1979

Flow rate of simple bulk solids from mass flow bins

Arnold G. McLean
University of Wollongong

FLOW RATE OF SIMPLE BULK SOLIDS FROM

MASS FLOW BINS

A thesis submitted in fulfilment of the

requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

from

The University of Wollongong

by

A.G.McLean

B.E.(N.S.W),Grad,I.E.Aust.

Department of Mechanical Engineering

1979

This is to certify that this work has not been submitted for a degree to any other university or institution.

ARNOLD GRANT McLEAN

1.   Abstract

There is hardly an industry which does not employ gravity flow bins for the storage of bulk solids.Consequently there has been considerable activity and research to provide the engineer with information that will enable him to design bulk solid storage facilities for unobstructed and predictable flow.There also has been an increasing tendency in industry to handle finer materials which has led to considerable difficulties especially in cases where the actual flow rate was considerably less than plant capacities.Such misfortunes have prompted a number of investigations in this field in an endeavour to understand the flow of fine materials and to make suitable modifications to gravity flow bins to improve the flow situation.

This thesis is concerned with the prediction of the flow rates of fine bulk solids from mass flow bins and hoppers.In this initial treatment the two-phase nature of the flow will become apparent.The analysis requires the simultaneous consideration of the continuity of the bulk solid and the interstitial fluid,and the inclusion of the effects of the interstitial gas pressure gradients in the equation of motion of the flowing bulk solid.

This analysis will be applied initially to an incremental element of bulk solid,the flow through which is described by a number of partial differential equations whose solution requires considerable numerical effort.An approximate analysis is then be developed by considering the flow through an assumed element.Three non-linear total differential equations result which also require numerical techniques for

their solution.

By making suitable assumptions for the form of the flow stress field ,analytical solutions for the flow rate,the interstitial gas pressure distribution and the flow stress field are obtained for channels with or without surcharge.Results for coarse bulk solids are then derived by neglecting the effects of interstitial fliud pressure gradients.

The predicted flow rates compare favourably with observed flow rates from an experimental plane flow bin.

It must be stressed that this is only an initial treatment, extensive work still is required to completely understand and predict the flow of general bulk solids from bins.

2. <u>Acknowledgements</u>

Table of Contents

List of Figures

* (-) opposite page

Chapter 4

Chapter 5

<u>List of Plates</u>

<u>Chapter 9</u>

List of Tables

List of Programs

1.   <u>Nomenclature</u>

a   -   exponent used to relate permeability coefficient to
            consolidation stress,eqn.(3.19)

A   -   area of flow channel

A_1,A_2,A_3- variables defined by eqns.(6.27),(6.28),(6.29)
            respectively

A_4,A_5,A_6- variables defined by eqns.(6.44),(6.45),(6.46)
            respectively

A_7,A_8,A_9- variables defined by eqns.(7.23),(7.24),(7.25)
            respectively

b   -   exponent used to relate bulk density to
            consolidation stress,eqn.(3.18)

$\bar{b}_1$,$\bar{b}_2$ - body forces used in eqns.(4.30) and (4.31)

B   -   width or diameter of outlet of flow channel

c   -   permeability coefficient of bulk solid,eqn.(3.19)

c_o -   permeability coefficient of bulk solid when $\sigma = \sigma_o$

C   -   constant relating mean stress at hopper outlet to
            dynamic head at outlet,eqn.(5.111)

C_1 -   constant of integration used in eqn.(6.18),
            defined in eqn.(A5.18)

C_3 -   constant of integration used in eqn.(7.9),
            defined in eqn.(7.17)

C_4 -   constant of integration used in eqn.(7.10)

C_5 -   constant of integration used in eqn.(8.16),
            defined in eqn.(8.20).

