Modelling of landslide runout in sensitive clays

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ABSTRACT
Landslide risk assessment and management requires a reliable estimate of the runout of the landslide masses. Few models address the runout of landslides specifically for sensitive clays. A new model was tested on the Rissa landslide in Norway. The Rissa landslide had scarp on land, with most of the sliding volume extending in a lake. The numerical model is an extension of the Bing model in Eulerian coordinates with two horizontal dimensions, implementing the full Herschel-Bulkley rheology to compute dynamically the depth of the moving material and the shear layer. The back-calculated runout (runout distance, maximum flow velocity and debris thickness) for the Rissa slide are compared to the observed values, where available. The results show that the runout in sensitive clays is controlled by, in addition to the terrain topography, the rate of the remolding process and the initial release volume initiating the slide. Analyses with different remolding rates were run to obtain a statistical description of the runout distance and the maximum velocity over the flow domain as the slide occurs. The model, still under development, provides interesting results for this type of landslides in sensitive clays. The paper discusses the suitability of the model for the prediction of landslide runout in sensitive clays.

1 INTRODUCTION

Landslides in sensitive clays are among the most dangerous and most damaging of natural hazards in eastern Canada, Scandinavia and northern Russia. Flow-like landslides in sensitive clays, travel far, very rapidly and are a threat to life, property and environment. Runout analyses are needed to identify the elements at risk and to make decisions on the optimum mitigation measures. Different analytical and empirical models for estimating the runout in sensitive clays can be found in the literature (e.g. Tavenas, 1984, Issler et al. 2014, Strand et al. 2017, Turmel et al. 2017). The prediction methods are based on travel distance and event magnitude, volume balance, mass point methods, remolding energy, or other limiting criteria such as critical slope angle (Kim et al. 2017). Empirical relationships usually fall short because they involve several simplifications and approximations. Therefore, analytical dynamic runout models for may present a better alternative.

This paper describes a new numerical model to predict runout in sensitive materials. Runout will be characterized with distance travelled, the maximum flow velocity and debris thickness in the runout area. The results of several runout analyses conducted for the 1978 Rissa slide in Norway are compared to observations.

2 NUMERICAL MODEL

A new model, called *BingClaw*, was developed to predict the runout of landslide in sensitive clays. This model is an extension of the Bing model (Imran et al. 2001) in Eulerian coordinates in two horizontal space dimensions. Locat and Demers (1988) and Grue et al. (2017) suggested that the Herschel-Bulkley rheology is suitable for sensitive clays. This rheology was used for the dynamic computation. Due to the limited space, only selected governing equations of the BingClaw model is presented here. Readers are encouraged to refer to Kim et al. (2017) or Løvholt et al. (2017) for a more detailed description of the new BingClaw model.

For simple shear conditions, the Herschel-Bulkley rheological model can be described as the following (Kim et al. 2017):

$$\left|\frac{\dot{\gamma}}{\dot{\gamma}_r}\right|^n = \begin{cases} 0, & \text{for} \quad |\tau| \le \tau_y, \\ \left(\dfrac{\tau}{\tau_y sgn(\dot{\gamma})} - 1\right), & \text{for} \quad |\tau| > \tau_y. \end{cases} \qquad [1]$$

where $\dot{\gamma}$ is strain rate; $\dot{\gamma}_r$ the reference strain rate ($= (\tau_y/\mu)^{1/n}$) with dynamic viscosity μ and exponent n; and τ and τ_y the shear and yield stress. The exponent n is taken between 0 and 1, and n = 1 represents the Bingham fluid case.

The model accounts for the plug and shear layers. The mass balance is integrated over the flow's depth, and two separate momentum balance equations are integrated over the plug and shear layer. The upper diagram in Figure 1 illustrates the Herschel-Bulkley model with a constant velocity profile for the plug and a parabolic velocity profile for the shear layer. The viscosity measurement done in the laboratory by Grue et al. (2017) (the lower diagram in Figure 2) showed that remolded Norwegian sensitive clay behaves as a shear thinning fluid and can be characterized using the Herschel-Bulkley rheology. This observation is in line with Locat and Demers (1988) who observed the same for Canadian sensitive clays.

