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Mechanics of Granular-Frictional-Visco-Plastic Fluids in Civil and Mining Engineering

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Abstract. The shear stress generated in mine backfill slurries and fresh concrete contains both velocity gradient dependent and frictional terms, categorised as frictional viscous plastic fluids. This paper discusses application of the developed analytical solution for flow rate as a function of pressure and pressure gradient in discs, pipes and cones for such frictional Bingham-Herschel-Bulkley fluids. This paper discusses application of this continuum fluid model to industrial materials like mine and mineral slurries, backfills and fresh concrete tests.

Keywords: pipe, pipeline, cohesive, viscous, frictional, depositing, non-Newtonian, slurry, coal mining, Bingham-Herschel-Bulkley (BHB), plastic, yield, analytical solutions, subsidence

INTRODUCTION

Slurries with very fine aggregates are used to backfill underground voids and mines to prevent subsidence and surface structural damage. Backfilling and injection of granular materials into mining induced voids, separated beddings and cracks, as either diluted slurry or concrete paste, is widely used to control subsidence. High quality concrete for deep foundations needs to meet particular performance criteria to achieve the required workability and stability. Fresh concrete, fly ash and mining slurries are all granular-frictional-visco-plastic fluids. Fresh concrete flow in Tremie pipes is used to control concrete flow rate and minimise bleeding and dilution when concrete is poured into deep submerged excavations for pile foundation construction. As a viable environmental solution, mine waste and rejected materials from underground coal seams are used in both backfilling and injection mine operations. The large cavern created by an underground mine may eventually lead to failure of the overburden rock, propagating layer by layer to the surface, resulting in substantial ground surface subsidence [1]. Grouts and slurries made of mine and power plant wastes and rejects are viable environmental backfill solutions to both ground stability and mine waste management problems – See Figure 1 for some applications. Recent laboratory and field experiments on mine-backfill fluids, slurries, cements, pastes and concretes proved their wide range of shear resistance and complex behaviour in response to shearing necessitating development of a general, nonlinear, cohesive, viscous, frictional, nonlinear, non-Newtonian model of shear stress versus shear strain rate, as an extension to the classical Bingham-Herschel-Bulkley (BHB) fluid [2-11]. The value of the shear strength function at zero shear strain rate, i.e. plastic yield and the tangent slope of the stress-strain rate curve (viscosity), at any given shear rate, are the two most important parameters of such fluids – Figure 2. The aim is to extend application of this continuum model to industrial materials like mine and mineral slurries, backfills and concrete. The theoretical solutions are based on fundamental equations of continuum mechanics [2-3] developed for slurries in the general context of a Non-Newtonian BHB fluid, in which fluid cohesion (plastic yield strength), viscosity and friction, are variable and functions of the flow direction axis (x_1) normal to the pipe or disc section area. Solutions from derived equations provide formulae for the field quantities such as: minimum injection pump pressure, local fluid pressure (p) and pressure gradient functions (dp/dx_1), local wall shear stress function τ (at $x_2 = h$, i.e. τ_{hx2}), volume flow rate (Q), fluid velocity (u) and velocity gradient ($y=du/dx_1= u_{1,2}$).

ANALYTICAL SOLUTIONS FOR FRICTIONAL BHB FLUIDS

Referring to Figure 2, the general constitutive equation, relating fluid shear stress to shear rate for such general nonlinear, non-Newtonian, viscous, plastic, frictional fluids, which can be applied to fresh concrete, mine backfill slurries and high frictional multiphase fluids, is as follows [2-4]:

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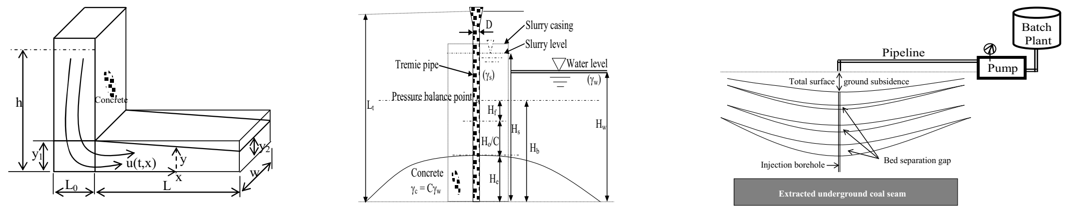

(a) Concrete flow testing (b) Concrete tremie pipe flow (c) Slurry flow in pipe and strata

FIGURE 1. Various applications of viscous slurry and paste fluids: (a) channel flow for workability and consistency testing of concrete; (b) Concrete tremie pipe flow into submerged foundations; (c) multi-phase slurry flow in pipes and fractured rock strata for void backfilling.

