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Numerical simulation for runout behaviour of sensitive clay landslides using the material point method

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ABSTRACT: Landslides in sensitive clays are usually triggered by natural causes (e.g. erosion in ravines, intensive rainfall) and/or human activity (e.g. construction work). The propagation of such landslides often exceeds several hundred meters. It is vital to model the complete process, including initiation and runout, of landslides in sensitive clays in order to improve the method for hazard zone mapping in use today. This study conducted material point method (MPM)-based simulations to investigate the runout behaviour of the recent sensitive clay landslide in Gjerdrum in Norway. A strain-softening Mohr-coulomb model is adopted to simulate the tendency toward progressive failure of the sensitive clay slope. The undrained shear strength of the soil block at the slope toe was significantly reduced in the simulations to imitate the slide initiation caused by erosion in the creek at the foot of the sensitive clay slope. The simulations results suggest that a throughgoing shear band is formed in the sensitive clay layer, triggering the landslide with a large extent of movement. The parametric analysis suggests that the strain-softening parameters and the spatial variability of undrained shear strength significantly affect the runout behaviour. Overall, the proposed simulation approach can capture the slide's initiation and progressive failures in one combined analysis.

Keywords: Progressive failure; Erosion; Sensitive clay; Landslide; Material point method

1 INTRODUCTION

Landslides in sensitive clays pose a major socio-economic threat to population, infrastructure, property, and the environment because of their retrogressive characteristics and extreme mobility (Liu et al., 2021). A recent example is the fatal sensitive clay landslide at Ask in Gjerdrum in Norway on the early morning of December 30, 2020. The landslide caused 10 fatalities, destroyed over 31 dwellings, forced the evacuation of over 1,500 residents in pandemic times (which exacerbated infections), and resulted in chaos on the roads, services (e.g., sewers, freshwater pipelines) and the ecosystem downstream of the landslide. An expert panel was commissioned by the Government of Norway in 2021 to investigate the landslide. They concluded that the landslide occurred due to erosion in Tistilbekken having worsened over several years with already poor stability on the slope (Ryan et al., 2021).

Estimation of the initiation and runout of landslides in sensitive clay is crucial for establishing maps of landslide hazard and risk in our communities. The use of the Material Point Method (MPM) to analyse the stability of slopes and their post failure response in sensitive clays is a rapidly growing area of interest for both academics and practitioners (e.g., Yerro et al., 2016; Tran and Sołowski, 2019; Dong et al., 2020). The purpose of the paper is to investigate the initiation and runout behaviour of the Gjerdrum landslide using the MPM.

2 THE 2020 GJERDRUM LANDSLIDE, NORWAY

2.1 *Landslide triggering and development*

At approx. 4 a.m. in the morning of 30th December 2020 a large quick clay landslide was triggered at Ask in the municipality of Gjerdrum, Norway (Figure 1). The release area was approx. 600 m wide and 300 m long, giving a total volume of approx. 1.3 million m^3 (Ryan et al., 2021). The runout distance was approx. 2 km, and the thickness of the slide debris deposited in the lower part of the runout area was approx. 10-12 m.

Analysis of the Gjerdrum landslide (Ryan et al., 2021) shows that the triggering factor was most likely erosion in a creek running through the area (Figure 2), along a known quick clay zone. The erosion occurred at the foot of a 30 m high clay slope with assumed low static stability prior to the event (profile 1, Figure 1). After the triggering event in the east-west direction, the slide is assumed to have developed retrogressively in a counter-clockwise direction, finally reaching the populated area in the north (Figure 1). In this phase several houses were taken by the slide, resulting in a total of 11 fatalities including an unborn child.

After the main landslide event on December the 30th 2020, several afterslides occurred. In particular, the North-Eastern part of the landslide experienced a number of consecutive landslides between July and September 2021.

An important feature of the landslide is the fact that the propagation started out in the East-West direction, before rotating and propagating in the North-South direction. Increased focus on potential sideways retrogression should be a major point of learning from the Gjerdrum landslide for future risk mapping in quick clay areas, as well as increased attention to erosion protection in known hazard areas. A relatively modest mitigation measure in the release area would probably have prevented the initial failure that resulted in the development of the disastrous landslide (DiBiagio et al., 2022).

2.2 Stratigraphy and geotechnical properties of Gjerdrum clay

Extensive geotechnical ground investigations have been conducted after the landslide including 160 borepoints covering areas both inside and outside the landslide (DiBiagio et al., 2021; Hovind et al., 2021; Reutz and Heyerdahl, 2022). Total soundings or rotary pressure soundings have been conducted in all borepoints, CPTU in most, and in 57 borepoints intact samples have been extracted.