Sensitive, at times quick, clays have the following characteristic: they disintegrate from an intact state to a fully remolded state during the sliding process. Thakur and Degago (2013) and Thakur et al. (2017) demonstrated the "quickness" of Norwegian clays with different newer laboratory experiments.

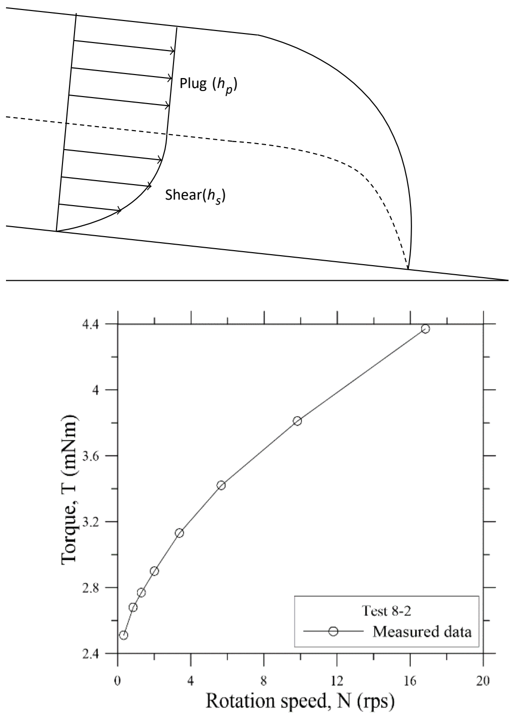

Figure 1. Upper diagram: Schematic Herschel-Bulkley model of plug and shear (Kim et al. 2017); lower diagram: behaviour of a Norwegian sensitive clay in laboratory viscosity test (Grue et al. 2017)

To characterize the remolding process, the following expression is proposed:

$$\tau_y(\gamma) = \tau_{y,\infty} + (\tau_{y,0} - \tau_{y,\infty})e^{-\Gamma\gamma} \quad [2]$$

where $\tau_{y,0}$ and $\tau_{y,\infty}$ are the initial and remolded yield stress (or shear strength), and Γ (dimensionless) is a coefficient describing the rate of remolding. The change in τ_y because of remolding is made directly proportional to the quantity -$e^{\Gamma\gamma}$. Small Γ values imply that large accumulated shear is needed for remolding. Figure 4 exemplifies the average yield stress for different Γ-values, using the values of peak and remolded shear strength of the Rissa clay as input parameters. Because the remolding process is assumed to be a non-reversible process, the average yield stress decreases in time.

The proposed model calculates the runout distance, maximum velocity over the flow domain, and the average deposit thickness over the runout area.

The numerical implementation, using a finite volume method, has three steps: (1) the earth pressure is compared to the yield stress in each cell. If the yield stress is larger than the earth pressure, no motion is allowed. If the two adjacent cells do not deform, there is no displacement at the interface; (2) if one of the cells deforms, the equations without friction terms are solved. At each cell interface, a Riemann problem is solved with the wave propagation algorithm of the finite volume method; and (3) the friction forces are then included using a Godunov fractional step method. (Kim et al. 2017).

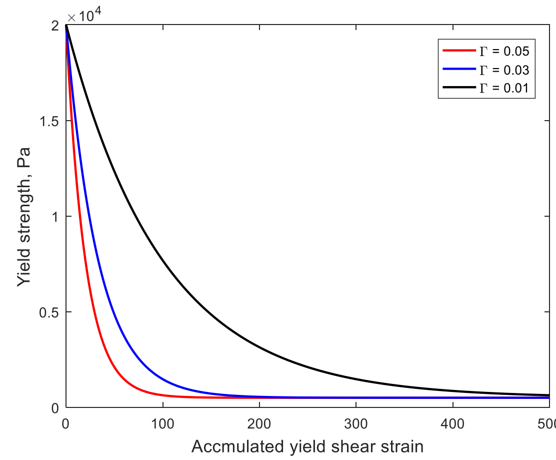

Figure 2. Example of effect of Γ-value on averaged yield stress ($\tau_{y,0}$ = 20 kPa, $\tau_{y,\infty}$ = 0.5 kPa)

3 RUNOUT ANALYSES

3.1 Description of the Rissa slide

The 1978 quick clay landslide at Rissa is the largest landslide to have occurred in Norway in the 20^{th} century. Seven farms and five single family homes were taken by the landslide. Of the 40 people caught in the landslide, one died.

