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Fall velocity of particles in shear flow of drilling fluids

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Abstract

Viscoplastic drilling fluids discharge excavated solid particles in soft soil tunnelling. Deposition of particles in pipes and boreholes should be kept to a minimum. To quantify the fall velocity of particles in shear flow different combinations of fluid properties and particle sizes were tested. It is shown that co-rotation of the particles with the flow and vertical equilibrium of forces determine the fall velocity in these fluids. The use of a Stokes type formula for fall velocity in shear flow of tunnelling fluids is justified.

Keywords: Solids; Slurry; Non-Newtonian; Viscoplastic fluid; Soft soil tunnelling; Fall velocity

1. Introduction

The Dutch subsoil typically consists of sand, peat and clay. Also gravel is found. Different drilling techniques are being employed for the renewal and expansion of railway lines, motorways, pipelines and utility services.

With the horizontal directional drilling (HDD) technique distances of tens of metres up to 1 km are drilled. The diameter of the borehole is of the order of 0.1–1.5 m and drilling depths range from a few metres up to 30 m. Ongoing research activities in the Netherlands are described by Seters (2003). Drilling fluids are water-based bentonite suspensions. The fluid has two important functions: providing stability to the borehole and transportation of excavated material to the surface.

On a different scale there are traffic tunnels, the diameter of which can exceed 8 m and cover distances of more than 1 km. Drilling methods and tunnel boring machines (TBM) are described by Maidl et al. (1996). Their construction technique is referred to as macro-tunnelling. In slurry shield tunnelling, the same type of drilling fluids stabilise the soil at the face and the excavated soil is transported to the surface by means of the drilling fluid.

Traditionally a distinction is made between settling and non-settling slurries based on the sediment transport capacity; however, the demarcation between both is unclear. Two different approaches seem to be followed in tunnelling. In design-calculations for HDD the slurry is considered to be non-settling, since no account is made for settling of particles. In macro-tunnelling the slurry in the discharge pipeline seems to be considered as the settling type because of the high design flow velocities (being equal to those needed for transport by water). This is in contrast to the slurry in the mixing chamber at the face, where it apparently behaves as a non-settling slurry; mixture densities up to 1450 kg/m^3 have been found (Bakker et al., 2003). Because of this unclear situation and the fact that many slurries display settling tendencies under flowing conditions, the fall velocity of particles in shear flow of tunnelling fluids has to be quantified.

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Nomenclature

List of symbols

a_{cr}	coefficient in yield stress criterion (dimensionless)
c	volumetric concentration of particles (dimensionless)
d	particle diameter (m)
d_{cr}	critical particle diameter (m)
d_{50}	median particle diameter (m)
$F_{1\text{-}4}$	forces acting on particle (N)
g	gravity (m/s^2)
G	immersed weight of particle (N)
K	viscosity parameter (Pa s^n)
n	exponent in rheological model (dimensionless)
u	horizontal velocity (m/s)
u_t	particle tangential velocity (m/s)
U	main flow velocity (m/s)
v	vertical velocity (m/s)
w_s	particle fall velocity (m/s)
z	vertical coordinate (m)
α	empirical coefficient (dimensionless)
ϕ	angular coordinate (rad)
$\dot{\gamma}$	shear rate (1/s)
κ	von Karman constant ($\kappa = 0.4$) (dimensionless)
η	apparent viscosity main flow (Pa s)
ρ	density (kg/m^3)
ρ_f	fluid density (kg/m^3)
ρ_s	particle density (kg/m^3)
τ	shear stress (Pa)
τ_y	yield stress (Pa)

The settling tendencies of particles in shear flow have been investigated in relation to oil exploration. Novotny (1977); Hannah and Harrington (1981); Roodhart (1985); Jin and Penny (1994); Gheissary and Van den Brule (1996) found that the fall velocity increased with the shear rate of the main flow. Fluids being employed were an oil-brine based fracturing fluid, aqueous solutions of hydroxy ethyl cellulose (HEC), hydroxy propyl guar (HPG), xanthan, carboxy methyl cellulose (CMC), Xanvis and Carbopol. However in fluids with pronounced elastic properties the fall velocity decreases with shear rate (Van den Brule and Gheissary, 1993).

2. Rheology of drilling fluids

The drilling fluids typically used in soft soil tunnelling are water-based bentonite suspensions, to which various viscosifiers and surfactants may be added to enhance the fluid's performance. The flow characteristics of such a suspension are largely governed by the electrochemical properties of the colloidal bentonite clay particles that form a network with certain strength. When compared to drilling fluids used in the petroleum industry, the bentonite concentration is generally higher (approximately 5–10% by weight [2]) and as a result, the shear thinning and thixotropic behaviour of this type of suspension is more emphasised in tunnelling fluids.

When modelling the rheological properties of drilling fluids, these have to be represented as accurate as possible whilst keeping a restraint on the number of parameters involved. Instead of the two-parameter Bingham model, which has often been applied to drilling fluids, we prefer the three-parameter Herschel–Bulkley model with the relation between shear stress and shear rate given by

$$\tau = \tau_y + K(\dot{\gamma})^n, \tag{1}$$

in which: τ, shear stress; τ_y, yield stress; K, viscosity parameter; n, exponent; $\dot{\gamma}$, shear rate (=du/dz).

This model is in much stronger agreement with the true rheology especially at low shear rates. This is particularly important to HDD where the flow is laminar and has a low shear rate.

It was found that the rheological parameters of 'pure' untreated bentonite suspensions and suspensions of so-called peptised bentonite with polymeric additives display clear differences. On the basis of the collected data, rough estimates can be made of the rheological parameters as a function of mass percentage bentonite and the type of drilling fluid, see Fig. 1.

3. Experiments

3.1. Fall velocity experiments

An annular flume and a vertical-axis concentric cylinder tester were used. These provided horizontally and vertically sheared Couette flows.

A transparent model fluid was used which has the same characteristics as a drilling fluid. It consisted of a blend of Laponite RD (synthetic clay) and CMC (polymers: Blanose 7M1). Two blends of Laponite + CMC (ratio 2:1) were employed, Fig. 2. The Herschel–Bulkley parameters are given in Table 1.

[2] The mass percentage is expressed here as mass bentonite/mass water.