Towards a Numerical Run-Out Model for Quick-Clay Slides

Dieter ISSLER[1,*], Jean-Sébastien L'HEUREUX[2], José M. CEPEDA[1] and Byron QUAN LUNA[3]

[1] Natural Hazards Division, Norwegian Geotechnical Institute, Oslo, Norway
[2] Geotechnics and Natural Hazards Trondheim Group, Norwegian Geotechnical Institute, Trondheim, Norway
[3] DNV GL AS, Høvik, Norway
[*]Corresponding author. E-mail: di@ngi.no

Mapping the hazard from quick-clay slides (QCS) needs to consider, not only the release area, but also the entire flow path. However, models and an associated method for estimating the run-out distance are currently missing. A comparative analysis of field observations reveals the run-out distance to scale linearly with the retrogression distance and as a power of the slide volume. Back-calculations of selected events with different numerical models (BING, DAN3D, MassMov2D) show that models developed for other slide types are not suitable for predicting run-out distances in an objective way, based on measured soil properties. A numerical run-out model for QCS needs to include the progression of remolding, the rafting of non-sensitive soil at the top, and retrogressive failure, which must be either computed or specified through the initial conditions. In most cases, a (quasi-)3D code will be needed.

Key words: quick-clay slides, rheological properties, mathematical run-out models

1. INTRODUCTION

Throughout Norway's written history up to the present day, there are many reports on landslide disasters—the worst of which claimed hundreds of lives—that struck unexpectedly and occurred, not in steep slopes, but in prime settlement areas with rolling hills where no-one would suspect any such danger. We now know that highly sensitive clays cause those events and that many low-lying areas in Scandinavia, eastern Canada, Alaska and Russia are prone to this type of slope instability.

During glaciation, ice streams deposited huge amounts of clay in the shallow near-shore waters of those times. Flocculation mediated by salts caused these clays to form a card-house-like texture with high water content. Isostatic rebound after the last glaciation lifted these glacio-marine clays above sea level. As fresh water or ground water leach the salt, the repulsive inter-particle forces increase and make these clays highly sensitive [*Rosenqvist*, 1953]. If structural collapse occurs, the leached clay behaves as a liquid of low yield strength and viscosity. An external trigger, like earthquakes, destabilization of a riverbank by fluvial erosion, or anthropogenic loads, may remold the sensitive clay sufficiently to liquefy. Amateur video footage from the 1978 event at Rissa near Trondheim captured the material behavior of quick clay and the extent of such events impressively (http://www.youtube.com/watch?v=3q-qfNlEP4A).

Modern geotechnical and geophysical techniques are able to locate potential release areas of quick-clay slides and assess their stability with reasonable accuracy and reliability, e.g. [*L'Heureux et al.*, 2014a]. In Norway, a nation-wide program to map the risk of quick-clay slides according to a three-level scale is underway. In some cases, the slide masses will flow out along existing rivers or into the sea without causing problems. In other cases, people and infrastructure downstream may be at high risk so that one needs to determine the potential run-out area. However, there are presently no established methods for doing this, and the extraordinary mobility of quick-clay slides makes this a challenging task.

In the next section, we summarize the features of quick-clay slides that are relevant for model development, based on a recent report [*L'Heureux*, 2012b]. Before embarking on the development of a dedicated model, it is instructive to apply existing models for other slide types to quick-clay slides in order to determine to which degree they can reproduce the observations and where they fail. Section 3 therefore describes simulations with three different models of one of three test cases from the report [*Issler et al.*, 2012].

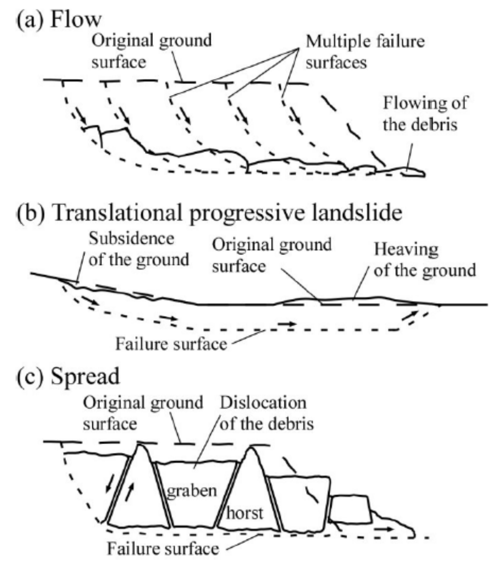

Fig. 1 Schematic representation of the most frequent types of landslide in sensitive clays. From [*Locat,* 2012].

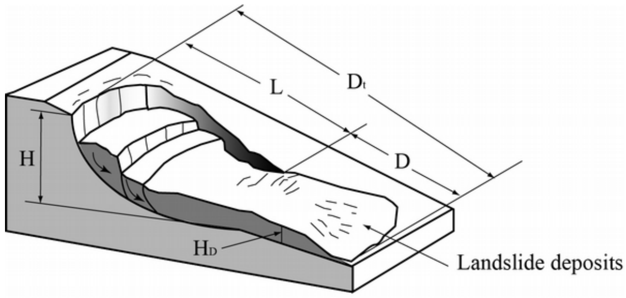

Fig. 2 Conceptual landslide model showing some of the morphological parameters compiled in the study [L'Heureux, 2012b], in particular the run-out length from the gate, *D*, and the retrogression distance, *L* (after [*L'Heureux*, 2012a]).