Gregersen (1981) explains the retrogressive slide evolution in detail. An initial slide (Stage 1) was triggered by the stockpiling of clay from a small excavation along the lakeshore. During Stage 1, 70–90 m of the shoreline slid out into the lake, including half of the stockpile. The scarp was 5–6 m high and extended 15–25 m inland. The landslide developed retrogressively in the southwestern direction over the next 40 minutes. The sediments completely liquefied during the sliding and the debris poured into the lake like a fluid. At this time, the landslide area had the shape of a long and narrow pit open towards the lake (Fig. 3). The 450-m long sliding area covered 25–30,000 m^2 or 6–8 % of the final slide area (Gregersen 1981; L'Heureux et al. 2012).

The main landslide (Stage 2) started almost immediately after the initial sliding. Large flakes of dry crust (150×200 m^2) started moving towards the lake, not through the existing opening, but in the direction of the terrain slope (flakes A and B, Fig. 3). The velocity was initially moderate (flake A), about 2.7–5.5 m/s (10–20 km/h), but increased to 8.3–11.3 m/s (30–40 km/h) (flake B). On the landslide video, houses and farms can be seen floating on top of the sliding masses. A series of smaller and retrogressive slides followed over a short period of time. The sliding propagated to the mountain side where it stopped. The main sliding stage lasted for approximately 5 minutes. The total landslide area (Stages 1 and 2) was 330,000 m^2. The total volume of mobilized sediment was between 5–6×10^6 m^3.

The observed runout parameters of the Rissa landslide are illustrated in Figures 3 and 4 (L'Heureux et al. 2012). The observed runout distance under Stage 2 was 1200 m from the lakeshore. The maximum velocity was 8.3–11.3 m/s and the deposit height, based on seismic reflection, was a maximum of about 7.5 m. The inferred average deposit height over the 1200-m runout was about 4 m.

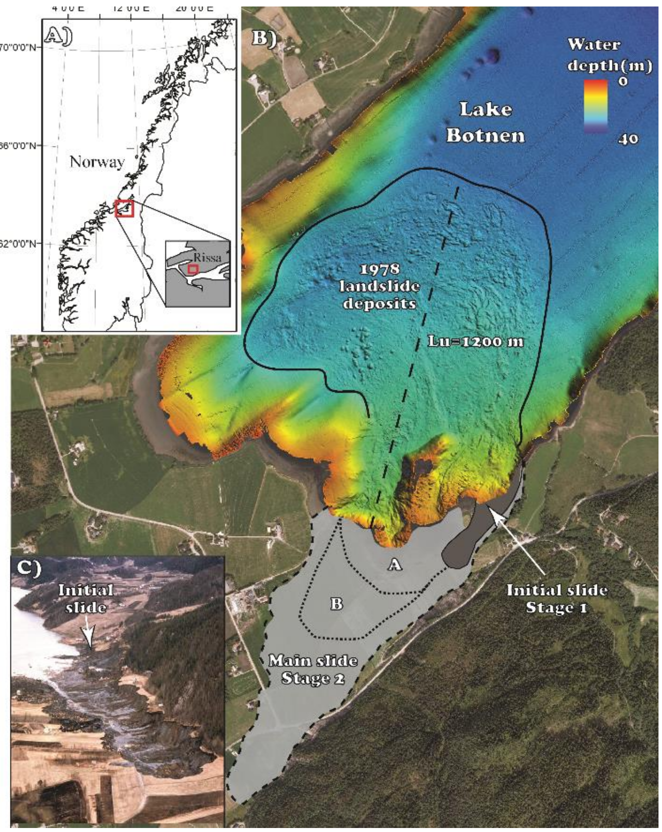

Figure 3. Rissa landslide: A) Map of Norway; B) Lake Botnen bathymetry, periphery of deposit and outline of Stage 1 slide (darker grey), the two major flakes A and B and Stage 2 main slide (lighter grey); C) Aerial view of the slide (Aftenposten) (L'Heureux et al. 2012)