C_6 -   constant of integration used in eqn.(8.17)

$\bar{f}_1, \bar{f}_2$ - fluid drag force, used in eqns.(4.30) and (4.31)

ff - flow factor for a converging channel

ff_a - 'actual' flow factor for a flow situation

F - unconfined yield strength of a bulk solid

FF - flow function of a bulk solid

g - acceleration due to gravity

G_1, G_2, G_3 - constants defined in eqns.(6.11),(7.7) & (8.15)

       respectively

H - moisture content

I - integrand defined by eqn.(5.7) or by (5.14)

       respectively

k - coefficient

    $k = +1$ for the major principal stress

    $k = -1$ for the minor principal stress

    $k = 0$ for the mean stress

L - length of a plane flow hopper outlet

m - coefficient

    $m = 0$ for plane flow (end effects neglected)

    $m = 1$ for axisymmetric flow

m_e - suspended mass in experimental bin

$\dot{M}$ - bulk solid mass flow rate

$\bar{M}$ - vertical momentum component

n, n_1, n_2 - exponents used in the analytical expressions for

       the flow stress field

N - number of divisions over which approximate gas

       pressure distribution is evaluated

p   -   interstitial gas pressure

p(R) -   interstitial gas pressure at distance R from hopper

              vertex

p(r)   -   function defined by eqn.(A5.3)

Q   -   bulk solid mass flow rate,eqn.(6.34)

Q_D -   dimensionless flow rate,used in eqn.(6.51)

Q(r)   -   function defined by eqn.(A5.4)

r   -   radial distance from the vertex of the flow channel

r_o -   radial distance to hopper outlet,eqn.(6.30)

r*   -   the distance from the vertex of the channel to

              where the stress is assumed to be zero,Fig.(1.5)

R   -   radial distance from the vertex to the transition

              of a hopper

s   -   stress function,used in eqns.(6.1),(7.1),(8.8)

              respectively

t   -   time

T   -   temperature

T_e -   tensile force in load cell in experimental

              installation,eqn.(9.1)

T_1,T_2,T_3- variables defined by eqns.(6.13),(6.19),(6.20)

              respectively

T_4,T_5,T_6- variables defined by eqns.(6.21),(7.3),(8.10)

              respectively

u   -   interstitial fluid velocity

V -   bulk solid velocity

V_e -   representative velocity in experimental installation

V_o -   bulk solid velocity at the outlet of a channel

$V1$ -   major consolidation load

W_1 -   variable defined by eqn.(6.17)

X -   variable used in Enstad theory,defined in eqn.(5.103)

Y -   variable used in Enstad theory,defined in eqn.(5.104)

YY -   variable defined in eqn.(5.82)

z -   component direction

             distance along a plane flow hopper,Fig.3.2

             meridional direction in axisymmetry,Fig.3.3

Z_1 -   variable defined by eqn.(6.14)

Z_2,Z_3,Z_4 - variables defined in eqns.(8.26),(8.27),(8.28)

             respectively

α -   hopper half angle

β -   angle between major principal stress and normal to hopper wall for flow conditions,defined in eqn.(3.16)

Γ -   porosity of a bulk solid,defined in eqn.(3.20)

δ -   effective angle of internal friction of a bulk solid

θ -   angular co-ordinate in plane radial co-ordinates and in the meridional plane in axial symmetry

ξ -   integration variable

ρ - bulk density of a bulk solid, eqn.(3.18)

ρ_o - bulk density when $\sigma = \sigma_o$

ρ_f - density of the interstitial fluid

ρ_g - density of the interstitial gas

ρ_s - density of solid particles

σ - mean stress

σ_o - mean stress at outlet of flow channel

σ_w - normal stress along the wall

$\sigma(R)$ - value of the mean stress at the transition

σ_1, σ_2 - major and minor consolidation stresses

σ_r, σ_θ - consolidation stresses in the r and θ direction respectively

ϕ - kinematic angle of friction between a bulk solid and a bin wall

τ - shear stress

τ_w - shear stress along the wall

$\tau_{r\theta}$ - shear stress component defined in Fig. 3.6

ψ - angle between the co-ordinate ray and principal stress direction, defined in Fig. 3.6

ψ^* - angle defined in Fig. A2.1

ω - angle related to θ and ψ, defined in Fig. 3.6

Subscripts

r   —   r component

θ —   component

e   —   experimental

f   —   interstitial fluid

g   —   interstitial gas

s   —   solid particles

o   —   pertaining to the outlet of the flow channel

R   —   pertaining to distance R from vertex of flow channel

T   —   pertaining to the transition of the flow channel

w   —   denotes conditions at the wall

c   —   conical

p   —   plane flow

Superscripts

′ denotes Enstad co-ordinate system,defined

in Fig.5.1

Prefix

Δ —   finite change