Ocean Engineering 79 (2014) 50–57

Contents lists available at ScienceDirect

Ocean Engineering

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

Wall friction of coarse grained sediment plugs transported in a water flow through a vertical pipe

J.M. van Wijk [a,b,*], C. van Rhee [c], A.M. Talmon [c,d]

[a] MTI Holland B.V., Smitweg 6, 2963 AW Kinderdijk, The Netherlands
[b] Delft University of Technology, Section of Offshore and Dredging Engineering, Mekelweg 2, 2628 CD Delft, The Netherlands
[c] Delft University of Technology, Section of Dredging Engineering, Mekelweg 2, 2628 CD Delft, The Netherlands
[d] Deltares, PO Box 177, 2600 MH Delft, The Netherlands

ARTICLE INFO

Article history:
Received 14 March 2013
Accepted 18 January 2014
Available online 5 February 2014

Keywords:
Vertical hydraulic transport
Sediment
Plug flow
Riser blockage
Ocean mining

ABSTRACT

Hydraulic transport is an energy effective means of transporting vast amounts of solid bulk goods suspended in a fluid flow, encountered in many fields in industry. The case of vertical hydraulic transport of suspended sediments and ore is of special interest in the fields of dredging, terrestrial mining and ocean mining. From field experience it is known that during vertical hydraulic transport over long distances, solid sediment plugs can develop that pose the risk of riser blockage. In this paper an investigation into wall friction of layered sediment plugs is set out. Knowledge about this specific type of plugs and their associated wall friction is necessary for the design of vertical transport systems. First a model is developed, and then an experiment is conducted to verify the model. The model input consists of soil mechanical parameters like the internal angle of friction of the sediment and the coefficient of friction between the sediment material and the riser wall, and geometrical properties such as plug length and riser diameter. By using common values for both the internal angle of friction and the kinetic friction coefficient, the model predicts the outcome of the experiments reasonably well.

1. Introduction

The problem of riser blockage and plug formation in general has been addressed by Shook (1988). He mentions the development of large radial stresses and their accompanied wall shear stress in highly concentrated plugs. Grain contacts are the driving mechanism for wall friction, and he refers to stresses in bins as a comparable case. The development of plugs cannot be described by the theory presented in Shook (1988). Although plug friction is mentioned, an analysis of the stresses in plugs is not given. The paper primarily focuses on the development of concentration in space and time in highly concentrated slugs consisting of two types of particles, in two batches, calculated by numerical simulation. Wall friction is of minor importance in his analysis. Three different initial concentration distributions are analyzed, and plug formation out of highly concentrated slugs is indeed identified as a risk for the vertical transport operation.

The risk of riser blockage by a plug of solid particles is also known from terrestrial mining activities as described in Van den Berg and Cooke (2004). In their paper a series of vertical hydraulic transport systems is analyzed on operational aspects. These systems are used in mine shafts to hoist ore over distances from 270 m to 2222 m by using a riser system with positive displacement pumps. One of the design considerations relates to the riser feeding, which can be done by several systems including a fluidization feeder. This type of feeder fluidizes the ore before inserting it into the riser. The fluidization feeder acts as a separation column in this case: the largest, heaviest particles remain at the bottom of the feeder vessel while the finer ore particles are transported to the top of the fluidized bed. Upon opening the feeder vessel after fluidization, first the coarse and heavy particles enter the riser, followed by the finer fractions. Due to differences in slip velocity the finer fractions tend to overtake the more coarse and heavy fractions, thus causing accumulation and eventually causing a plug to develop. The plug thus developed could block the riser.

Riser blockage by the mechanism described above is indicated as a major risk for vertical transport in ocean mining as well. Talmon and Van Rhee (2011) show by means of numerical simulation that subsequently filling a riser with batches of particles, starting with a batch of relatively large particles and then inserting more and more finer material, indeed results in

---

* Corresponding author at: MTI Holland B.V., Smitweg 6, 2963 AW Kinderdijk, The Netherlands.
E-mail addresses: jm.vanwijk@mtiholland.com (J.M. van Wijk), C.vanRhee@tudelft.nl (C. van Rhee), A.M.Talmon@tudelft.nl, Arno.Talmon@deltares.nl (A.M. Talmon).
URL: http://www.deltares.nl (A.M. Talmon).