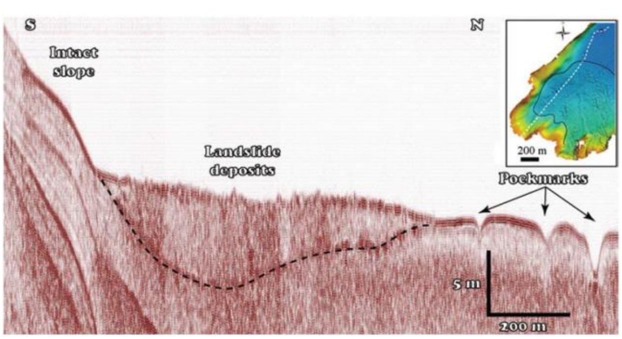

Figure 4. Seismic reflection showing the thickness of the 1978 landslide deposits on top of the original topography; the cross-section is shown by a white line in the inset (L'Heureux et al. 2012).

3.2 Parametric study

Retrogressive failure is a common occurrence in sensitive-clay landslides, and one of the advantages of using BingClaw is that it can capture the retrogressive failure to some degree. The key ingredient is the remolding model: Where the non-remolded yield strength of the clay is larger than the combined effect of gravity and the earth pressure gradient, the slide will not start to move. However, if the failure criterion is met at the toe of the release mass (either due to a larger earth pressure gradient where the terrain surface is steepest or due to a lower local value of the yield strength), part of the potential release mass will start moving. Progressive remolding will make this mass more mobile and it will leave the release area. This will increase the earth pressure gradient at the newly formed escarpment and lead to the release of more mass.

Only Stage 2 of the Rissa landslide was modelled. The peak undrained shear strength and remolding shear strength were well studied based on an extensive soil investigation carried out in and around the slide area, consisting of soundings, vane borings and undisturbed soil sampling (Gregersen, 1981; L'Heureux et al. 2012). The peak undrained shear strength of 20 kPa and the remolding shear strength of 0.5 kPa were used in the simulations, respectively.

Parameter Γ characterizes the speed of the remolding process and remains difficult to quantify. Parametric studies of the remolding rate Γ are desirable. Five different Γ values of 0.05, 0.04, 0.03, 0.02 and 0.01 were tested firstly. And then, special attention was taken to four different Γ values in the range between 0.02 and 0.01 based on the simulation results from the first five simulations.

4 RESULTS

The first five analyses present the best estimate of the parameters, without adjustment to make the results fit the observations. In the modelling, it was necessary to release the mass sequentially, Stage 1 and Stage 2. The initial release volume of the landslide was taken as the small darker grey portion on Figure 3. This selection was based on the witness accounts. The height was taken as 18.3 m.

Results from the different Γ values are reported in Table 1. Figures 5 and 6 show the runout distances from the lakeshore and the maximum velocities over the flow domain with different values of remolding rate Γ, respectively.

Table 1. Simulations with Γ values between 0.05 and 0.01

Γ values	Runout distance (m)	Maximum velocity (m/s)
0.05	1261	15.6
0.04	1252	15.4
0.03	1234	14.1
0.02	1225	13.2
0.01	662	8.1

Both runout distance and maximum velocity increased with increasing rate of strength decrease (remolding). It is interesting to note that there is a rapid increase with the remolding rate in the range between 0.01 and 0.02.

