Ocean Engineering 101 (2015) 58–66

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Simulation and experimental proof of plug formation and riser blockage during vertical hydraulic transport

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ARTICLE INFO

Article history:
Received 19 July 2014
Accepted 5 April 2015
Available online 22 April 2015

Keywords:
Riser blockage
Vertical hydraulic transport
Deep ocean mining
Flow assurance

ABSTRACT

In deep sea mining, the vertical transport of excavated material from the seafloor to a vessel at the sea surface is a key process. Stationary flow is preferred, and blockage of the riser would terminate the entire operation.

For a blockage to occur there needs to be accumulation of material, the formation of a solid plug, and the plug needs to exert sufficient friction on the riser wall. The formation of a blockage is a complex chain of events, described in detail in this paper.

The hypothesis presented in this paper on the formation of plugs and on the conditions for a blockage to occur is checked with the results of a unique experiment. We developed a test setup in which the conditions for riser blockage are enforced. We were able to conduct a reproducable blockage experiment, which shows that the mechanism presented in this paper is a very accurate description of the blockage process.

To ensure safe operations and high production levels, the transport system needs to be designed for maximum flow assurance. Knowledge of the mechanism and conditions for riser blockage can be used in the design of feeding systems and strategies for the vertical transport system.

1. Introduction

Vertical hydraulic transport for terrestrial mining is common practice, see for instance Condolios et al. (1963), Sakamoto et al. (1978), Sellgren (1982), Evans and Shook (1991) and Berg and Cooke (2004). In terrestrial mining the slurries are often engineered for transport purposes, consisting of many fines and exhibiting stable flow.

In deep sea mining applications however, means for slurry preparation are not readily available or practically applicable due to the harsh environmental conditions in the deep sea. Manganese nodules, one of the resources looked for, are very large ($d = O(10^{-1})$ m) which introduces totally different flow regimes. See for instance the work of Clauss (1971), Engelmann (1978), Chung et al. (1999), Xia et al. (2004), Yang et al. (2011) and Talmon and Van Rhee (2011).

Despite the long history of research on vertical hydraulic transport, only few researchers have identified the risk of riser blockage during transport. Shook (1988) identified the risk of slug flow (i.e. the occurrence of intermittent plugs and clear water sections in the riser), but in his work no theory is presented on the actual formation of plugs. Berg and Cooke (2004) describe existing vertical transport systems operated in terrestrial mining sites, and they make notice of possible riser blockage. In their paper a fluidization feeder system is described. The fluidization process causes separation of the individual fractions in the particle size distribution. Upon loading the riser, first the coarse material will enter, followed by more and more finer fractions. This initial condition can result in the formation of a solid plug or even blockage of the riser. Talmon and Van Rhee (2011) identified a similar risk for vertical hydraulic transport in deep sea mining.

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http://dx.doi.org/10.1016/j.oceaneng.2015.04.015
0029-8018/

Nomenclature

A	cross section area (m^2)
c_v	volume fraction of solids (–)
$c_{v,max}$	volume fraction of solids (–)
C_D	drag coefficient (–)
d	particle diameter (m)
d_i	particle diameter at i% mass passing the sieve, where $i = 5, 10, 15\ldots$ (m)
D	riser internal diameter (m)
g	gravitational acceleration (m/s^2)
h	height (m)
L	plug length (m)
L_i	initial batch length (m)
m_s	mass of the solids (kg)
n	Richardson and Zaki exponent (–)
p	pressure (Pa)
Q_f	fluid flow (m^3/s)
Re_p	particle Reynolds number (-)
t	time (s)
V_m	volume of the mixture (m^3)
V_s	volume of the solid fraction (m^3)
v_f	fluid velocity (m/s)
$v_{f,i}$	initial fluid velocity (m/s)
v_s	solid's velocity (m/s)
v_{slip}	particle slip velocity (m/s)
w_t	terminal settling velocity (m/s)
z	axial coordinate (m)
ϵ_z	axial dispersion coefficient (m^2/s)
ϕ	angle of internal friction (°)
μ_f	fluid dynamic viscosity (Pa s)
μ_k	Coulomb friction coefficient (–)
λ	wall friction coefficient (–)
ρ_f	fluid density (kg/m^3)
ρ_s	solid's density (kg/m^3)
τ_f	wall shear stress (Pa)
$\overline{\tau'_w}$	length averaged effective plug wall shear stress (Pa)
CCM	conductivity concentration meter

They describe how batches of fines can overtake batches of coarse material. Numerical simulation of this phenomenon as presented in their paper clearly shows that the volume fraction of solids can reach very large values, up to $c_v \approx 0.65$.

