Introduction

Submarine slides can reach enormous runout distances on slopes with only a few degrees inclination, as can be seen by the ancient Storegga slide showing a runout of about 800 km on a slope with a mean angle of less than 1° (Bryn et al. 2005) or in the case of the more recent Grand Banks event from 1926, which extended more than 1000 km (Locat & Lee 2002). These observed long runout distances are not explainable with simple rheological models based on measured in situ (remolded) soil properties. However, in-depth understanding of this phenomenon is one of the urgent needs for risk assessment for coastal regions and offshore constructions. An overview of the current understanding of submarine slides is found in the above-mentioned article by Locat & Lee (2002) and also in (Elverhøi et al. 2005). Both articles emphasize the frontal behavior as one key factor for the understanding of long runouts.

Numerical model

In this section, we give a brief description of the numerical model approach used for the back-calculation of the laboratory experiments. The slide and the ambient water are modeled by a two-phase model (see Figure 1). For both, the slide and the ambient water, the continuity equation and momentum equation are solved. The water is considered as a turbulent flow that needs a turbulent closure. In the presented case, the rheological behavior of the slide is described as a Bingham fluid with a constant yield strength and consistency (Bingham viscosity). The model is implemented in the commercial flow solver CFX4 from ANSYS (CFX4.3, 1999).
which uses a finite volume approach. The sliding mass is assumed to be sufficiently wide so that a two-di-
men-
sional (vertical) treatment can be justified.

Governing equations

The mass balance for ambient water (marked with the subscript $w$) and the one for the slide (marked with the subscript $s$) can be written in the form

$$\frac{\partial V_w \rho_w}{\partial t} + V \cdot (V_w \rho_w V_w) = 0,$$

(1)

$$\frac{\partial V_s \rho_s}{\partial t} + V \cdot (V_s \rho_s V_s) = 0,$$

(2)

where $V$ is the velocity, $\rho$ the intrinsic density of the respective phase, and $v_w$ and $v_s$ are the volume fractions of the water and slide, respectively ($v_s = 1 - v_w$). $\partial/\partial t$ denotes the local differentiation in time and $V$ is the gradient operator. The momentum equation for the ambient water reads

$$\frac{\partial}{\partial t} (V_w \rho_w V_w) + V \cdot (V_w \rho_w V_w \cdot V_w) + 2 \mu_w \nabla V_w = -\nabla p + \rho g,$$

(3)

here $\otimes$ indicates the tensor product, $p$ is the common pressure, $g$ the gravitational acceleration. The effective viscosity of water, $\mu_w$, is given by

$$\mu_w = \mu_l + \mu_t,$$

(4)

where $\mu_l$ is the laminar viscosity and $\mu_t$ the turbulent viscosity. In this case, either the standard $k$-$\varepsilon$ (Rodi, 1989) or a LES (Ferziger & Peric 1999) approach is used for the turbulent closure. The last term on the right hand side in Equations (3) and (5) describes the mutual drag between the slide and the ambient water (opposite in contribution in the respective phase). The momentum equation for the slide reads as follows

$$\frac{\partial}{\partial t} (V_s \rho_s V_s) + V \cdot (V_s \rho_s V_s \cdot V_s) + C^* D = -\nabla p + \rho g,$$

(5)

For the coupling term in (3) and (5), a simple mixture model is used and the coupling drag is

$$D_{\text{ext}} = C^* D = C^* \frac{v_s \rho_s + v_w \rho_w}{v_w} (V_w - V_s),$$

(6)

where $C^*$ is a drag coefficient.

Numerical simulation and comparison with laboratory experiments

The laboratory experiments were carried out at the St. Anthony Falls Laboratory, University of Minnesota. They are described in detail by Ilstad et al. (2004a, b, c). Figure 2 shows the principal setup of the experiments. Most experiments were performed
in a 0.2 m wide and 9.5 m long channel suspended in a larger glass-walled water tank. For the experiments back-calculated in this study, the slope of the sliding surface was kept to 6°. In all experiments, premixed and stirred slurry was released into a flume from a 160 l reservoir by rapidly opening an approximately 5.5 cm high gate. The setting for the numerical study differs slightly from the experimental setup. Here, we focused only on the development along the first 3 m of the channel. In addition, we simulate the slide release as a slab with an initial depth of 10 cm, in contrast to a flow from a reservoir. This should be kept in mind when directly comparing the results of the experiments with those of the numerical simulations. The experimental slide gains a considerable amount of potential energy from the raised reservoir, which is probably most important shortly after release. This fact might also partly explain why the yield strength used in the simulations needed to be lower than the one initially measured in the laboratory. However, the derived yield strengths during the later stages of the flow (Ilistad 2004b) are similar to those used in the simulations. The initial setting of the numerical grid is also shown in Figure 2b. For a better illustration, the number of grid cells, which are shown in the figure, are reduced by a factor of 5 in comparison to the grid used in the simulation. The calculation domain was resolved by 320×75 volume cells; in this way, the horizontal resolution was approximately 1.25 cm and the vertical resolution close to the sliding surface was approximately 3 mm.