The stratigraphy in the area of the landslide consists of a stiff top layer of dry crust approx. 2-3 m thick and a clay layer with variable thickness overlaying a layer of quick clay (i.e. clay with remoulded shear strength < 0.5 kPa, according to NS8015). In some areas a thin layer of glacial till is found above bedrock. In most of the release area of the landslide both the till layer and the bedrock is found to be deeper than the slip surface, hence these layers did not affect the landslide triggering directly.

The active, undrained shear strength of the clay (quick and non-quick) is subject to spatial variability. However, it is generally seen to be quite high (between 40 and 60 kPa) and often pseudo-constant in the upper 5-12 m, for thereafter to increase with depth. The measured remoulded undrained shear strength of the quick clay from the fall cone test ranges between 0.1 and 0.5 kPa, whereas the measured remoulded undrained shear strength of the non-quick clay ranges between 2 and 10 kPa.

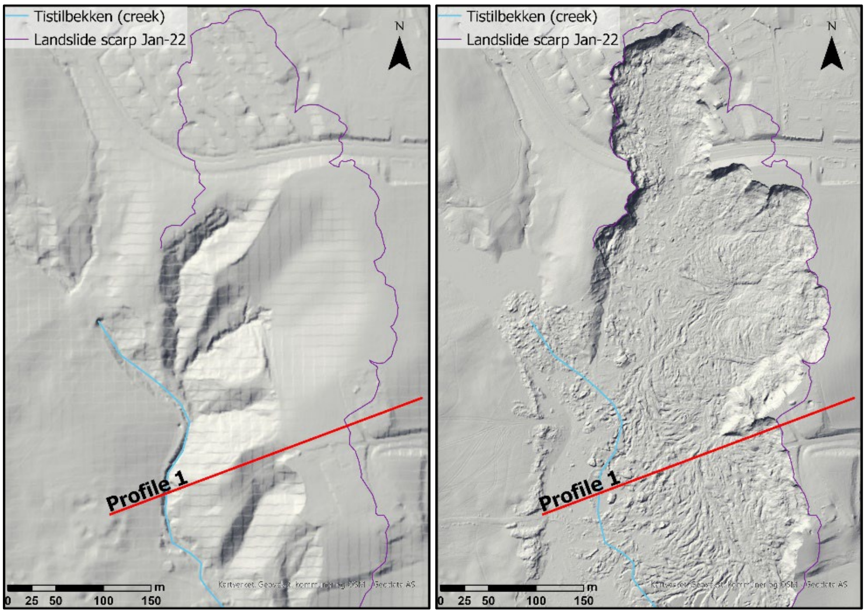

Figure 1. Area affected by the quick clay landslide at Gjerdrum, Norway that occurred the 30th of December 2020. Left: terrain before the landslide event. Right: terrain in January 2021, a few days after the main event. The purple line shows the landslide scar after the last after-slide, which happened in January 2022. Profile 1 is used for stability calculations with the MPM method.

3 MODELLING OF THE GJERDRUM LANDSLIDE

Simulating the runout behaviour of a landslide requires a numerical approach that can model large deformation during the computation process. The MPM provides an efficient tool to solve large displacement problem, which discretizes the problem domain into a series of material points that carry all information (soil properties, strain, stress and state variables) for large deformation analysis. The background mesh is fixed and used to update the information (Soga et al. 2016). In this study, the MPM is adopted to model the runout behaviour of the Gjerdrum landslide, and is implemented based on the open-source MPM software Anura 2022 (http://anura3d.com).

3.1 MPM model

A 2D plane-strain MPM model (Figure 2) is constructed based on the cross-sectional profile (shown as Profile 1 in Figure 1) at the triggering event in the east-west direction of the Gjerdrum landslide. The triangle background mesh was set with a sufficiently large domain to cover the landslide runout region. The element size of the slope body is set as 1.8 m and each element is discretized into 3 material points. In this model, there are roughly 10000 elements and 27000 material points in total. The bottom of the slope is fixed in all directions and the lateral sides are fixed in the horizontal direction.

