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Stability of vertical hydraulic transport processes for deep ocean mining: An experimental study

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ABSTRACT

Vertical hydraulic transport systems for deep ocean mining have lengths up to a few kilometers from seafloor to sea surface. Typical ratios of particle diameter d over riser diameter D are $d/D = O(10^{-1})$, and the feeding of the riser is irregular. These conditions make the vertical transport operation susceptible to propagating density waves which is detrimental for the transport process. There is however few experience with hydraulic transport on this scale.

We adopt a continuum description of the transport process and use stability analysis theory from the field of fluidization technology. We indicate the similarities and differences between fluidization and vertical hydraulic transport to show that the theory can be extended to transport conditions as well.

We demonstrate the applicability of the theory with a fluidization experiment using particles having $d/D \leq 0.26$, which is an extension of the d/D range in classic hindered settling theory. Our transport experiment with similar particles shows differences with the fluidization experiments, indicating that flow stability in vertical transport might actually improve compared to fluidization.

1. Introduction

In deep ocean mining, the vertical hydraulic transport of polymetallic nodules or large rock cuttings is a key process. With $d/D = O(10^{-1})$ (particle diameter d, riser diameter D), relative particle sizes found in this industry exceed the conventional hydraulic transport parameter range by far. Different transport modes or regimes are very likely to occur, so knowledge of these regimes is essential for design and operation of vertical transport systems. Since there is a strong analogy between vertical hydraulic transport and fluidization technology, we will use the latter as a starting point for this research.

In fluidization theory, two extreme regimes are discerned. There is the state of homogeneous fluidization on one side, where all particles in the fluidized bed are homogeneously distributed, and there is the plug flow regime on the other side of the spectrum. In the plug flow regime, particles move through the fluidization column as density waves, collecting particles on top of the plug and loosing particles at the bottom. The plug flow is associated with system instability, i.e. the density waves might actually grow and form large solid plugs. It is expected that similar regimes can also occur in vertical transport systems. The occurrence of the plug flow regime in a vertical transport system will be detrimental for the operation, so this regime should be avoided.

In his review article, Di Felice (1995) reports on 26 liquid-solid fluidization experiments from the period 1948–1991 in 10 of which void waves or plugs have been observed. In a fluidized bed plugs thus are a quite common feature. Studies in the field of fluidization technology that focus on stability criteria for fluidized beds are for instance Verloop and Heertjes (1970),Foscolo and Gibilaro (1984,1987), Batchelor (1988) and Nicolas et al. (1994). Only few researchers however have addressed the problem of plug flow occurring in transport systems.

The vertical transport of large particles (manganese nodules) has been studied by amongst others (Clauss, 1971; Engelmann, 1978; Xia et al., 2004) and (Yang et al., 2011), but only the latter shows a photograph of different flow regimes. Research at IHC MTI in 2008, in which mono-disperse mixtures of glass beads were transported in a vertical water flow, showed the occurrence of plugs that propagated through the riser ($D = 100$ mm) as waves with a very large volume fraction. The density waves seemed to be dependent on particle properties. Especially the larger particles ($d > 20$ mm) showed propagating plugs. These experiments