Figure 3 shows a time-lapsed sequence of video snapshots taken from a fixed position along the channel. The position was 7.6 m down from the inlet gate and the head structure was fully developed. Two things attract attention, i) the foremost part of the head is hydroplaning and ii) behind the head, water pockets get enclosed between the sliding surface and the sliding mass as the slide passes by. The first feature is described by Mohrig et al. (1998) and by Harbitz et al. (2003). The consequences of the latter feature are not fully understood. However, it is known that the shear strength strongly depends on the water content (Locat & Lee 2005; Cossout 1997). Hence, the enclosed water might contribute to a decrease of shear strength at the base of the sliding mass as it is molded by shearing. Elverhøi et al. (2005) coined the term shear-wetting for this process. The process of shear-wetting was not taken into account in the present numerical study.

Figure 4 depicts a sequence of time steps from a numerical simulation shortly after release. One can observe the development of hydroplaning at the head. De Blasio et al. (2004) did similar simulations; however, they considered a rigid body of finite length in a laminar flow. Mohrig et al. (1998) proposed the following relationship for the onset of hydroplaning:

\[ U_c = \left( \frac{2}{\rho_s - \rho_w} \right) gh \cos \phi, \]

where \( U_c \) is the critical velocity of the slide front at onset, \( h \) the thickness of the head, \( \phi \) the slope angle,
and $k$ is an empirical constant, which ranges between 0.3 and 0.4. The other symbols are defined above. Comparing this relationship with the simulation, we find a good agreement for the critical velocity. Figure 5 shows the development of a high-pressure wedge of ambient water underneath the head of the slide and of under-pressure along its upper surface. The pressure difference constitutes a lift force, which is responsible for the onset of hydroplaning.

Further, in Figure 4, one can observe how the approaching slide displaces the ambient water in front of its head. The acceleration of the water causes a retarding force on the slide. In simple models like BING (Imran 2001), this effect has to be taken into account separately by a drag factor, as it is done in De Blasio et al. (2004). Otherwise, the slide velocity might be largely overestimated.

Another effect, which can be observed in the simulation, is stretching within the slide body. In Figure 4 one observes that beside the marked vertical velocity gradient, $\partial u/\partial z$, close to the sliding surface, there is also a noticeable horizontal gradient, $\partial u/\partial x$ (higher speeds at the front than in the following body). Usually this effect is disregarded in a one dimensional model. Hence, in those models using a Bingham rheology, the shear rate differs from that used in equation (8). In those cases, a simple plug is assumed that rides on top of a shear layer; this is an oversimplification. Figure 6 shows the equivalent shear rate (in a logarithmic scaling). First of all, one observes the high shear rate close to the sliding surface, as already mentioned above, with shear rates as high as 100 s$^{-1}$. However, instead of a "rigid" plug, plug-like zones are separated by zones in which stretching occurs. This stretching is especially pronounced between the hydroplaning head and the slide body. This zone might be prone to crack formation and even detachment. The high pressure below the hydroplaning head (especially at the transition to the non-hydropla-
ning body) might contribute to the crack formation. How this detachment occurs can be nicely seen in a photo sequence in (Ilstad 2004a, Fig. 5). The stretching itself causes remolding of the material that leads to a softening (if not already totally remolded), and so stretching may contribute to an increase of mobility. In addition, crack formation might lead to water intrusion, which enhances mobility by reducing the shear strength.

Concluding remarks

The numerical simulations resemble the laboratory experiments reasonably well. They also help to enlighten some of the basic concepts of slide movement–based on experimental and numerical studies–with a high clay content; a thin water layer might intrude underneath the front part forming a hydroplaining head. This thin water layer might also supply water at the base of the remaining slide; in this case a shear-wetted basal layer develops with decreased yield strength enhancing the lubrication. This was not modeled in the presented study. In addition, stretching and thinning of material add to the softening of the material and, finally, may lead to progressive detachment of the head and development of out-runner blocks. However, not all of the effects are totally understood with all their consequences. One important question is to what extent does the intrusion of water underneath effectively enhance the runout? The introduction of a shear-wetting layer into numerical models constitutes a challenge, as this requires monitoring of the water content within the slide. A further challenge is the modeling of the detachment, which might require a different approach from that presented here. Furthermore, the laboratory experiments show that slides with lower clay content (less than 25%) behave quite differently from those modeled in this study. In cases with less than 25% clay, the sandy body seems to be partly fluidized by water infiltration. This fluidization, in contrast to the model used here, would be better described by a model that treats the slide material as a dispersed phase in the ambient water.

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