Investigations of Rheological Flow Properties Based on Lab Data of Fluid Mud Samples and an Extended Model Approach

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Summary

Fluid mud parameters like mass concentration, yield point and apparent viscosities are derived by means of fluid mud sampling along the tidal reach of river Ems and subsequent lab analysis regarding suspended sediment concentration, bulk density and rheological parameters. Equilibrium flow curves were obtained for every sample by means of constant-rate analysis with a high resolution lab rheometer. Comparisons of samples from different locations show good correlation between fluid mud mass concentration and yield point. A reliable method for yield point detection based on creep and recovery rheometer tests and a semi graphical approach was found to deliver the best results. In order to reproduce the large spread of viscosities occurring in reality, the Toorman model was extended by means of an empirical fit with respect to suspended sediment mass concentration. The comparison shows a good correlation between model results and measured constant-rate-test data. Also the thixotropic behavior due to weakening and strengthening as a result of disintegration and build-up of the internal floc structure is reproduced.

Keywords

fluid mud, Ems estuary, constant rate curves, yield point, rheological model

Zusammenfassung

Die Untersuchung befasst sich mit der Parametrisierung der kinematischen Eigenschaften von Flüssigschlick. Proben aus dem Ems-Ästuar wurden nach Konzentration, Bewegungsbeginn und Viskosität analysiert. Unter Einsatz eines hoch auflösenden Laborrheometers wurden Gleichgewichtsfließkurven unter Anwendung jeweils konstanter Scherraten erzeugt. Diese erlauben den Vergleich von Proben aus einer Vielzahl von Entnahmestellen und die Kalibrierung des von Toorman erweiterten nichtlinearen Fließmodells nach Worral und Tuilani. Der Toorman-Ansatz wurde durch einen empirischen Fit zur Berücksichtigung der Suspensionskonzentration des Flüssigschlicks erweitert, um die große Bandbreite real auftretender Viskositäten abzudecken. Der Vergleich zwischen den gemessenen und den durch das erweiterte Modell berechneten Ergebnissen zeigt eine gute Übereinstimmung hinsichtlich der Reproduktion des thixotropen und nicht-Newtonschen Fließverhaltens von Flüssigschlick und insbesondere des Übergangs in den Gleichgewichtsbereich.

Schlagwörter

Flüssigschlick, Ems Ästuar, Constant-Rate Kurven, Fließgrenze, Rheologisches Modell

Contents

1 Introduction

The Ems estuary is located in the NorthWest of Germany, connected to the border of the Netherlands. The estuary spreads out of a total length of 110 km starting from the east Frisian island Borkum to the tidal weir in Herbrum with an average fresh water inflow around 80 m³/s. The tidal range at the mouth is 2.2 meters and increases up to 3.2 meters in Papenburg. The estuary is important for the German and Dutch economy, since main harbors are located along the estuary (Eemshaven, Delfzijl, Emden and Papenburg) and a yard delivering large cruise-vessels several times a year resides in Papenburg. In order to satisfy the navigability needs engineering measures were applied in the past decades like deepening, canalization, groyne and tail fittings. Furthermore, a storm surge barrier in Gandersum nowadays protects the hinterland against flooding and allows raising the upstream water level for the initial passage of cruise ships from Papenburg to the open sea. The engineering measures led to massive changes in tidal dynamics, resulting in short, but strong periods of flood flow in combination with weaker ebb flow lasting over longer durations. HERRLING (2008) has shown an increased tidal range in the Lower Ems estuary in a comparison of data from 1937 and 2005. Furthermore HERRLING (2008) has shown, that the effect of deepening can be observed from Emden up to the tidal weir in Herbrum. In combination with the intensified baroclinic circulation this led to massive accumulation of fluid mud in the Lower Ems. As a result of the intensified flow dynamics and the high availability of suspended fines the sediment distribution along the estuary changed considerably, since a stratified system by means of a lutocline and a fluid mud layer of 2m -4m thickness below it can be found along the innermost 50km of the estuary. The obvious interactions between suspended sediment and the tidal currents become even more complicated because of the non-newton flow behavior within the fluid mud.

2 Fluid mud properties and dynamics

Fluid mud is a suspension of mainly cohesive fines (clay) some non-cohesive minerals like sand and other contents of biogenic origin. NASNER (2004) reports absolute mass concentrations up to 220 g/l and ignition loss ranging from 10 % to 20 % for several German tidal harbors. The complex rheological behavior of fluid mud is a result of the clay as well as the biogenic content by means of extracellular polymeric substances. The latter influencing the time dependent behavior even more than the electrostatic forces between clay particles.