Finally, in Sec. 4, we discuss what these studies imply for the next steps in the development of a realistic dynamical run-out model for quick-clay slides.

2. RELEVANT PROPERTIES OF QUICK-CLAY SLIDES

The criteria for classifying a clay material as quick vary somewhat between countries and are subject to change, but they are typically based on the sensitivity, $S_t = s_{uu}/s_{ur}$, of the soil and a threshold value of the remolded shear strength. In this paper, we denote the unremolded undrained shear strength by s_{uu} and the remolded undrained shear strength by s_{ur}. Norwegian practice considers clays as quick if $s_{ur} <$ 0.5 kPa and as highly sensitive if $S_t > 30$ [*NGF*, 1974].

According to [*Tavenas,* 1984; *Karlsrud et al.*, 1984], the sensitive clays of Canada and Scandinavia give rise mainly to (i) single rotational slides, (ii) multiple retrogressive slides (aka. earthflows or flows), (iii) translational progressive landslides (flakes), (iv) spreads. The last three types (**Fig. 1**) occur very suddenly and often cover large areas. Translational progressive landslides are uncommon in eastern Canada, but occur often in Scandinavia [*Aas*, 1981; *Karlsrud et al.*, 1984]. Among the large landslides occurring in sensitive clays, flows are the most common in Norway [*Bjerrum*, 1955; *Tavenas*, 1984; *L'Heureux*, 2012a] and in eastern Canada. [*Karlsrud et al*., 1984] underline that a combination of the four types of landslides can often be observed in one event.

Flows are multiple retrogressive slides resulting from an initial failure, the debris of which becomes strongly remolded and flows out of the crater, leaving an unstable scarp. A second slide may then occur with the remolded clay also flowing out of the crater, generating yet another unstable scarp. This process continues until a final stable backscarp is formed (**Fig. 1**.a). An empty crater (in some cases with a bottleneck shape) is characteristic of this type of landslide. Multiple retrogressive slides tend to occur when the following requirements are met: (i) There is sufficient potential energy in the slope to remold the clay effectively. (ii) The remolded clay is liquid enough to flow out of the landslide crater (i.e., liquidity index $I_L > 1.2$ or remolded shear strength $s_{ur} < 1$ kPa [*Lebuis et al.,* 1983; *L'Heureux et al*., 2012]. (iii) The topography allows evacuation of the debris.

Translational (or flake-type) landslides result from the development of a shear surface parallel to the ground surface, above which the soil mass displaces downhill [*Cruden and Varnes*, 1996]. Translational progressive landslides exhibit a zone of subsidence at the head of the slope and an extensive compressive heave zone located far beyond the toe of the slope, in less inclined ground (**Fig. 1**.b).

[*Cruden and Varnes*, 1996] attribute spreads to the extension and dislocation of the soil mass above the failure surface, forming horsts and grabens that subside in the underlying remolded material forming the shear zone (**Fig. 1**.c). Those geomorphologic shapes are key elements distinguishing spreads from other retrogressive landslides.

In considering the mobility of a landslide, one can distinguish between two components (**Fig. 2**): the retrogression (L) and the run-out distance (D). The data compiled in **Fig. 3** shows the retrogression always to be less or equal to the run-out distance, except in situations where the slide did not develop into a flow. There is a clear linear trend for both the lower and the upper limit of the mobility, which differ by a factor of 10. Note that the data span three orders of magnitude in both L and D. No significant difference is visible between the Norwegian and Canadian

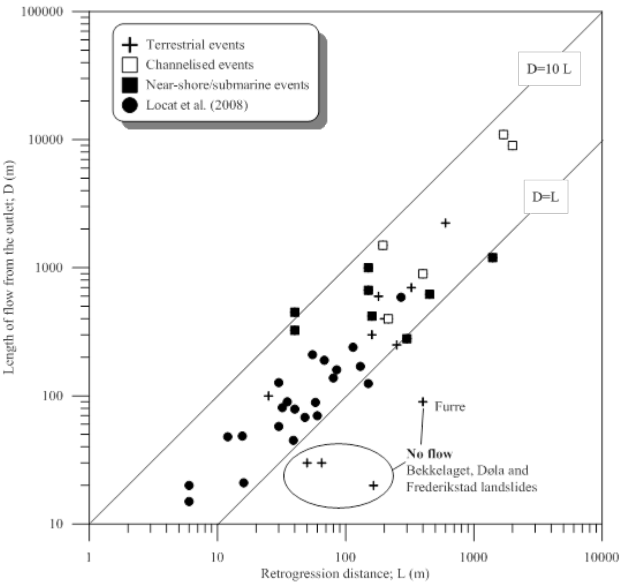

Fig. 3 Mobility estimated for Norwegian quick-clay landslide as a function of the retrogression distance (extended data set from [*L'Heureux*, 2012a]). The data is compared to landslides in sensitive clays from eastern Canada [*Locat et al.*, 2008].

