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River Flow with Excessive Suspended Sediment Load

An Evaluation of Turbulent Flow Characteristics

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P. Andreasson and A. Sellgren
Luleå University of Technology, Sweden

River flows with high volume concentrations (20-50%) of silty sediments generally imply that the mixture has non-Newtonian properties. In this study, the rheological behaviour of mixtures with solids particles smaller than 0.1 mm was identified experimentally with viscosimeters. Characteristic flow parameters, such as energy losses and depths, were then determined in several examples for turbulent open channel flows.

Introduction

Volcanic activities, earthquakes or heavy rainfalls in mountain districts occasionally release humid landslides or muddy avalanches. As they surge down the mountain, debris is eroded and incorporated into water from the river valleys. These mud flows, which travel at high velocities over long distances and with very high solid concentrations, can cause enormous damages to life and property.

In the large loess areas in Asia the amount of suspended sediment carried by streams and rivers is very large. For example, in the Yellow River and its tributaries, volume concentrations of sediment as high as 35% and 56%, respectively, have been gauged during the flood season (Zhaohui 1982). On such occasions throughout history "China's sorrow" has periodically broken its banks and devastated the surrounding countryside.

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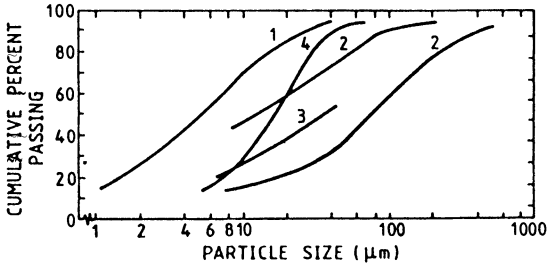

Fig. 1. Example of Particle size distributions in rivers with excessive sediment loads, and properties of the mineral used in this work. Solids densities of 2,650 to 2,750 kg/m^3.

1. Sediment deposit in the Yellow River at Hauyuankou, Zhenhuan et al. (1983).
2. Suspended sediment in the Yellow River at Huangpuchuan, Xiangjun (1983).
3. Wenhai et al. (1983).
4. Mineral product used in this study.

Many unusual phenomena observed in flows with excessive solid loads cannot be explained simply, using existing sediment transport theory. In many situations they may be associated with the rheological properties of the sediment-water mixture and non-Newtonian flow behaviour.

Objectives and Scope

The overall objective of this study was to identify and examine the characteristics of steady non-laminar open channel flows with excessive sediment loads of particles smaller than about 0.1 mm.

This objective induced determination of important parameters, such as energy losses and flow depths for turbulent flows with hyperconcentrated sediment-water mixtures which behave in a highly non-Newtonian way at laminar flow conditions.

The non-Newtonian behaviour was established using reliable methods of rheological measurement and analysis of representative suspensions of mineral particles and water. The particle sizes and size distributions in a natural river with excessive sediment load were found to vary greatly (Fig. 1).

For the mineral sample used here the open channel flow can be considered to be homogeneous, i.e. no sediment concentration gradient is observed under typical flow conditions. It was also assumed that no larger particles are available and that no deposition or erosion take place. Furthermore, it was schematically assumed that the bottom was stable and flat with a roughness represented by the largest particles in the mixture i.e. about 0.1 mm. Finally, all calculations have been based on the assumption of one-dimensional flow which means that the channel width must be much larger than the flow depth.

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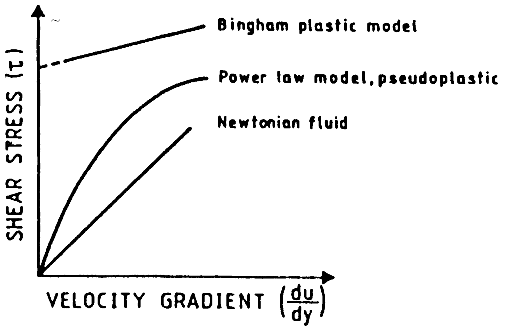

Fig. 2. Common rheological models represented in rheogram.

Rheological Analysis

Fluids are called Newtonian if shear stress, τ, is directly proportional to rate of velocity gradient, *du/dy,* starting with zero stress and zero gradient

$$\tau = \mu \frac{du}{dy} \tag{1}$$

where μ is the dynamic viscosity. Any type of relationship between τ and *du/dy* not described by Eq. (1) is said to define a non-Newtonian fluid. The parameters required to define rheological behaviour are generally determined using rheological models, Fig. 2.

The Bingham plastic model is defined by the constitutive relationship

$$\tau = \tau_0 + \eta \frac{du}{dy} \tag{2}$$

where τ_0 is the yield stress and η is the coefficient of rigidity or plastic viscosity. For $\tau < \tau_0$ the structure of the medium is assumed to be capable of preventing motion.

The Power law model reads

$$\tau \equiv K \left(\frac{du}{dy} \right)^n \tag{3}$$

where *K* is the Power law coefficient and *n* is the Power law exponent. Values of *n* of less than one define pseudoplastic fluids.