In the numerical model, the erosion is modelled through reducing the undrained shear strength of the block at the creek at the foot of the slope to 0.1 kPa as shown in Fig. 2. The block size is around 6 m × 2 m, assumed based on Ryan et al. (2021). The soil layers along the depth are named, respectively, dry crust, clay 1, quick clay, clay 2, and till. Table 1 presents the soil parameters of different soil layers adopted in this study, which were derived from the laboratory tests and in-situ piezocone tests (CPTU) (DiBiagio et al., 2021; Hovind et al., 2021). The undrained shear strength of each soil layer is first considered as the average value. The effect of spatial variability of the undrained shear strength will be discussed later.

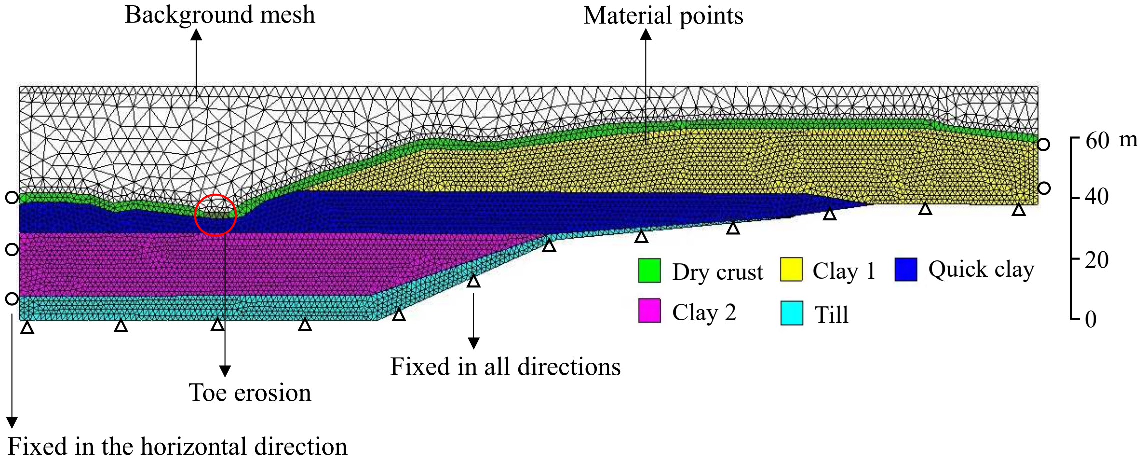

Figure 2. Background mesh, material points, boundaries and soil layers of the Gjerdrum landslide (Profile 1 in Figure 1) based on MPM

Table 1. Soil parameters used in the MPM model

Soil layer	Dry crust	Clay 1	Quick clay	Clay 2	Till	Toe erosion
Soil density (kg/m^3)	1980	1920				1980
Young's Modulus (kPa)	10000					
Poisson's ratio	0.3					
Peak undrained shear strength (kPa)	/	50	60	70	/	0.1
Remoulded undrained shear strength (kPa)	/	10	0.5	/	/	/
Softening parameter	/	20	7	/	/	/
Drained friction angle (°)	32	/	/	/	/	/

3.2 *Strain softening*

The strain softening behaviour of clay and quick clay in this region is considered in the numerical simulation to capture the progressive failure of the landslide. In the MPM simulation, the strain softening model with Mohr-Coulomb failure criterion is applied to the Clay 1 and Quick clay layers. The variation of the undrained shear strength with plastic shear strain is described based on the following equations (Yerro et al., 2016):

$$c_u = c_{ur} + (c_{u0} - c_{ur})e^{-f\varepsilon^P} \tag{1}$$

$$\varepsilon^P = \sqrt{\frac{2}{3}\delta_{ij}^P\delta_{ij}^P} \tag{2}$$

where c_u is the undrained shear strength, c_{ur} is the remoulded undrained shear strength, c_{u0} is the peak undrained shear strength, f is the softening parameter, ε^p is the plastic shear strain, and δ_{ij}^p is the deviatoric part of the plastic strain tensor. The peak and remoulded undrained shear strength of clay 1 and quick clay are shown in Table 1. According to triaxial test results, the softening parameters of the Clay 1 layer and the Quick clay layer are fitted as 20 and 7, respectively, as shown in Figure 3. The elastic model is applied to the till layer and the basic elasto-plastic model with the Mohr-Coulomb failure criterion is applied to the Dry crust and the Clay 2 layers.

4 RESULTS OF LANDSLIDE RUNOUT ANALYSES

Figure 4 plots the initial displacement of the landslide at the physical time of 2 s after the initial erosion failure.