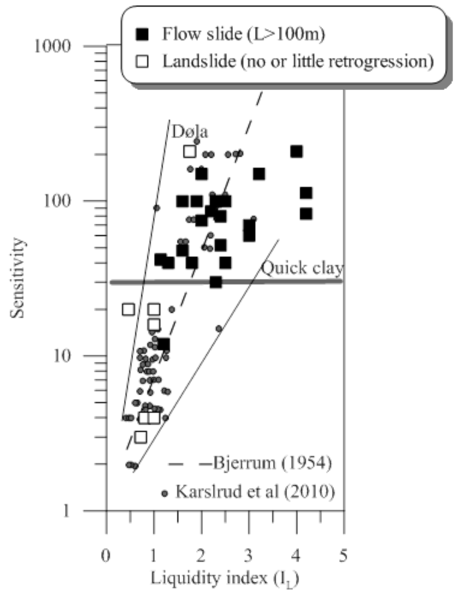

Fig. 4 Liquidity index plotted against sensitivity for landslides in sensitive clay observed in Norway. The horizontal line S_t = 30 designates the lower limit for highly sensitive clays according to Norwegian practice. From [*L'Heureux*, 2012b].

slides. We conjecture that these linear relationships are the result of geometric similarity within the range of distances over which quick-clay slides can occur. We have only very tentative explanations for the lower and upper limit of the ratio *D*/*L*: A value near or below 1 implies that a significant portion of the released mass remains in the crater and thus stabilizes the escarpment by its weight and by reducing the slope angle. This can occur because of incomplete remolding or topographic impediments. A large ratio, on the other hand, requires rapid remolding and unimpeded outflow. If the clay is easily remolded (and readily flows out), the creep induced in the slide scar by the missing pressure from the released masses will be enough to remold the next portion of soil so that retrogression continues. Retrogression may also stop because the reservoir of sensitive clay is exhausted. The largest values of *D*/*L* in **Fig. 3** may well be due to this effect.

Another important factor contributing to retrogression and the mobility of the landslides in sensitive clays is the ability of the clay to flow out of the landslide crater when remolded. This depends on the consistency of the remolded material and on the liquidity index. Comparison of the geotechnical data of the landslides in our database in **Fig. 4** shows that flow-slides generally occur when I_L > 1.1–1.2 and the sensitivity is greater than 30. This is similar to the findings of [*Lebuis et al.*, 1983] for landslides in eastern Canada. The 2011 landslide at Døla is an outlier that remained mostly as limited deformation despite its very high sensitivity value. However, this value does not represent the entire slide mass because the

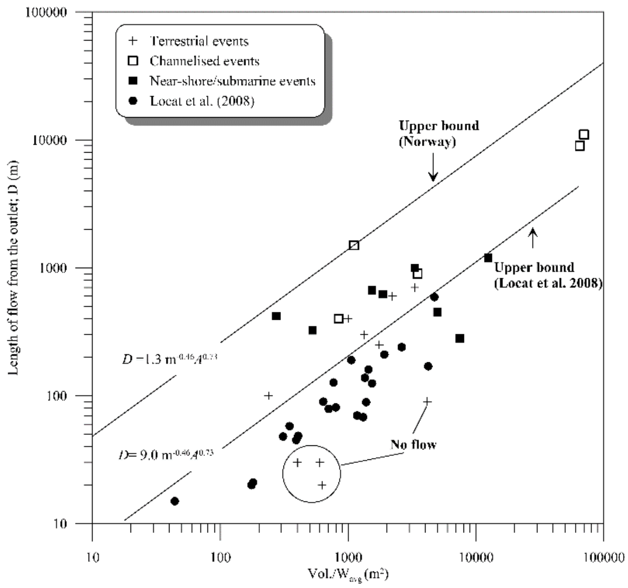

Fig. 5 Mobility of Norwegian quick clay landslides as a function of the normalized volume of disturbed material per unit width (extended data set from [*L'Heureux*, 2012a]). The Norwegian data is compared to landslides in sensitive clays from eastern Canada [*Locat et al.*, 2008].

quick-clay layer was 1–2 m thick and covered by more than 5 m of sand and gravel.