The flow behavior of fluid mud ranges from Newtonian turbulent flow for low concentrations of suspended sediment to non-Newtonian, shear-thinning and thixotropic behavior with changes in viscosity by an order of magnitude and more. Due to the density difference to the less concentrated regions of the flow, dynamic stratification as a result of local damping of turbulent momentum exchange and turbulent mixing takes place, leading to lutocline formation.

3 Rheological Approach

Since fluid mud rheological behavior exhibits non-linear shear dependency as well as time dependency, none of the 'simple' rheological models like Bingham, Hershel-Bulkley etc. should be applied. We here focus on the TOORMAN (1997) Model and extend it with a straight-forward approach by means of an empirical fit of its model constants. In analogy with the model proposed by MOORE (1959), which based on describing the thixotropic behavior of clay suspension, WORRALL and TULIANI (1964) extended their work by adding a yield stress term. TOORMAN (1997) gives a formulation with a more general equation of state, based on the Worrall and Tulliani model, which is independent on the rate equation and which can be applied to any flow history. For the thixotropic model and explicit shear stress description, Toorman gives the following equation which depends on yield stress, shear rate and degree of structure in suspension,

$$\tau = \lambda\tau_0 + \left(\mu_\infty + c\lambda + \beta\tau_0\lambda_e\right)\dot{\gamma} \tag{1}$$

$$\lambda_e = \frac{\lambda_0}{1+\beta\dot{\gamma}} \tag{2}$$

where β = b/a, a aggregation parameter, b structure break-down parameter, μ_∞ the Bingham viscosity, $c = \mu_0 - \mu_\infty$ and μ_0 is the initial differential viscosity. λ is the degree of structure in suspension, which basically covers the thixotropic behavior (0-fully broken, 1-fully structured). It is described by the following ordinary differential equation:

$$\frac{d\lambda}{dt} = -\left(a + b\dot{\gamma}\right)\left(\lambda - \lambda_e\right) \tag{3}$$

4 Experimental Setup

In this study, fluid mud samples were taken in a longitudinal cross-section of the Lower Ems, as well as from the harbor of Emden. 20 Samples in the Lower Ems were taken in

August 2009 every 2 km during ebb phase, starting from the storm surge barrier in Gandersum up to the tidal weir in Herbrum and 5 samples were taken in the Emden tidal harbor. All samples were collected with a Ruttner-Sampler closely above the nautical bottom in the deep channel. Density measurments were carried out using a lab density meter (oscillating tube). For rheological parameters a Rheologica Stresstech HTHP rotational rheometer was used (lowest detectable stress level: 0.00125 mPa).

The yield point was investigated by stepwise increasing the shear stress and recording the corresponding shear rate. This measurement mode has to be started from a shear stress level well below the yield stress then being stepwise increased unless plastic motion dominates the process. Given a sufficiently sensitive rheometer even shear stress levels below the yield point result in (very small) shear so a decision has to be made which point within the shear curve is the 'real' begin of motion.

The yield point determination may depend on the problem itself and also the measurement equipment used. For fluid mud good results were obtained by means of a semi graphical procedure, the so called "tangent" method (METZGER 2006, Fig. 1). Applied at log scaled flow curves it allows reproducible determination of yield points which were consistently confirmed by creep-recovery-tests (FRANZ 2009).

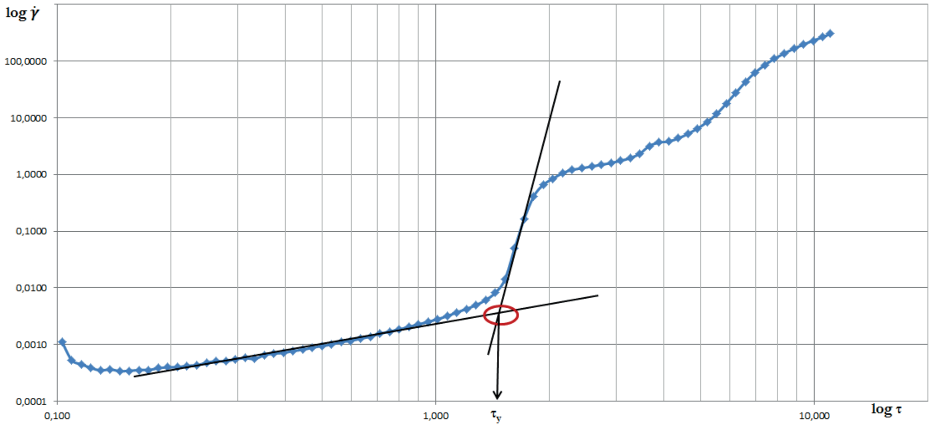

Figure 1: Example of the determination of the yield point with the tangent method (FRANZ, 2009).