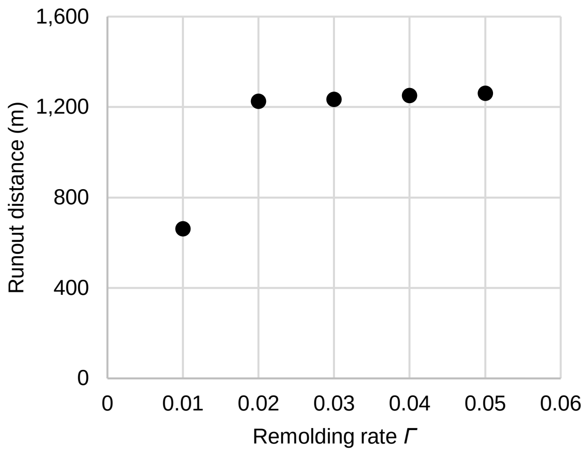

Figure 5. Runout distance for Γ between 0.01 and 0.05

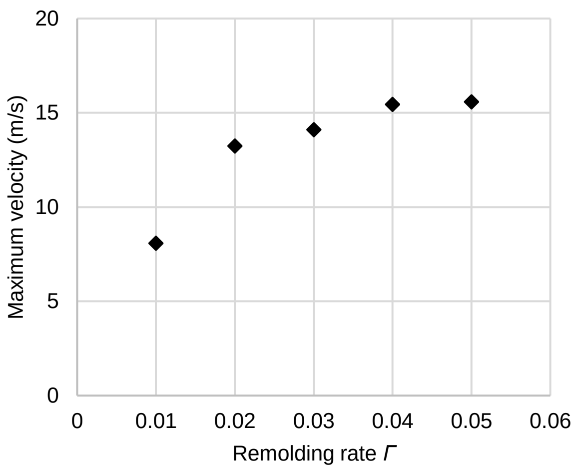

Figure 6. Maximum velocity for Γ between 0.01 and 0.05

The observed values under Stage 2 of the Rissa landslide (L'Heureux et al. 2012; L'Heureux 2013) were runout distance of 1200 m, maximum velocity of 8.3–11.3 m/s over the entire flow domain and deposit height a minimum of 0, maximum of about 7.5 m (Fig. 4). The calculation with remolding rate between 0.01 and 0.02 gave runout close to that observed.

Results from Γ values in the range between 0.01 and 0.02 are reported in Table 2. Figures 7 and 8 show the runout distances from the lakeshore and the maximum velocities over the flow domain with different values of remolding rate Γ in the range between 0.01 and 0.02, respectively. The resulting remolding rate Γ was 0.016.

Figure 9 shows the progression of the Stage 2 landslide after 3, 9, 15 and 21 min for Γ value of 0.016. To the right, the scale for the average deposit thickness in m is given.

Table 2. Results for Γ values between 0.01 and 0.02

Γ values	Runout distance (m)	Maximum velocity (m/s)
0.01	662	8.1
0.012	939	11.6
0.014	1038	11.6
0.016	1207	11.6
0.018	1207	12.5
0.02	1225	13.2

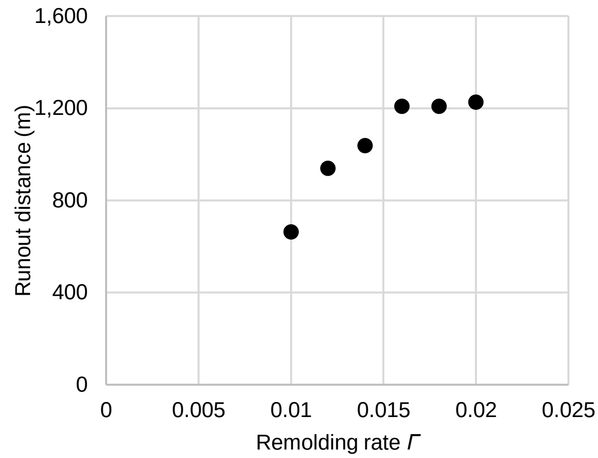

Figure 7. Runout distance for Γ between 0.01 and 0.02

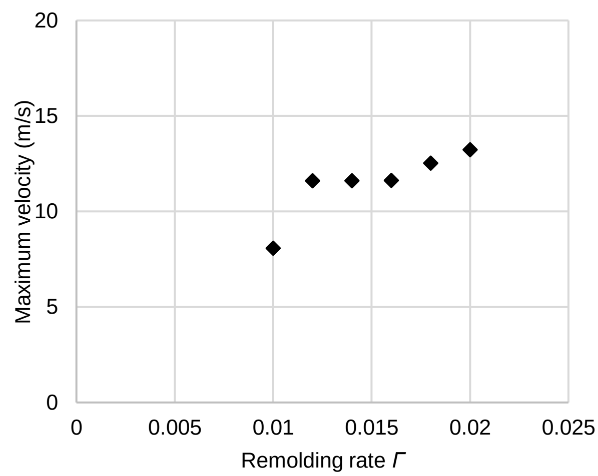

Figure 8. Maximum velocity Γ between 0.01 and 0.02

Figure 10 compares the predicted and observed runout after 30 minutes. Figure 11 shows the predicted deposit thickness at the cross section shown in Figure 4 (white dashed line) after 60 minutes. Using the scales in Figures 4 and 10, the predicted maximum thickness is about 7 m, while the measured maximum thickness is 7.5 m. The agreement appears reasonably good.