The dependence of the run-out distance on the slide volume is a well-known (and controversially discussed) phenomenon. Such dependence is also present in quick-clay slides, as **Fig. 5** shows. We chose to plot the run-out distance versus the release volume *V* divided by the average width W_{avg}, i.e., the average area $A = V / W_{avg}$ of longitudinal sections

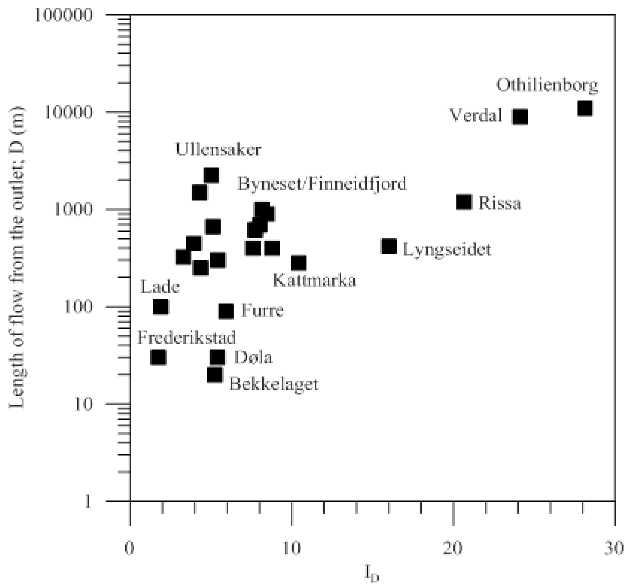

Fig. 6 Run-out distance, D, vs. destructuration index, I_D, for Norwegian quick-clay slides. H_G in Eq. (3) was approximated by 2/3 H (cf. **Fig. 2**).

through the release area. The run-out distances of investigated Canadian quick-clay slides fall into a strip characterized by

$$0.4\ \mathrm{m}^{-0.46} A^{0.73} < D < 1.3\ \mathrm{m}^{-0.46}\ A^{0.73} \quad (1)$$

with A measured in m^2. Norwegian slides appear to have a similar lower bound, but a significantly higher upper bound:

$$0.45\ \mathrm{m}^{-0.46} A^{0.73} < D < 9.0\ \mathrm{m}^{-0.46}\ A^{0.73}. \quad (2)$$

The higher upper bound reflects differences between Canadian and Norwegian quick-clays, which may be due to differences in mineralogy and the lesser degree of consolidation of Norwegian clays. We do not presently know, however, whether the larger variability of Norwegian quick-clay slides is due to a wider span of clay properties or to topographic limiters. Note in this context that Norwegian slides that fall below the lower bound in (2) are of non-flow type.

Obviously, the spread in Eqs. (1) and (2) is far too large to make them useful in hazard mapping. We need a much better understanding of the factors that affect the coefficient in these relations. The very fact that the coefficient has dimension of a length to some power indicates that there must be an additional relevant length scale in the run-out dynamics. With a view towards simple dimensional analysis, it is tempting to replace the exponent 0.73 by ¾, but we caution that there is not enough data to determine the exponent empirically with great confidence; an exponent of ½ would also give plausible envelopes for both the Canadian and Norwegian data sets and would make the coefficient dimensionless. By ana-

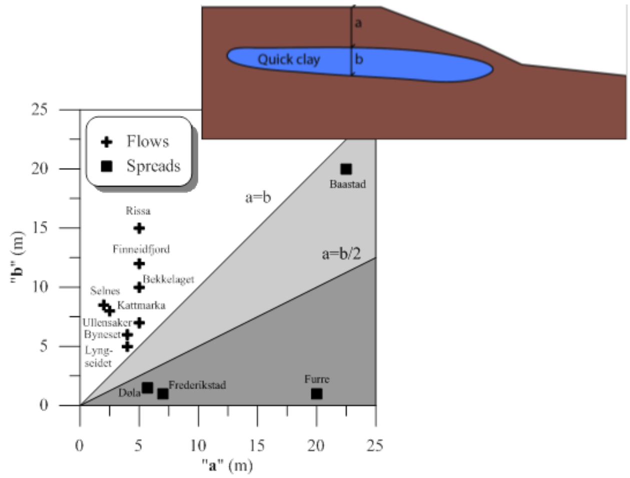

Fig. 7 Influence of the thicknesses of the quick-clay layer, b, (ordinate) and the overlying non-sensitive layer, a, (abscissa) on the slide type for Norwegian quick-clay slides. From [*L'Heureux*, 2012b].

lyzing a larger number of slides, one may hope to arrive at results that are more conclusive. Only little information on each slide is required, but for many slides, the run-out distance may not be retrievable because the slide debris was washed away by a river.

An immediate candidate for the relevant length scale in the run-out problem is the drop height H_G of the center of mass. If we accept the functional form of Eq. (1) or (2) and suppose that H_G is the only relevant length scale, we obtain the rather counter-intuitive result $D = k\ H_G^{-1/2}\ A^{3/4}$, where k is a non-dimensional coefficient. This suggests that other processes and other relevant scales govern this phenomenon. Attacking the problem from a different angle, [*Vaunat and Leroueil*, 2002] studied the role of the mechanical work per unit mass, w_R, that is required for remolding the sensitive clay. w_R can only come from the potential energy of the slide mass; therefore, those authors defined the destructuration index by

$$I_D = \frac{g H_G}{w_R}, \quad (3)$$

where g is the gravitational acceleration. [*Locat et al.*, 2008] approximated $w_R \approx 16\ s_{uu} I_P$ based on published data on Canadian quick-clays. s_{uu} and I_P are the undrained unremolded shear strength and the plasticity index, respectively. Even though there are no corresponding data on Norwegian quick-clays and we suspect that this relation might underestimate w_R in some cases, we plot D vs. I_D for Norwegian quick-clay slides in **Fig. 6**. There is a wide spread in I_D from 1 to 28. For $I_D < 10$, no correlation is apparent; for slides with $I_D \approx 5$, D ranges over two orders of magnitude. There is, however, an indication of an exponential lower envelope,

$$D \geq 5\ \mathrm{m}\ e^{0.267\ I_D}. \quad (4)$$

Fig. 8 Bird's eye view of the 2012 Byneset quick-clay slide. The crater in the middle of the image is 8–10 m deep and about 350 m long. Erosion at the bend of the river caused the initial failure that opened the narrow gate through which the masses flowed out, both downstream towards the rear of the image and upstream to the left. From [*Lyche*, 2012].