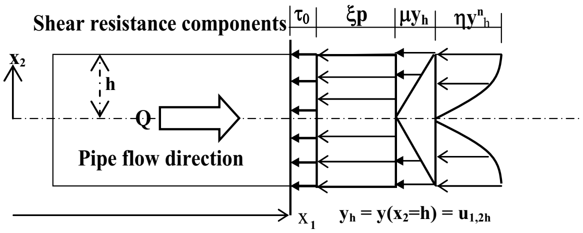

FIGURE 2. Schematic diagrams showing various shear stress components in Equation (1). τ_0 is the constant uniform plastic yield component, with no viscosity; μ is the Newtonian linear viscosity coefficient of the linear velocity gradient y with a wall value y_h.; η is the non-linear viscosity; ξ is the friction coefficient of the fluid pressure p.

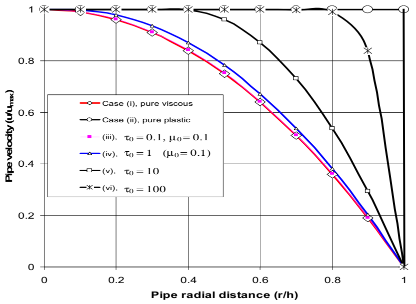

FIGURE 3. Comparisons of normalised velocity profiles for different slurries of various viscosity (μ) and plasticity (τ) in a pipe flow.

$$\boldsymbol{\tau}(t,\ \mathbf{x}) = \mu(t,\ \mathbf{x})\left(-\frac{\partial \mathbf{u}(t,\ \mathbf{x})}{\partial \hat{\mathbf{x}}}\right) + \eta(t,\ \mathbf{x})\left(-\frac{\partial \mathbf{u}(t,\ \mathbf{x})}{\partial \hat{\mathbf{x}}}\right)^{n} + \boldsymbol{\tau}_{\mathbf{0}}(t,\ \mathbf{x}) + \xi(t,\ \mathbf{x})p(t,\ \mathbf{x}). \tag{1}$$

In Eq. 1 τ is shear stress tensor, **u** is velocity vector, μ and η are linear and nonlinear viscosities, $\boldsymbol{\tau}_0$ is plastic yield, p is fluid pressure and ξ is concrete friction coefficient. The last term, involving the friction and pressure terms (ξp), is a frictional resistance term which can be applied only when a pipe blockage occurs due to the concrete granular material friction and needs to be reopened by a higher pressure flow, otherwise it can be ignored [2-11]. Governed by the classical continuum theory, the moment equilibrium requires symmetry of the shear stress tensor, which can be normalised and indicated by *Italic fonts* [2-4], i.e.

$$\tau_{ij} = \tau_{ji} = -\mu(u_{i,j} + u_{j,i}) - \eta(u_{i,j} + u_{j,i})^{n} + \tau_{0i,j} + \xi p \delta_{ij}. \tag{2}$$

Exact equations can be derived [2-4] to relate the fluid flow rate Q to the fluid pressure p, e.g. in a pipe or radial disc. The results are integral equations relating velocity gradient $u_{1,2}$, and its value at the boundary $x_2 = h$, i.e. $u_{1,2h}$, to the flow rate Q [2-4].

Pipe Flow:

$$Q = \int_A \vec{u}.d\vec{A} = 2\pi\int_0^h x_2 u_1 dx_2 = \frac{\pi}{3}h^3\left(u_{1,2h} - F_h^{-3}G_h\right). \tag{3}$$

Radial Flow:

$$Q = \int_A \vec{u}.d\vec{A} = 2\pi\int_0^h x_2 u_1 dx_2 = 2\pi h^2\left(u_{1,2h} - f_h^{-2}g_h\right). \tag{4}$$

In Equations (3) and (4), f, g, F and G are functions of geometry and flow properties [2-4]. Slurry flow may be assumed to stop in the case of a blockage (Q →0), which means the boundary values of the velocity gradients $u_{1,2h}$ and $g(u_{1,2h})$ are identically zero. This is due to the effects of the cohesive frictional terms (ξ and τ_0) introduced in the shear stress Equation (1), which now become dominant in blocking the slurry flow. The above general theory is certainly reducible to simpler classical Newtonian and Bingham models with appropriate parameter substitutions [2-4] – Figure 3.