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Nomenclature

a	Empirical coefficient, Eq. (21) [–]
A	Cross section area [m^2]
A_p	Particle projected area [m^2]
Ar	Archimedes number [–]
b	Empirical coefficient, Eq. (21) [–]
c_v	Volume fraction of solids [–]
c_{vd}	Delivered volume fraction of solids [–]
$c_{v,h}$	High volume fraction of solids in a shock [–]
$c_{v,l}$	Low volume fraction of solids in a shock [–]
$c_{v,0}$	Initial volume fraction of solids [–]
$c_{v,max}$	Maximum volume fraction of solids [–]
d	Particle diameter [m]
D	Pipeline inner diameter [m]
E	Modulus of elasticity [Pa]
F	Solids flux [m/s]
F_B	Buoyancy force [N]
F_D	Drag force [N]
F_F	Friction force [N]
F_G	Gravity force [N]
g	Gravitational acceleration [m/s^2]
h_0	Initial batch height [m]
h	Batch height [m]
i_t	Total hydraulic gradient [Pa/m]
i_f	Hydraulic gradient due to fluid phase wall friction [Pa/m]
i_s	Hydraulic gradient due to solid phase wall friction [Pa/m]
$i_{s,s}$	Hydraulic gradient due to static weight of solid phase [Pa/m]
k_r	Coefficient in dynamic wave velocity equation, Eq. (4) [m^2/s^2]
k_e	Coefficient in dynamic wave velocity equation, Eq. (4) [–]
λ	Linear volume fraction of solids [–]
m_s	Mass of solids in an experiment [kg]
μ_f	Dynamic fluid viscosity [Pa s]
n	Richardson and Zaki index, Eq. (7) [–]
N	Number of frames [–]
ρ_f	Fluid density [Kg/m^3]
ρ_s	Solids density [Kg/m^3]
Re_p	Particle Reynolds number [–]
$Re_{p,tr}$	Particle Reynolds number at regime transition [–]
τ_f	Fluid phase wall shear stress [Pa]
τ_s	Solid phase wall shear stress [Pa]
v_d	Dynamic wave velocity [m/s]
v_f	Fluid velocity [m/s]
v_{front}	Front velocity of a plug [m/s]
$v_{f,fl}$	Fluid velocity at fluidization [m/s]
$v_{f,tr}$	Fluid velocity at regime transition [m/s]
v_k	Kinematic wave velocity [m/s]
$v_{k,s}$	Shock front velocity [m/s]
v_m	Mixture velocity [m/s]
v_s	Solids velocity [m/s]
v_{slip}	Slip velocity between solids and fluid [m/s]
V_p	Particle volume [m^3]
w_t	Terminal settling velocity of a single particle [m/s]
$w_{t,a}$	Terminal settling velocity of a single particle including the influence of wall friction [m/s]

motivated us to conduct more experiments, which are reported in this paper.

Yang et al. (2011) conducted hydraulic lifting experiments in a setup of 30 m high and 200 mm in diameter. They provide pictures showing plugs similar to those observed in the IHC MTI laboratory in 2008, but no information is given on the demarcation of the different regimes. It is however clear from these experiments that particles with $d/D = O(10^{-1})$ typically show the plug flow behaviour.

Propagating plugs have been studied more thoroughly in the field of vertical pneumatic conveying. Niederreiter and Sommer (2004) developed a sensor for measuring the forces on pneumatically conveyed plugs of solids. Their experimental facility has a transparent vertical pipe with $D = 50$ mm, in which plastic beads with $d = 3$ mm are transported. Camera stills given in their paper display the propagation of a plug very similar to those observed in our experiments in 2008 and those shown in Yang et al. (2011). In Strauss et al. (2006) experiments with the setup of Niederreiter and Sommer (2004) are compared with DEM simulations. These simulations again show plugs being propagated through the riser, but no analysis is made of possible flow regime transitions.

An extensive analysis of flow regimes and regime transitions for vertical pneumatic conveying systems and fluidized beds (gas-solid, liquid-solid) is given by Rabinovich and Kalman (2011). They differentiate between dense phase flow and dilute phase flow. Within the dense phase flow, one can find the separate plugs and plugs with particle rain, and in the dilute phase flow one finds transport of homogeneous mixtures. The plugs with particle rain or density waves are in fact the plugs that are studied by Niederreiter and Sommer (2004) and Strauss et al. (2006). For our research the regime transition from plug flow to the state of homogeneous flow is important.

The occurrence of propagating plugs would be a serious risk for the hydraulic transport operation as they can result in riser blockage. This problem has not got much attention so far, while instabilities in fluidized beds have been investigated thoroughly. Therefor we start our analysis of the problem by a review of literature on fluidization, and from there we take the step to the occurrence of plug flow in vertical hydraulic transport. When the conditions at which plugs occur are known, the design of vertical hydraulic transport systems can be optimized for flow stability. To this end, first a continuum model is presented to find a theoretical description of the propagation of disturbances through a riser. Then fluidization experiments and transport experiments are presented in which the propagation velocities of disturbances are measured and compared with theory. Based on these results we discuss the stability of the internal flow in vertical transport systems.

2. Theory

2.1. Stability of fluidized beds

Di Felice (1995) reports on many unstable liquid-solid fluidized beds, in which density waves, plugs, voidage waves etc. were observed. The propagation of disturbances has been studied extensively in the literature in an attempt to explain the turbulent nature of many fluidized beds, and the sometimes sudden transition from highly unstable to almost perfect homogeneous fluidization.

Much of the work on stability of fluidized beds can be traced back to Wallis (1969). The essence of his stability theory of fluidized beds is the existence of two types of propagating