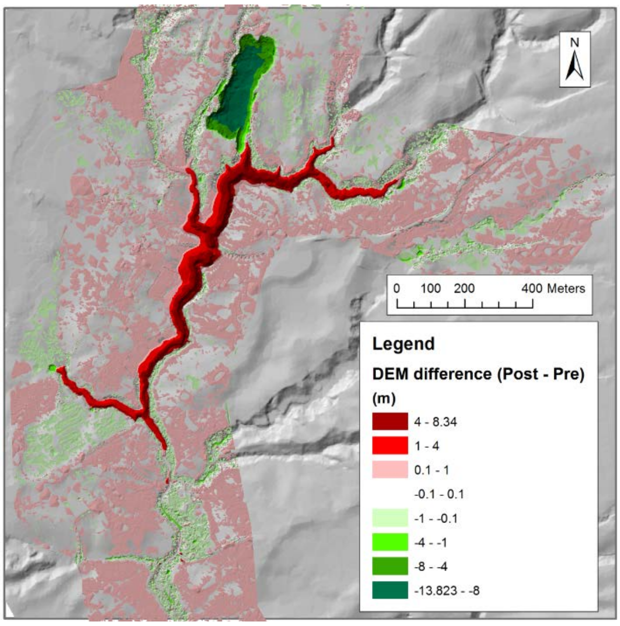

Fig. 9 Map of the Byneset slide with the elevation change due to the slide coded in color (the crater in dark green and the deposit in dark red). Note the eastern branch along the upstream reach of the little river and the blocked tributary to the southwest. (From [*Issler et al.*, 2012]).

This is yet another indication that numerous other effects influence the run-out distance profoundly.

As one example of such an influence, we position a number of Norwegian quick-clay slides, for which both the mean thickness of the quick-clay layer, b, and the mean thickness of the overlying non-sensitive layer, a, are known, in the a-b-plane (**Fig. 7**). There is no overlap of the areas occupied by flows and spreads, respectively. For all flows, $b > a$, and for all spreads $b < a$. Except for the Båstad slide, the dividing line could equally well be drawn at $b = 2.5$ m, independent of a. More data combined with mechanical considerations are needed to determine whether **Fig. 7** can be extended into a "phase diagram" for quick-clay slides.

3. BACK-CALCULATION OF SELECTED SLIDES WITH EXISTING MODELS

[*Issler et al.*, 2012] assessed the capability of existing numerical flow models to capture the most important aspects of quick-clay slides by back-calculating three different, well-documented events in Norway. The Byneset slide 2012 (approx. 0.3×10^6 m^3) was subaerial, the Finneidfjord slide 1996 (approx. 1×10^6 m^3) mostly subaqueous, and the famous Rissa slide 1978 ((5–6)$\times10^6$ m^3) passed from subaerial to subaqueous. For lack of space, we will focus on the Byneset slide here, but use insight from the other cases as well in our assessment. See also [*L'Heureux*, 2012b] for a modeling study of the Rissa slide.

3.1 The Byneset slide

Quick-clay is copious in and around Trondheim, the third-largest city in Norway. In the first hours of 2012, more than 250 000 m^3 of material unexpectedly slid out at Byneset, a rural area about 10 km WSW of Trondheim. The cause was erosion of the bank of the small river Brenselbekk that destabilized a 3–6 m thick quick-clay deposit overlaid by 2–4 m of non-sensitive clay, sand and gravel. The crater, which has a length of about 350 m and a width of up to 100 m, was almost completely emptied (**Fig. 8**). From the narrow port, the slide retrogressed 400 m, and ran 870 m downstream. With a drop height of 42 m from the top of the escarpment to the toe of the deposit, the run-out angle was 1.9°. The deposit depth decreased from 7 m below the gate to about 3 m at the most distal point. A substantial part of the slide masses turned sharply to the left at the gate and progressed about 500 m upstream in the riverbed. Only 100 m upstream of the stopping point, the slide also filled the gully of a small tributary over a length of 250 m (**Fig. 9**).

There is only little information about the temporal aspects of the slide event. Indirectly, we may infer that the slide in all likelihood was retrogressive at least in its early stages because the narrow port prevented rapid movement and remolding of large masses until the lower part of the crater was emptied. Likewise, high velocity would have led to the slide spilling over the bends of Brenselbekk and bypassing the upper reach as well as the tributaries. We conjecture that the velocity remained below 10 m s^{-1}.

