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Consolidation behaviour of thick suspension in centrifugal dewatering with and without supernatant

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ABSTRACT

This study proposes an analytical method considering the consolidation behaviour in centrifugal dewatering of compressible filter cake. The main focus is on the consolidation behaviour after the disappearance of the supernatant in centrifugal dewatering of thick suspension. Solving the consolidation equation under the boundary condition proposed in this study, which represents the no flow rate due to the stable meniscus at the cake surface, it is possible to describe the shrinkage of the cake after the disappearance of the supernatant. Moreover, the analytical results show that, after the disappearance of supernatant, the meniscus at the cake surface plays an important role on the drastic increase of the solid compressive pressure near the surface and it has been clarified that the shrinkage of the cake mainly occurs near the surface.

1. Introduction

Since centrifugal dewatering is one of the effective methods for solid–liquid separation, it is used in many industrial processes (e.g. chemical, food, pharmaceutical and biotechnological processes).

Cake formed during centrifugal filtration can be classified into two types—incompressible and compressible cake. After the filtration, further dewatering of incompressible cake proceeds by the drainage of the residual liquid in the cake; on the other hand, that of compressible cake proceeds by the consolidation in addition to the drainage. Drainage is defined as the dewatering that proceeds with the decrease of the liquid level in the cake without rearrangement of particles while consolidation is defined as the dewatering that proceeds with the rearrangement of particles, keeping the saturation of cake equal to unity. The difference between drainage and consolidation is depicted in Fig. 1.

One of the methods to analyse the dewatering process of incompressible cake was proposed by Nenniger and Storrow based on the film drainage model [1]. Their concept was extended by Shirato et al., considering the pore size distribution of flow channel in the cake [2]. Hwang et al. [3] proposed a numerical method to estimate the change in the cake saturation of compressible cake over time in centrifugal dewatering, using the relation among the capillary pressure, cake permeability, and cake saturation. Wakeman and Vince [4] proposed the equation describing centrifugal drainage of unsaturated incompressible filter cake using the relative permeability of the cake to the liquid phase flowing through its voids.

In most cases of centrifugal dewatering, the liquid–cake interface appears within a certain duration of time after the centrifugal dewatering begins (Fig. 2(a) → (b)). The dewatering proceeds as the supernatant permeates through the cake layer (Fig. 2(b) → (c)). At the instant when the supernatant is entirely discharged through the cake, the cake will undergo a consolidation process, resulting in shrinkage of the cake (Fig. 2(c) → (d)). This is because of the existence of the meniscus at the entrance of flow channel of the cake [5]. The disappearance of supernatant is, therefore, important for an efficient dewatering. However, the consolidation behaviour after the disappearance of supernatant has been nearly ignored in the analysis of centrifugal dewatering.

In this paper, the centrifugal dewatering process, after the disappearance of supernatant, proceeding the consolidation mechanism only is analysed. The particle size of the model material used in this study is so fine that the drainage does not occur due to the existence of the meniscus at the cake surface. The time courses of the distribution of both solid compressive pressure and void ratio of compressible cake in centrifugal dewatering are presented.

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Nomenclature

e	local void ratio of the material, $\varepsilon/(1-\varepsilon)$, dimensionless
e_1	initial void ratio, dimensionless
l	distance of supernatant surface from filter medium, m
l_0	initial thickness of a slurry from filter medium, m
L	thickness of cake, m
p	centrifugal pressure, Pa
p_L	local liquid pressure, Pa
p_{max}	centrifugal pressure at filter medium, Pa
p_s	local solid compressive pressure, Pa
r	distance from the centre of the centrifuge, m
R_1	principal radius of the curvature of meniscus, m
R_2	principal radius of the curvature of meniscus, m
u	apparent liquid velocity, m/s

Greek letters

α	hydraulic specific resistance, m/kg
γ	surface energy, J/m^2
ε	local porosity, dimensionless
θ	time, s
μ	viscosity of liquid, Pa s
ρ	density of liquid, kg/m^3
ρ_s	density of solid, kg/m^3
ω	net solid volume per unit cross-sectional area extending from the drainage surface up to an arbitrary position in the material, m^3/m^2
ω_0	total solid volume per unit cross-sectional area, m^3/m^2
Ω	angular velocity, rad/s