Whether a plug of solids is able to cause riser blockage largely depends on its associated wall friction. van Wijk et al. (2014b) developed a model to calculate the wall friction of layered sediment plugs, and they conducted experiments to verify the model. Both the model and the experiments show that the wall friction developed by a layered sediment plug can be as large as several times its submerged weight. The associated friction forces are very well able to exceed the pumping capacity of the system, thus inducing blockage of the riser.

The risk of riser blockage is evident once a plug is present, but the development of these plugs is an unknown phenomenon hardly described in the literature. In this paper we therefor elaborate on the mechanism of plug development by interaction between batches with different transport velocities. We have designed an experiment to demonstrate that the mechanism described in this paper indeed causes a solid plug to develop, and that these plugs can cause actual blockage of the riser. This experiment is the first of its kind in literature. The results of the experiments are discussed and compared with the theory. It proves that the concept of plug development and riser blockage as presented in this paper perfectly matches the experimental results.

2. Theory

2.1. Transport of solids

For the development of plugs we are interested in the axial development of the volume fraction of solids, hence the continuity equation can be simplified to the z direction only. This results in the transport equation for the volume fraction of solids c_v

$$\frac{\partial c_v}{\partial t} + \frac{\partial (c_v \cdot v_s)}{\partial z} = \frac{\partial}{\partial z} \cdot \epsilon_z \frac{\partial c_v}{\partial z} \tag{1}$$

The transport equation consists of advection of solids with velocity v_s and the axial dispersion of solids, described with ϵ_z. Axial dispersion is introduced to model the effects of axial stretching due to a non-uniform radial velocity and turbulent mixing of solids which partly counteracts the stretching, see van Wijk et al. (2014a).

For modelling v_s we assume that the particles have a slip velocity with respect to the fluid velocity, in line with modelling sediment transport according to Evans and Shook (1991) and Van Rhee (2002)

$$v_s = v_f - v_{slip} \tag{2}$$

In Eq. (2), v_f is the average fluid velocity Q_f/A and v_{slip} is the solids velocity with respect to the fluid. The slip velocity of solids is modelled according to Richardson and Zaki (1954) and Mirza and Richardson (1979)

$$v_{slip} = 10^{-d/D} \cdot w_t \cdot (1 - c_v)^{n-1} \tag{3}$$

The factor $10^{-d/D}$ is introduced by Richardson and Zaki (1954) in the case of fluidization instead of sedimentation. This factor becomes very significant when looking at relatively large particles. The exponent n depends on the particle Reynolds number. Its value ranges from 2.36 for relatively large particles to 4.7 for relatively small particles. Rowe (1987) gives n as

$$n = \frac{4.7 + 0.41 \cdot Re_p^{0.75}}{1 + 0.175 \cdot Re_p^{0.75}} \tag{4}$$

The particle Reynolds number Re_p is given by

$$Re_p = \frac{\rho_f \cdot w_t \cdot d}{\mu_f} \tag{5}$$

In Eq. (3), w_t is the terminal settling velocity of a single particle. It is given by

$$w_t = \sqrt{\frac{4 \cdot g \cdot (\rho_s - \rho_f) \cdot d}{3 \cdot \rho_f \cdot C_D}} \tag{6}$$

The drag coefficient C_D is a function of Re_p as well. For spherical particles we use the equation of Brown and Lawler (2003)

$$C_D = \frac{24}{Re_p} \cdot \left(1 + 0.15 \cdot Re_p^{0.681}\right) + \frac{0.407}{1 + 8710 \cdot Re_p^{-1}} \tag{7}$$

The solids encountered in deep sea mining, e.g. rock cuttings or nodules, show all possible shapes but perfectly spherical. The drag coefficient of irregularly shaped particles is larger than the coefficient of a sphere. This effect can be corrected for by for instance introducing the particles sphericity, which would result in an