Geotechnical data on the slide material that are available to us indicate a mean density of 1865 kg m^{-3}, undrained unremolded and remolded shear strength of 10–25 kPa and 0.2–0.3 kPa, respectively, giving a sensitivity of 35–125. The plastic index was 5%, the liquidity index around 4. Quick clay accounted for 50–70% of the depth of the released material.

3.2 Main characteristics of the models

Three different numerical codes were tested, all of which assume locally plane-shear flow in a vertical plane and implement a variant of Herschel–Bulkley rheology. According to the latter, the material behaves as a solid if the shear stress is less than the yield strength, τ_y, and flows like a power-law fluid with rheological exponent $q > 0$ above this threshold. It stipulates the following relation between the modulus of the shear stress, $\tau = \left(\tau_{xz}^2 + \tau_{yz}^2\right)^{1/2}$, and the shear rate, $\dot{\gamma} = \partial_z \sqrt{u^2 + v^2}$:

$$\dot{\gamma}(z) = \begin{cases} 0, & \tau < \tau_y \\ \left(\frac{\tau - \tau_y}{K}\right)^{1/q}, & \tau \geq \tau_y \end{cases} \tag{5}$$

Like the majority of present-day mass-flow codes, the models in our comparison exploit the relative thinness of most gravity mass flows by integrating the governing equations over the flow depth. This reduces the computational load substantially, but one loses the capability to account for vertical variations of the flow variables or the material properties.

BING by [*Imran et al.*, 2001] is a quasi-2D visco-plastic model, i.e., it solves the equation of motion along a path profile $Z(X)$. The rheological exponent can take any value > 0. The initial condition is a parabolic mass at rest, whose length and maximum height the user needs to specify. BING approximates the shape of the instantaneous velocity profile by that of a flow at equilibrium, but calculates the depth of the plug-flow layer on top dynamically from a separate equation of motion for the plug layer. BING accounts for buoyancy and added-mass effects, but not for hydrodynamic drag. This causes no problems when simulating subaerial slides or small to moderately large subaqueous ones, but for large slides with very long run-out, unphysical velocities result. BING solves the equations of motion in the Lagrangean scheme, i.e., the computational cells move together with the flowing mass. This makes for an efficient code because no computation is necessary where there is no flow material.

The code DAN3D by [*McDougall and Hungr*, 2004] offers a choice of friction laws, including Coulomb (i.e., dry friction only), Voellmy (dry friction plus drag) and Bingham (Eq. (5) with $q = 1$), of which the purely plastic law ($K = 0$) and Newtonian fluids ($\tau_y = 0$) are limiting cases. However, in applications the Coulomb and Voellmy laws are probably most often used. Some simple, empirical bed entrainment laws are also available, but were not used in our simulations. What sets DAN3D apart from most other models with similar capabilities is the numerical scheme, namely Smoothed Particle Hydrodynamics (SPH) [*Monaghan*, 1992]. SPH is Lagrangean in spirit, but avoids the distortion of computational cells that occurs in 2D and 3D flows by not using a mesh, but interpolating field values from the properties of "particles" advected with the flow. SPH codes are particularly suited for calculating flow splitting, splashing and similar phenomena. We should mention that we used the (somewhat outdated) 2009 version of DAN3D in our simulations and that [*Pastor et al.*, 2009] developed and applied a similar SPH code.

In contrast, MassMov2D [Beguería et al., 2009] is a "traditional" Eulerian code based on a fixed, non-staggered computational grid with quadratic cells, first-order explicit time-stepping and central spatial differencing. To increase accuracy, the bed friction terms are computed at half timesteps, and the well-known instability of central differencing is countered by adding a velocity-dependent amount of diffusion. A particular feature of MassMov2D is its implementation as a script embedded in a geographical information system (PCRaster, [*Karssenberg et al.*, 2001]), which makes pre- and post-processing particularly easy and fosters further development by the user community. (For performance reasons, key routines are compiled, however.)

3.3 Results of the simulations

BING does not allow flow on counter-slopes; accordingly, it was not possible to simulate the invasion of the upper reach of Brenselbekk and of its tributaries. Another immediate problem arising in the simulations with BING was how to represent the effect of the geometry with a wide crater, narrow gate and somewhat wider flow channel—if one disregards this difference, the simulated release volume will be less than one third of the factual volume. This affects the flow and deposit depth directly and has an indirect, but strong effect on the velocity and run-out distance. Compensating for the missing mass by tripling the release depth gives unrealistically large flow depths and, as a consequence, too high velocities. We resorted to extending the release area by about 800 m behind the upper end of the crater. This gives the correct mass and mimics the discharge-limiting effect of the narrow gate. However, there is much ambiguity in choosing the slope of the extension.