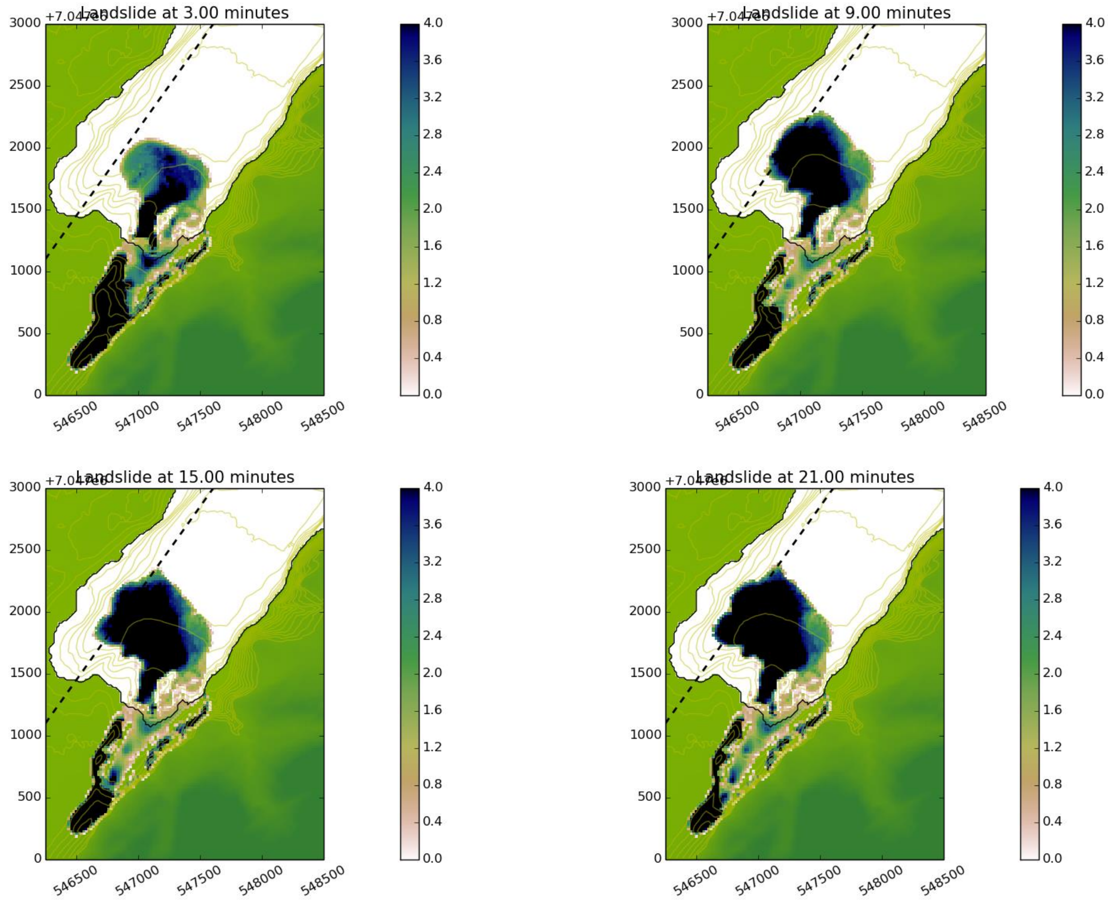

Figure 9. Predicted progression of Stage 2 Rissa landslide after 3, 9, 15 and 21 min (f deposit thickness (m) at right)