2. Experimental

The centrifugal filtration tube with an inner diameter of 31.7 mm and a height of 55.9 mm was used. A filter paper (Advantec; No. 5C) was set at the bottom of the tube as a filter medium. The distance from the centre of the centrifuge to the filter medium in the chamber was 12.5 cm. Batch-wise centrifugal dewatering experiments were carried out using a centrifuge (Kokusan; H-26F). The experimental material used was zinc oxide (Nacalai) which is hydrophobic with a density of 5.7×10^3 kg/m^3 and volumetric median diameter of 6.7 μm. The slurry of zinc oxide with a solid concentration of 5.0 Vol% in the consolidation region was prepared. A certain amount of slurry was poured carefully into the centrifugal filtration tube. After both the initial thickness of slurry and the initial overall weight of the tube were measured, the chamber was set to the centrifuge. At a certain elapsed time after the beginning of centrifugation, the thickness of the cake, the distance of the supernatant surface from the filter medium and the weight of removed liquid were measured. Within the experimental conditions of this study, the cake surface was satisfactorily flat. Measurements of the thickness of the cake using a depth micrometre were conducted at four points on the cake surface. To minimize the acceleration and deceleration effects, re-acceleration of the sample was not carried out.

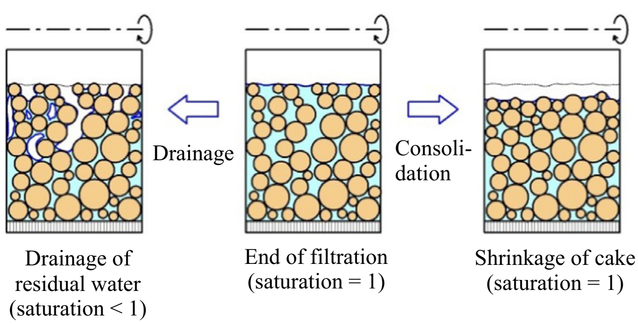

Fig. 1. Difference between dewatering by drainage and consolidation.

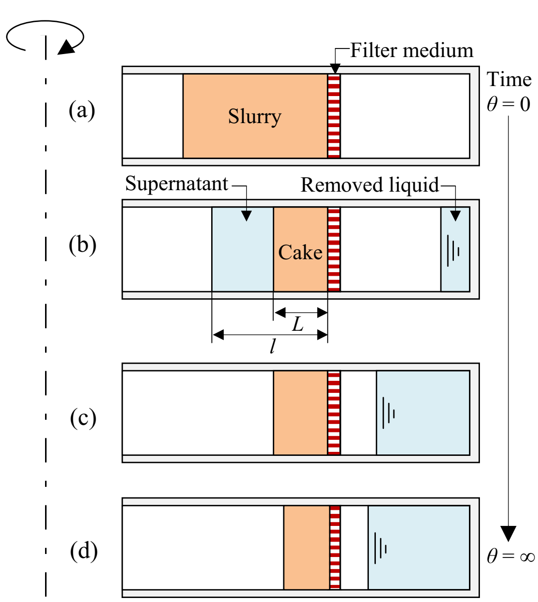

Fig. 2. Schematic diagram of process of centrifugal dewatering.

3. Analysis

At the beginning of centrifugal dewatering, the dewatering proceeds due to the liquid permeation through the sediment, accompanied by consolidation sedimentation. If the particle size of the slurry is so fine, after the disappearance of the supernatant, the drainage does not occur due to the existence of the meniscus at the cake surface, as will be explained later.

The apparent liquid velocity u in the centrifugal field is represented as follows (see Appendix): [6]

$$u = \frac{1}{\mu\alpha\rho_s}\left\{-(\rho_s-\rho)r\Omega^2 - \frac{\partial p_s}{\partial\omega}\right\} \tag{1}$$

where μ is the viscosity of liquid, α the hydraulic specific resistance, ρ_s the density of solid, ρ the density of liquid, r the distance from the centre of the centrifuge, Ω the angular velocity, p_s the local solid compressive pressure, and ω the net solid volume per unit cross-sectional area extending from the drainage surface up to the position r in the material.

The continuity equation is given by the mass balance in the thin layer of the cake:

$$\frac{\partial e}{\partial\theta} = \frac{\partial u}{\partial\omega} \tag{2}$$

where e is the void ratio and θ is the elapsed time.