We tested both the Bingham rheology ($q = 1$) and the Herschel–Bulkley rheology with $q = 0.5$, searching for τ_y values that matched the observed stopping point within 10 m, for four different values of K that span two orders of magnitude. Our main observations are as follows:

- We had to use different amounts of artificial viscosity to mitigate numerical instabilities in the tail of the flow. This affected the results to some degree.
- Different geometrical assumptions for the release area required vastly different values of the rheological parameters. Moreover, we suspect that the neglected effect of the channel banks was substantial in this case, but we cannot presently quantify it.
- Irrespective of these assumptions, the yield strength had to be at least a factor of 3 larger than the fully remolded shear strength from geotechnical testing. We can see three main reasons for this, namely (i) the model does not capture the progression of remolding, (ii) 30–50% of the slide mass is non-sensitive, but the model cannot reflect this, and (iii) the model neglects the extra resistance from the channel sides [*Cantelli*, 2009].
- (τ_y, K) pairs that correctly match the run-out distance predict similar maximum front velocities (within 15%). All of them are about 50% higher than our educated guess, though.
- There were moderate differences between simulations with q = 1 and q = 0.5, but there are too many other error sources to discriminate between the two rheological assumptions.

Simulations of the Finneidfjord and Rissa landslides with BING corroborated these findings. The Rissa case study (see also [*L'Heureux et al.*, 2012]) in addition highlighted the importance of considering retrogressive failure—even if in a crude way.

With DAN3D, an error in the code for Bingham rheology limited us to a purely plastic model with fixed τ_y (chosen lower than the measured fully remolded shear strength of 0.2–0.3 kPa) and K = 0. With this value, it reproduced the run-out distance of the Byneset slide fairly well and captured the run-up in tributaries. Examination of the deposit distribution shows that the mass is "splattered" thinly over the surroundings, even at high elevations above the channel (**Fig. 10**). The deposit depth diminishes gradually in the downstream direction as observed, but is almost an order of magnitude too small. The river channel downstream of the gate has an average inclination of 0.4°; with τ_y = 120 Pa, the flow should stop when the flow depth falls below 1 m, but DAN3D indicated a deposit depth around 0.1 m at the terminus.

This deficiency appears to be due to an insufficient number of computational "particles", which leads to numerical dispersion of the mass due to the interpolation method at the base of the SPH technique.

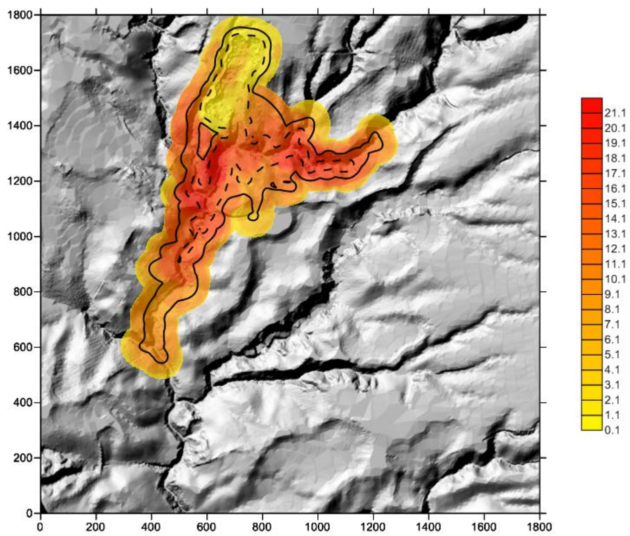

Fig. 10 Simulation of the 2012 Byneset slide with DAN3D: distribution of maximum flow velocities. Labels in color bar are in m/s. Full and dashed lines correspond to maximum simulated flow depths of 0.1 m and 1.0 m, respectively. From [*Issler et al.*, 2012].

Increasing the number of particles proved impractical, however, because the computation time for a single run would exceed one day.

We observed similar unphysical spreading of the slide mass when we applied DAN3D to the mostly subaqueous second stage of the Finneidfjord slide [*Longva et al.*, 2003; *Issler et al.*, 2012]. In order to account for buoyancy, we multiplied the depth of points below sea level by the factor $1-\rho_f/\rho_w$. With the measured fully remolded shear strength of 80 Pa, the simulated slide ran too far and too fast, again spreading in an unrealistic way. In this case, the deposit distribution did not match observations at all—the entire slide mass moved beyond the observed terminus. These deficiencies are attributable to (i) the use of s_{ur} from the start, (ii) the absence of viscous resistance, and (iii) the numerical problems discussed above.

Contrary to expectations, simulations of the Byneset slide with MassMov2D were much faster than with DAN3D. MassMov2D correctly predicted some slide material to run upstream in the main channel and tributaries at Byneset (**Fig. 11**). Another correct prediction is that the slide masses do not spill over the channel sides. Using the same low value of the fully remolded shear strength and zero viscosity as in DAN3D, MassMov2D overestimated the run-out distance. We do not presently have a clear understanding of why MassMov2D predicts absence of deposits along the first approx. 200 m downstream of the gate, where the observed deposit depth varied from 3 to 7 m. We plan to extend our tests with MassMov2D in the near future in order to assess the sensitivity on the yield strength and viscosity.