Fig. 1 shows that (extremely low) shear exists already at the lowest stress level applied. Those low deformations during shear stress levels below the yield stress partly result from elastic deformation. The underlying conceptual model for pseudo plastic granular or aggregated suspensions includes an 'inner' structure formed by aggregated grains, flocks and EPS which contribute to the overall mechanical shear resistance of the suspension and which has to be overcome before relevant plastic flow takes place.

For a time- and shear-dependent pseudo plastic suspension like fluid mud due to thixotropy there exists an theoretically unlimited number of flow curves depending (amongst other parameters) on the current shear rate and shear history. Therefore an equilibrium state as described by Worrall and Tuliani is a meaningful quantity, which demands rate controlled measurements that are continued until the equilibrium state is reached.

Lab rheometers are usually stress controlled. This makes a regulator circuit necessary in order to control the system by means of a constant shear rate. The regulator's characteristics can significantly influence the equilibrium time of the experiment. Especially when applied to different shear rate values which can probably span over orders of magnitude, appropriate regulator settings can vary quite a lot.

The aforementioned conceptual model for granular or aggregated suspension directly allows for the application of the thixotropic rheological model suggested by Toorman. It is based on the equilibrium flow concept derived from Worrall and Tuliani and incorporates an equation of state which describes the structural 'inner' strength of the aggregated suspension.

Equation (3) is a rate equation for a structural integrity parameter that brings a time dependency into the apparent kinematic viscosity calculation. Parameter λ is reduced by shear and build up based on the amount of structure already available. The coefficients a (scaling the build-up rate) and b (scaling shear-induced destruction rate of internal structure) therefore have to be derived from constant rate experiments by evaluating the adaption time of the suspension. $\lambda = 1$ represents full structure, it is per definitional set to 1, which means that λ in this model may vary between 0 and 1. The increase and decay of λ is controlled by the rate equation.

5 Comparison of lab data and extended model

The aim of this rheological study is the determination of equilibrium flow curves of suspensions with widely varying density. In the first step the yield stresses of given suspensions were evaluated by flow curves obtained by predefined a shear stress ramp and applying the tangent method. All Bingham parameters like (pseudo) Bingham yield stress, initial differential viscosity and Bingham viscosity were determined after WORRALL and TULIANI (1964) by using these flow curves. We call those parameters Bingham-like, since high resolution measurements confirm the widely discussed aspect that a real Bingham Yield point is rather caused by insufficient measurement resolution than the real physics. Also, from a hydrodynamic point of view the singularity in the momentum equation due to an infinite viscosity at a Bingham – like yield point confirms this.

Comparison of Worrall and Tuliani parameter with respect to sample concentration can be seen in Fig. 2. TOORMAN (1997) modified the model, which describes thixotropic behavior of suspensions based on equilibrium flow curves. The equilibrium flow curves found by WORRALL and TULLIANI (1964) can be written as:

$$\tau_e = \lambda_0 \tau_0 + \left(\mu_\infty + c\lambda_e \right) \dot{\gamma} \tag{4}$$

with τ_e the equilibrium shear stress. This equation for the equilibrium state in dependency of a given shear rate contains three empirical parameters (τ_0, μ_∞, c), which are characterized by analysis of the rheometer results of constant-rate curves.

The equilibrium structural parameter λ_e describes the degree of structure independent to shear rate in equilibrium state. Investigations of the behavior at transition to the equilibrium state after TIU (1974) is described in a first order equation:

$$\ln\left(\tau_y - \tau_{y,e} \right) = \ln\left(\tau_{y,i} - \tau_{y,e} \right) - kt \tag{5}$$

with t the time, which is between the start of measurement up to reaching the equilibrium by a constant shear rate ($d\lambda / dt = 0$). By this equation, the analytical solution of the recovery rate parameter a and the break-down parameter b can be determined with $k = a + b\dot{\gamma} = a(1 + \beta\dot{\gamma})$.