In practice, the rheological properties of a particle-water suspension are not unique over a very wide range of shear stresses, and thus the generalized approaches presented above in Fig. 2 cannot generally be fully identified for the complete flow, and they should be used with caution.

For example, for the pseudoplastic model, when extended to very large shear rates, the slope of the a rheogram decreases with increasing values of rate of shear, which is contrary to all physical experience. In practice, a constant viscosity is reached. Therefore, extrapolation of the pseudoplastic model outside the region of rheological measurement often results in underestimation of the losses.

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Non-Newtonian properties are less severe under turbulent flow conditions, and Newtonian methods may apply. One method for determining the turbulent friction loss is by using the conventional Darcy-Weisbach equation, where the Reynolds number is calculated with a limiting viscosity, obtained as an asymptotic value. The yield value in a Bingham fluid normally has a limited influence on the flow properties for large shear rates. The flow can often be characterized by the coefficient of rigidity, η. It is suggested here that the coefficient of rigidity represents the Newtonian viscosity for tubulent energy loss calculations with the Darcy-Weisbach friction factor f. A relationship similar to the Colebrooks equation with slightly modified coefficients is obtained when the Darcy-Weisbach approach is applied to open channel flows (A.S.C.E. 1963)

$$f^{-0.5} = -2 \log \left(\frac{k}{12.4R} + \frac{3.4}{Re\, f^{0.5}} \right) \qquad (4)$$

$$Re = \frac{U\, 4R\, \rho}{\mu_R} \quad \text{(Reynolds Number)}$$

where - R is the hydraulic radius, k is the roughness coefficient, ρ is density, and U is velocity.

Experimental Results

In order to cover a large span of rheological parameter data, a rotational Brookfield-viscosimeter was used in the experiments together with a tube viscosimeter (diameter 5 mm). The experimental procedures have been descibed in greater detail by Sellgren (1985).

The measurements were subjected to computations in order to obtain a direct relation of shear stress and shear rate (rheogram) with the non-Newtonian suspension (details of analysis omitted here, see for example Sellgren 1982). Rheological results at one solids concentration are shown in Fig. 3.

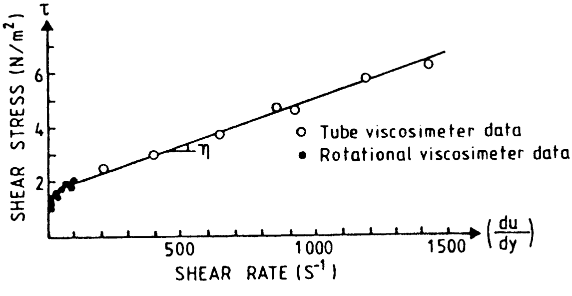

Fig. 3. Rheological results from rotational and tube viscosimeter measurements for a solids concentration of 25% by volume.

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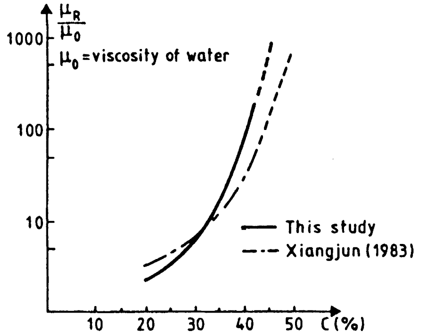

Concentration by volume (%)	Density of mixture (kg/m^3)
20	1330
30	1495
40	1660

Fig. 4. Experimentally evaluated representative viscosities versus solids concentration by volume for suspensions with the mineral shown in Fig. 1. Comparison with results by Xiangjun (1983) for a suspension with grain composition, similar to sediment 2 in Fig. 1.

Rheological results at different concentrations of the suspension were represented in a similar way, as shown here in Fig. 3. This rheogram data were then evaluated following the procedure discussed above for every concentration considered. The resulting coefficients of rigidity are shown in Fig. 4.

The results obtained here in Fig. 4 with an artificial sediment product can be considered to be rheologically representative of conditions normally encountered in rivers with excessive silt loads.

Discussion of Results

The development of the water profile in a channel upstream of a reservoir was simulated for turbulent flows with densities and viscosities evaluated in Fig. 4. It was assumed that the channel has an uniform slope and section and that the flow rate was constant. It was furthermore assumed that the constant water level in the reservoir is larger than the natural depth (Fig. 5).

Calculation of the water profile begins at the reservoir and proceeds upstream to the natural depth of the channel. The calculations of the gradually varied non-

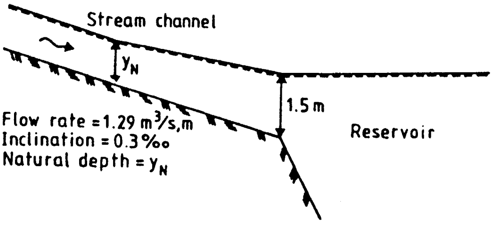

Fig. 5.
Background data and parameters used in the simulation.