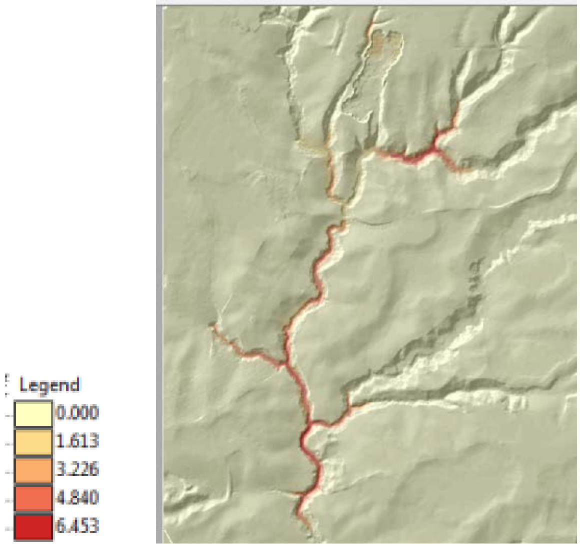

Fig. 11 Deposit depth (in m) of the Byneset slide after 400 s, as simulated with MassMov2D. The flow is contained in the channel everywhere, the crater is emptied almost completely, but there are no deposits inside the gate and about 200 m downstream. From [*Issler et al.*, 2012].

4. CONCLUSIONS AND OUTLOOK

Based on rheological studies of quick clays, the Herschel–Bulkley flow law appears to provide an adequate rheological framework as it features both yield strength and viscous effects; we do not expect granular friction to play a significant role in this context. All models in our back-calculation study implement this type of rheology, albeit with some differences. Yet it appears safe to conclude—despite the limited scope of our study—that existing models for other slide types will not make satisfactory tools for hazard mapping of quick-clay slides. Minor modifications, like inclusion of buoyancy, would improve their performance somewhat, but they fail to address some key issues:

- A realistic description of remolding is needed for reproducing the observed run-out distances with the measured geotechnical soil parameters. This is a prerequisite for using the model as a *predictive* tool.
- The model needs to implement a facility for describing retrogressive failure, at least in a user-prescribed manner. In many cases, an all-at-once, flake-type release may give unrealistically long run-out distances and high velocities.
- The thickness of on-sensitive topsoil rafted by the quick-clay layer may determine whether the slide develops into a flow or not; therefore, one should account for it explicitly in the model.

We expect the last-mentioned requirement to be the easiest to implement. If one opts for a depth-averaged formulation for performance reasons, a two-layer scheme will be necessary because the quick-clay and the non-sensitive material on top have widely different properties. It is an open question whether it is necessary to account for the observed progressive break-up of the topsoil and to include frictional behavior.

Ab initio modeling of retrogressive failure as a dynamic process is a complex task that involves not only successive slope-stability assessments, but also consideration of the early phases of the remolding process [*Gauer et al.*, 2005]. Observations from several slide events seem to indicate that the intervals between successive failures are long enough for treating them as separate events and that the exact timing is of little concern (except possibly for tsunami calculations). However, the model needs to include the interaction of the different slide portions with the deposits of their predecessors.

The most demanding task is to find a simple, yet accurate and widely applicable description of the remolding process. In practical applications, key geotechnical data like the liquidity index I_L, the plasticity index I_P, the undrained unremolded shear strength s_{uu} and the undrained fully remolded shear strength s_{ur} may be available. In contrast, the Herschel−Bulkley flow law requires knowledge of the rheological exponent q, the yield strength τ_y and the consistency K as functions of the degree of remolding. Obtaining them requires special laboratory equipment and expertise, as well as a considerable effort.

[*L'Heureux*, 2012] and [*L'Heureux et al.*, 2014b] review earlier investigations of the rheological properties of sensitive clays and their behavior under remolding. Despite the complexity of the matter, there is hope to find approximate, but widely applicable relations between the rheological parameters of the flow model and more readily measurable geotechnical parameters. We expect interesting results from a reanalysis of the data of [*Locat and Demer*s, 1988] on Canadian sensitive clays in terms of the more general Herschel–Bulkley rheology, rather than assuming Bingham rheology from the outset. There is, moreover, urgent need for testing highly sensitive clays from outside Canada along the lines indicated by [*Locat and Demers*, 1988; *Locat and Lee*, 2002; *Locat et al*., 2008].

Our study cases and our experience from consulting work also indicate a number of additional requirements that the future model should fulfill:

- In many cases, the topography is rather complex so that 3D or quasi-3D (depth-averaged) models are required for realistic modeling of flow heights and velocities.
- Many Norwegian quick-clay slides run out in a fjord where they may generate a sizable tsunami

that also needs to be assessed. For realistic input to tsunami models, it is desirable to account for buoyancy and hydrodynamic drag explicitly.

- The model should be efficient and user-friendly, so that users can carry out several simulations with different input data in a reasonable time span and pre- and post-process the data in a geographical information system.

The resulting model will thus be considerably more complex than existing models for landslides in non-sensitive soils. The strong two-way coupling between the flow dynamics and the rheology through the remolding process make this a highly non-linear system. One should expect the model predictions to depend sensitively on the choice of parameters and initial conditions. Applying the model in a meaningful way will therefore require experience and expert knowledge of this peculiar slide type.

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