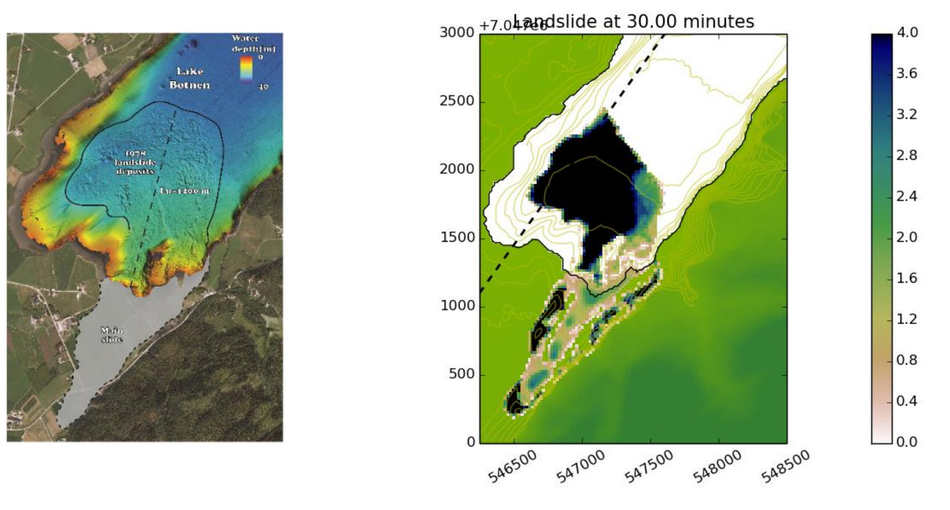

Figure 10. Prediction of runout extent and average deposit height of Rissa landslide (scale of deposit height (m) at right)

5 DISCUSSION

In these numerical simulations, the remolding rates were varied. With an depth-averaged model as this new numerical model, one should use the mean yield strength if the yield strength varies with depth and the residual yield stress should have been given a somewhat higher value to account for the non-sensitive material above the sensitive clay. With a well-defined yield strength and residual yield strength, it is possible to back-calculate the remolding rate that should be used to match the runout observations.

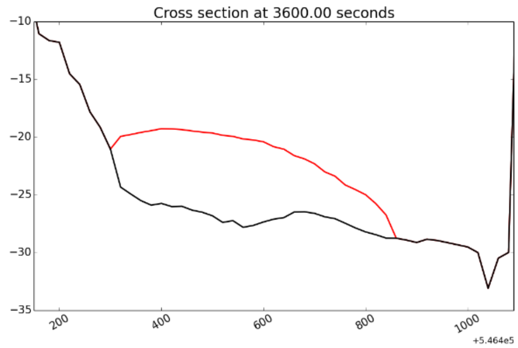

Figure 11. Predicted debris height in section in Figure 4.

A high value of remolding rate Γ implies that the clay reduces its shear strength very quickly with increasing deformation. Presently, Γ needs to be determined empirically. Based on the back-calculations, the remolding rate of 0.016 was obtained for the Rissa landslide. Løvholt et al. (2017) used a smaller Γ value for the larger Storegga slide offshore.

A conceivable reason for this apparent volume dependence of Γ is the fact that the parameters in BingClaw describe material properties that are averaged over the depth of the flow or the shear layer. The shear and thus the remolding are most intense at the bottom of the flow and potentially in layers with lower non-remolded yield strength forming shear bands (if the material is not perfectly homogeneous). Near the interface between the shear and plug layers, remolding progresses much more slowly. Large slides having thick shear layers, it is expected that the shear at the bottom must attain much larger values in large slides than in small ones for the remolding to become significant in the upper parts of the shear layer. However, more dedicated laboratory and theoretical studies are needed to arrive at a priori criteria for choosing Γ.

Although the results are still in progress, the results for the Rissa landslide appear very promising.

6 SUMMARY AND CONCLUSIONS

Estimation of runout distance is of great significance for landslide risk assessment and mitigation design. The paper presents a new numerical model to predict the runout of landslide in sensitive clays. The model, still under development, already provides promising results. The challenge resides in finding analysis parameters that are representative of the soil parameters as measured in the laboratory or in situ, especially the remolding rate.

The new model predicted reasonably well the runout distance, maximum velocity and debris thickness that occurred during Stage 2 of the Rissa landslide. One of several on-going improvements is to include in the analysis the non-sensitive topsoil riding above the sliding sensitive clay.

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