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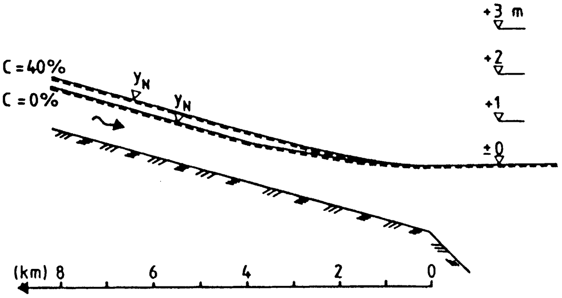

Fig. 6.
Profile for a highly concentrated flow (C=40%) compared with clear water conditions.

uniform flow were based on a finite formulation of the governing differential equation, known as the direct step method (see Andreasson *et al.* 1986). The energy losses here were directly related to Eq. (4) and additional losses were neglected. The altered flow depth conditions with a mixture compared to clear water flow are exemplified in Fig. 6.

It follows from the result in Fig. 6 that the natural depth increases by more than 20% and the backwater influence propagates about 1 km further up the channel. In Fig. 7 the backwater profiles for solid concentrations of 0, 30, and 40% are shown.

The natural depth for clear water flow in Fig. 7 was 0.91 m for the assumed flow rate of 1.29 m^3/s,m. When the water is heavily sediment loaded, a natural depth of 0.91 m corresponds to a lower flow rate. For example, if the solids concentration is 40%, a depth of 0.91 m corresponds to a flow rate of about 0.9 m^3/s,m, i.e. a reduction by nearly 30%.

So far only turbulent conditions have been considered. With laminar and Newtonian flow in a rectangular channel, the Darcy-Weisbach friction factor can be expressed by the following relationship

$$f = \frac{96}{Re} \tag{5}$$

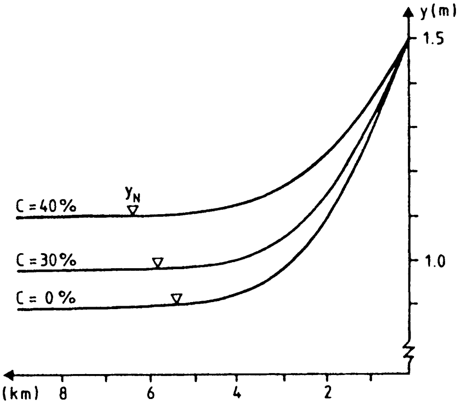

Fig. 7.
Profiles for different representative viscosities (turbulent conditions).

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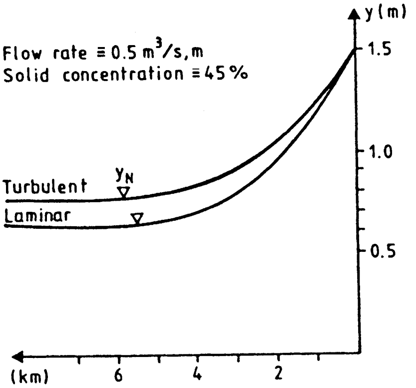

Fig. 8. Profiles calculated for laminar and turbulent conditions in the transitional region. (Re ≈ 3,500). Geometrical assumptions: see Fig. 5.

Prediction of energy losses in the laminar/turbulent transitional region is not a well-defined phenomenon, not even for Newtonian fluids. This is illustrated in Fig. 8 where both laminar and turbulent profiles have been simulted with a Newtonian approach.

High sediment concentrations of fine particles and viscous non-Newtonian effects exert considerable influence on the deposition/erosion pattern and the resitance to the flow. Zhaohui (1982) found that excessive suspended loads favour transition from dunes to plane beds, i.e. the flattening of the bed results in much smaller resistance. With normal suspended loads, decreased resistance to flow in alluvial channels has generally been related to dampening in turbulence, see for example Vanoni (1963). For turbulently flowing Bingham media, a friction reduction of up to about 15% can also be found under certain conditions.

Rheology has a considerable effect on the dynamics of larger particles, even a small yield stress in the non-Newtonian particle-water mixture can decrease the settling velocity greatly, which means that larger particles can be transported in a suspended regime. Therefore, high concentrations of fine particles in the flow influence the portion of larger sediment particles to be transported as suspended or bed load.

An unusual phenomenon known as "clogging" is of great practical importance in rivers with excessive suspended loads. Engelund *et al.* (1984), referring to observations by Qian *et al.* (1979), describes that the river, in a certain reach, stops flowing for a time as if wholly frozen with only extremly small velocities. In this reach the water level rises gradually, and after a certain time the river starts flowing again. Variations in water levels of up to several meters have been observed. The analysis of clogging phenomena includes very low shear rates which means that interpretation of yield stresses becomes important (Engelund *et al.* 1984). However, yield stresses in mixtures of water and mineral particles is not rheologically well-defined phenomena.

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Conclusions

Open channel flows flowing turbulently with very high concentrations of silty sediments (max particle diameter = 0.1 mm) can be characterized by viscosities of 10-100 Ns/m^2 for volume concentrations of 30-40%. At these high sediment concentrations and viscosities, the depths and energy losses are greatly influenced compared to clear water conditions. For example, with a constant natural depth in a channel, the flow rate was reduced by about 30% in a flow with a sediment concentration of 40% by volume.

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Address: Luleå University,
Water Resources Engineering Luleå, WREL,
S-951 87 Luleå, Sweden.

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