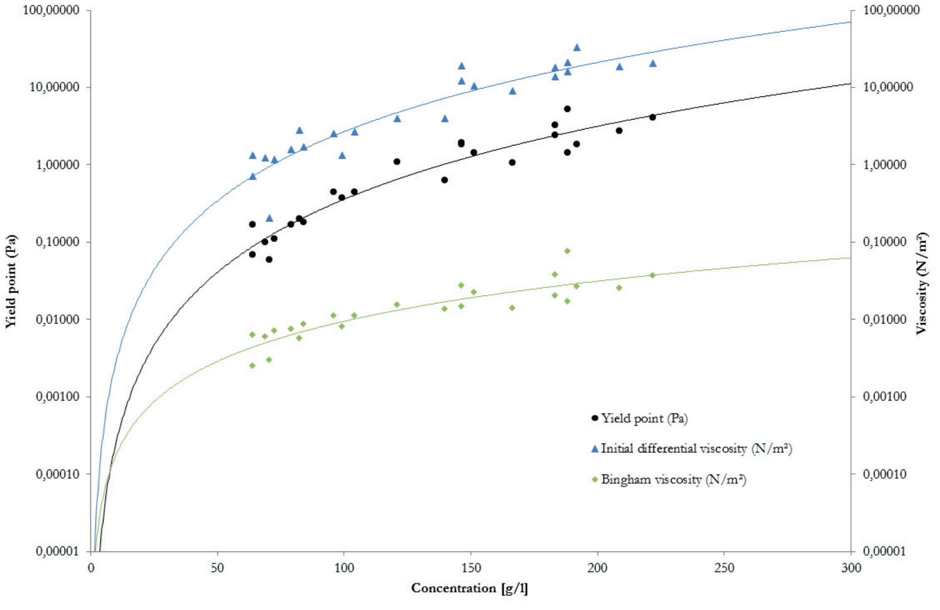

Figure 2: Graph illustrates comparisons of initial differential viscosity (blue), yield point (black) and Bingham viscosity (green) with respect to sample concentration.

After all parameters have been determined, fitting curves were calculated according to concentration of suspensions. The best fit for the concentration range from 63.5 g/l to 222 g/l is achieved with:

$$\mu_{\infty} = 3*10^{-6}*C^{1.72}$$

$$\mu_{0} = 3*10^{-6}*C^{2.97}$$

$$\tau_{y} = 2*10^{-7}*C^{3.13}$$

Fig. 3 shows comparisons of measured shear stress by rheometer and calculated equilibrium flow curves by Toorman model. Comparison of calculated and measured equilibrium flow curves indicating a very well correlation at higher shear rates and an overestimating at low shear rates of calculated shear stresses by above equation (4), which is due to the inherent stronger internal damping of the rheometer at very low shear rates.

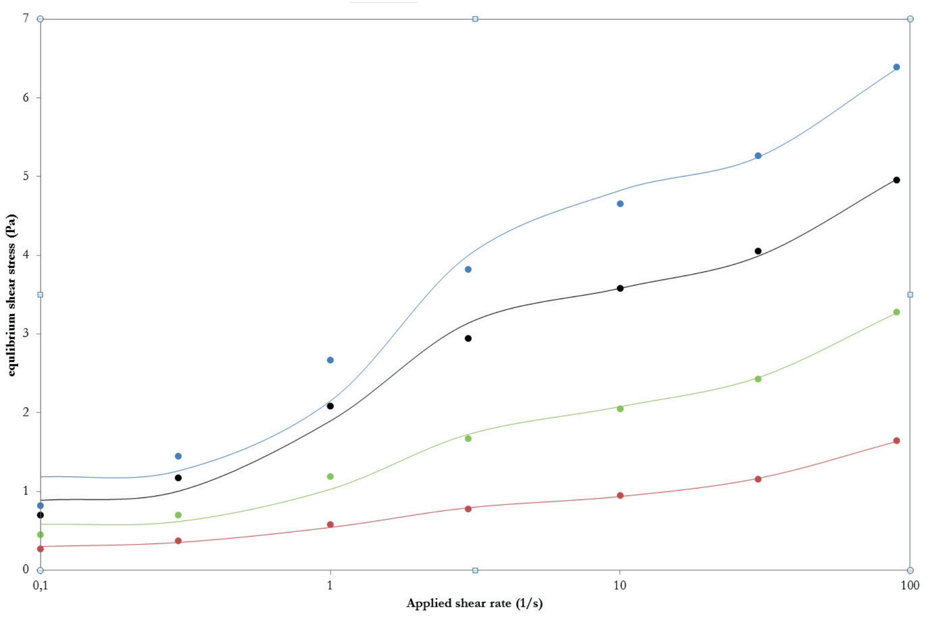

Figure 3: Comparison of calculated (dots) and measured (solid lines) equilibrium flow curves of 191 g/l (blue), 183 g/l (black), 139 g/l (green) and 99 g/l (red) in a log representation for the shear rate.

6 Conclusion

Based on fluid mud samples from river Ems and rheological lab analysis constants for the Toorman thixotropic rheological model were derived. In a straight forward empirical approach the model was extended in order to include the strong concentration dependency of fluid mud viscosity in real systems, spanning over an order of magnitude and more. The fitted model constants allow the model-based reproduction of the complex viscous behavior of fluid mud and especially its thixotropy dominated viscosity.

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