0029-8018/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2014.01.010

Nomenclature

A	cross section area (m^2)
c_v	volume fraction of solids (dimensionless)
d	particle diameter (m)
D	riser diameter (m)
g	gravitational acceleration (m/s^2)
L_1	vertical coordinate of bottom layer (m)
L_2	vertical coordinate of top layer (m)
L_{plug}	length of an arbitrary plug (m)
$\Delta L_{sensors}$	distance between the impulse tubes of the differential pressure sensor (m)
m_{plug}	plug mass (kg)
p	pressure (Pa)
p_e	excess pressure (Pa)
Q_m	mixture volume flow (m^3/s)
Q_f	water volume flow (m^3/s)
Q_s	solids volume flow (m^3/s)
t	time (s)
Δt_{plug}	time needed for a plug to travel the distance $\Delta L_{sensors}$ (s)
z	axial coordinate (m)
φ	angle of internal friction (deg)
μ_f	dynamic fluid viscosity (Pa s)
μ_k	kinetic friction coefficient (dimensionless)
κ	permeability (m^2)
κ_I	inertial permeability (m^2)
ρ_f	water density (kg/m^3)
ρ_s	solids density (kg/m^3)
σ_z	axial stress (Pa)
σ_z'	effective axial stress (Pa)
σ_r'	effective radial stress (Pa)
τ'_w	wall shear stress (Pa)
$\overline{\tau'_w}$	length averaged wall shear stress (Pa)

accumulation of material and plug development. This mechanism typically leads to layered plugs. This layered structure will prove to be a key factor in the risk of riser blockage, as will be shown in the section on the model development.

Research into plug flow and wall friction of plugs that are transported vertically is mainly found in the field of pneumatic transport. Gas–solid flows do differ in many ways from hydraulic transport, for the density ratio of the suspended phase and the carrier phase is much larger in pneumatic transport than it is for hydraulic transport, and the particles considered in pneumatic transport are orders of magnitudes smaller than the solids encountered in hydraulic transport of ore. Nevertheless, studying literature on pneumatic transport gives some very interesting references for model development.

Borzone and Klinzing (1987) have studied the flow and wall friction of powder plugs in vertical air flows. They used plugs of cohesive coal powder, transported in a vertical tube with $D=0.025$ m. They found that the pressure drop over a plug varied linearly with its length. At small gas velocities the plug velocity seemed to be independent of plug length. By analysis of the stress state of a monodisperse plug (i.e. a plug that only contains equally sized particles) they concluded that the only state possible is zero stress over the entire plug length, from which it follows that the submerged weight of the plug is carried entirely by the vertical flow and hence there is a linear relation between pressure drop (equal to the submerged weight) and the plug length.

Niederreiter and Sommer (2004) show the development of a sensor tube, which is used to measure the wall friction between a plug and the tube wall. The tube wall measures the force that is exerted by the passing plug. To interpret the data, they calculate the stress state of a plug with arbitrary boundary conditions for the stress at the top and the bottom. Since the boundary conditions of a plug in motion are unknown a priori, so they state, it is concluded that calculation of wall friction is only possible after measurement of the particle wall stresses.

Rabinovich et al. (2012) investigated the wall friction forces on plugs of coarse particles in a vertical column. Their friction model uses the stress state in a monodisperse plug with a nonzero stress boundary condition at the bottom. The authors wish to use the model in calculations for pneumatic conveying of plugs, so at a first glance the choice for this boundary condition seems incorrect for using the model for a freely suspended monodisperse plug. After all, Borzone and Klinzing (1987) already showed the zero stress state of a similar plug, so no wall friction could be expected at all. When looking at the test setup Rabinovich et al. (2012) used for their experiment, the choice for this nonzero boundary condition becomes clear: the monodisperse plug is directly supported by a permeable piston, which indeed poses a nonzero stress condition at the bottom. The experiment consists of pulling the piston upward through the vertical pipe, and then measuring the force needed for the pull for various pipe materials. No gas is flowing through the plug during the experiment, so the measurement only yields the mechanical friction between the plug particles and the pipe wall for the special case of a plug that is pulled through the pipe by a solid piston rather than by a gas flow.

The cases of powder transport and of coarse monodisperse plugs being lifted on a piston, as discussed in the literature review, are not very representative of the wall friction between a plug of coarse sediment that is transported hydraulically and the riser wall, but they are however very inspiring: it demonstrates that for a plug to exert friction on a pipe wall, a nonzero stress condition at the bottom of the plug is a necessity. This results in the following hypothesis are put to the test in this paper:

The layered plug that could develop in vertical hydraulic transport systems allows for a nonzero stress state at the interfaces between the different layers (due to differences in permeability between the layers), and thus allows for wall friction to be exerted on the riser wall.

The nonzero stress state between the layers should be explained in more detail. When a layer with permeability κ_1 is put on a layer with permeability κ_2, and when it holds $\kappa_1 \gg \kappa_2$, then the water flow through the bottom layer is insufficient to support the submerged weight of the top layer, so part of the submerged weight of the top layer has to be carried by the bottom layer. This results in a nonzero stress state at the interface, for the bottom layer partially carries the top layer.

2. Development of a plug friction model for a plug with two layers

Development of the layered plug friction model starts with considering a plug with two layers, as depicted in Fig. 1(a). The stress state on an incremental slice of this plug is depicted in Fig. 1(b). The total volumetric flow of solids and water through a riser is denoted Q_m. The flow of water is denoted Q_f, the flow of solids Q_s, so the continuity equation for a riser with plug flow is given by

$$Q_m = Q_f + Q_s \tag{1}$$