard tests, such as the Capillary Suction Time, the (Modified) Filtration test. However for better understanding special experimental methods have to be devised to measure properties of cakes under homogeneous pressure conditions. Also it should be verified whether indeed the rate-controlling factor for cake and floc deformation is the time needed for water displacement, or whether purely mechanical properties may also play a role. Experimental investigation of the DUAL FLOW model could be done with model systems.

5. Filtration and expression rate

In order to verify more fundamental models, of course filtration and expression experiments under various process conditions should be performed, both in dedicated laboratory equipment and in well-instrumented practical scale equipment.

3.2. Theoretical modelling

☐ The DUAL FLOW model must be tested and possibly refined.
☐ For the description of filtration and expression dynamics also the transport through the flocs should be accounted for.
As in reality filtration is not a one-dimensional process, a model should be formulated for the transport and deformation in 2- and 3-dimensional situations.

- Models for the strength of flocs as dependent on structure may be set up, as related to efforts in food and polymer technology.
- Models for the analysis of drying experiments will provide insight into the liquid motion in small pores.
- For the various standard tests more detailed models must be made in order to relate the macroscopic outcome to local properties and dynamics.
- Models for the binding of water must be compared with the outcome of freezing and sorption isotherm experiments.
- Equipment models must finally be made for the description of large scale dewatering. These models can then be used for analysis of existing situations and as a simulation tool for the definition of process conditions or the design of new equipment.

4. FINAL REMARKS

Although considerable work has been carried out in the past, it is clear that on the fundamental side still a lot is to be done. As some new elements in this paper the DUAL-FLOW model was introduced, and a consideration of the expression of a floc.

In the framework as sketched here I think it is possible to make a link between all kinds of tests, fundamental properties, and theoretical descriptions for practical dewatering processes. This will lead to a much larger predictability of these processes, and combined with the insight from the physico-chemical effects to practical solutions in difficult situations.

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