NUMERICAL (CFD) SOLUTIONS FOR FRICTIONAL BHB FLUIDS

CFD simulations can be carried out showing evidence that modern concrete behaves like a non-Newtonian frictional viscoplastic Bingham-plastic fluid. The CFD simulations demonstrate that the method is capable of shedding light on the "blind process" side of concreting deep and underground foundations, as a powerful prediction tool. Quality control, optimized ingredients and best operational procedures may be achieved by repeatedly simulating the process with different conditions and configurations to ensure high quality of the foundation concrete. Computational Fluid Dynamics (CFD - ANSYS Fluent 13.0) models have been developed [8,10] to simulate behaviour of slurry and concrete flow as occurs in laboratory experiments and field operations. Figure 4 shows the CFD modelling results of the familiar concrete slump test world widely used. The initial condition is that the test slump cone is fully filled with concrete and the simulation starts when the cone is lifted or removed. In this figure, the maximum CFD drop and spread are 252 and 410mm matching well an experimental test result. L-box test is used to test the flow behaviour of fresh concrete in tremie pipe applications [4-8]. The flow length, represented by the distance from the L-box gate to the tip of the concrete is recorded, as shown in Figure 5. It can be seen that the tip of the concrete reached the end of the horizontal box at about t=8 s, which matches the test result (7.56 s), indicating the CFD model is fully capable of simulating the tremie concrete flow very well.

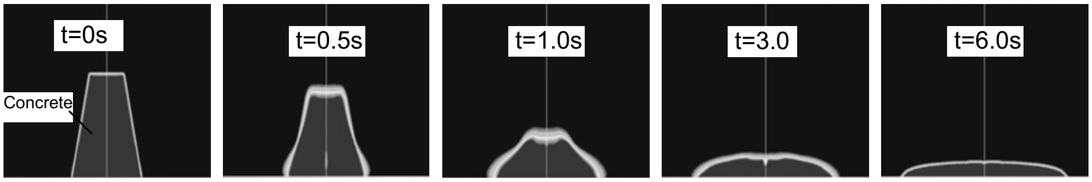

FIGURE 4. CFD simulation of concrete slump test at different times

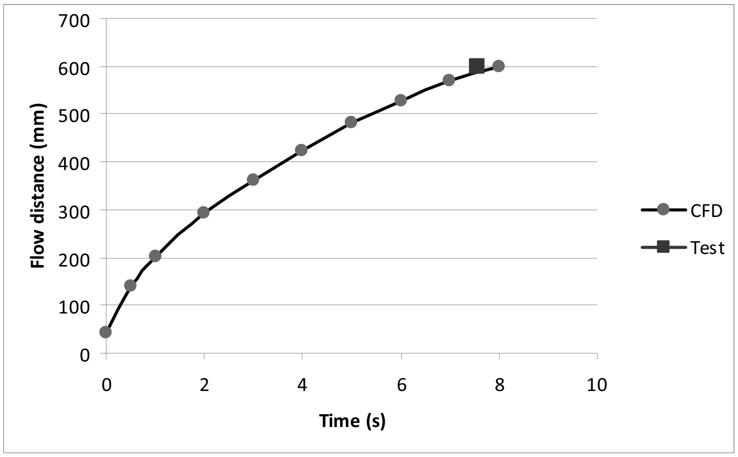

FIGURE 5. Comparison of CFD modelling results and L-Box tests of fresh concrete

CONCLUDING REMARKS

On the basis of continuum equations of fluid and soil mechanics, a comprehensive, versatile, slurry shear model has been developed for transportation of grout, paste and fill materials used in the civil and mining industries, covering a wide range of material characteristics and behaviour, namely from the flowing fluid slurries to consolidated solid deposits in underground coal mining induced rock fractures. The theory has been specifically tailor made for grout flows through uniform pipes, discs and tremies, in order to transport material to designated injection or backfill targets. The theory can mimic both flow and blockage behaviour of the fill material. The tool can be used to predict variations of pressure and velocity and their gradients, as a function of flow rate, in the entire backfill-placement system from batching plant to the borehole cracks and foundation excavations.

The shear theory can mimic shear resistance of both: (i) a cohesive, viscous flow and (ii) a stationary, cohesive, pressure-dependent, frictional, plastic soil. The pressure dependent frictional term in the shear stress model determines the frictional resistance of the deposited fill material during a blockage. Consistent with laboratory and field experiments, the theoretical pump pressure required to open a blockage is orders of magnitude greater than the amount needed for pumping the same material when it is under a steady state flow. This explains why very high pump pressures are often needed to clean blockages compared with much lower pressures required during steady state slurry flows.

Concrete flow and placement into deep foundations is normally performed under several harsh environmental conditions of tightness, inaccessibility and deep submergence. Therefore, it must be self compacting, self levelling and maintain its original quality, homogeneity and integrity all the way from the tremie pipe to the discharge point and then through the narrow paths between heavy reinforcements. Traditional slump and spread tests together with the L-box tests are used as indirect index tests to measure physical visco-plastic properties of concrete.

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