As noticed in this figure, the erosion block is extruded out by the adjacent soils and two slip surfaces with irregular shapes develop. The major part of the shallow slip surface follows the bottom of the quick clay layer and the deep slip surface goes through the entire slope body. The largest total displacement is about 4 m at the toe of the slope where erosion occurs. Figure 5 shows the shear strain at different physical time periods after the erosion to demonstrate the runout failure progress of the landslide. A through-going shear band propagates horizontally in the quick clay layer and the typical progessive failure can be observed. The simulation results suggest that the toe erosion initiates the failure nearby the slope toe and then the reduction of the lateral support triggers the failure of the subsequent soil regions.

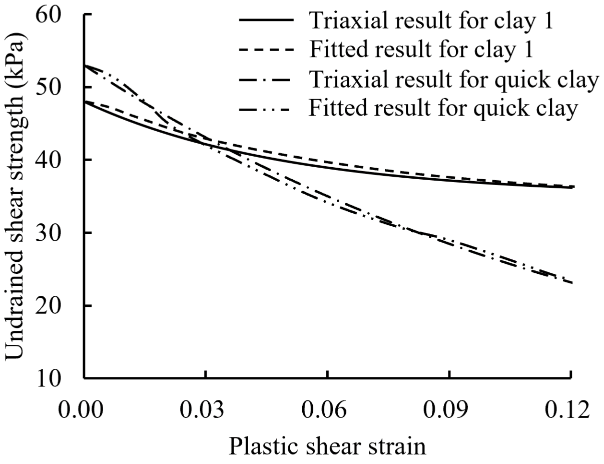

Figure 3. Calibration of strain softening parameters of the Clay 1 layer and the Quick clay layer based on traxial tests

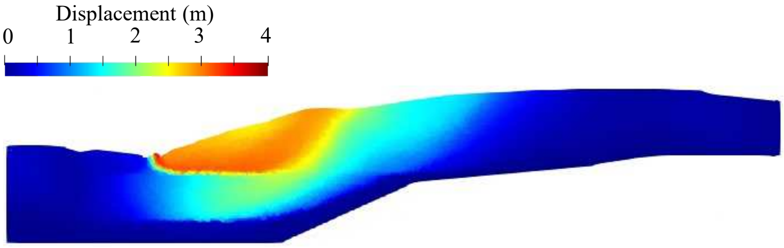

Figure 4. Initial displacement of the landslide

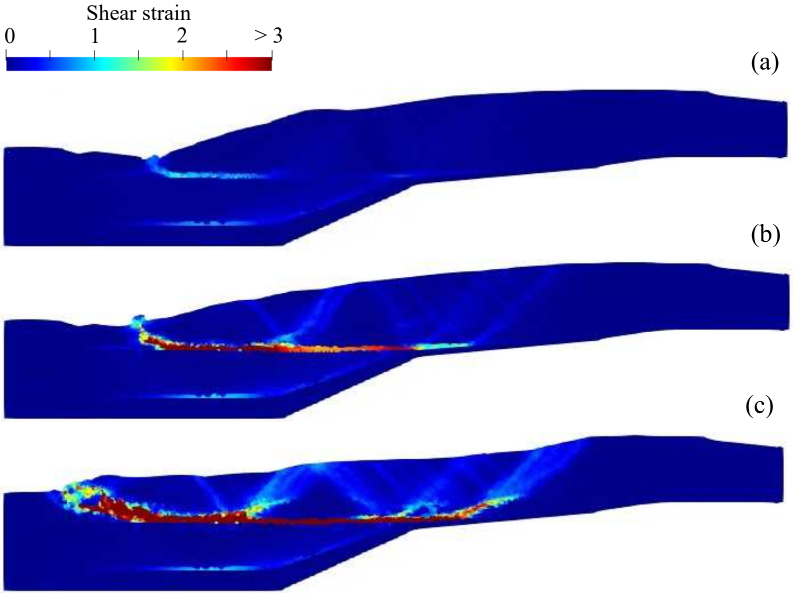

Figure 5. Shear strain of the landslide at different physical times: (a) 2 s, (b) 4 s, and (c) 8 s

4.1 *Effect of the softening parameter*

The softening parameter affects the undrained shear strength of the soil during the landslide failure, which subsequently affects the runout behaviour. Figure 6 compares the displacements of the landslide at the physical time of 8 s when the softening parameters of the quick clay are, respectively, 7 and 20. The comparison results suggest that as the value of softening parameter increases, the runout and retrogression distances both become more significant. A high value of the softening parameter results in rapid reduction of the undrained shear strength, which leads to a larger extent of the landslide runout.

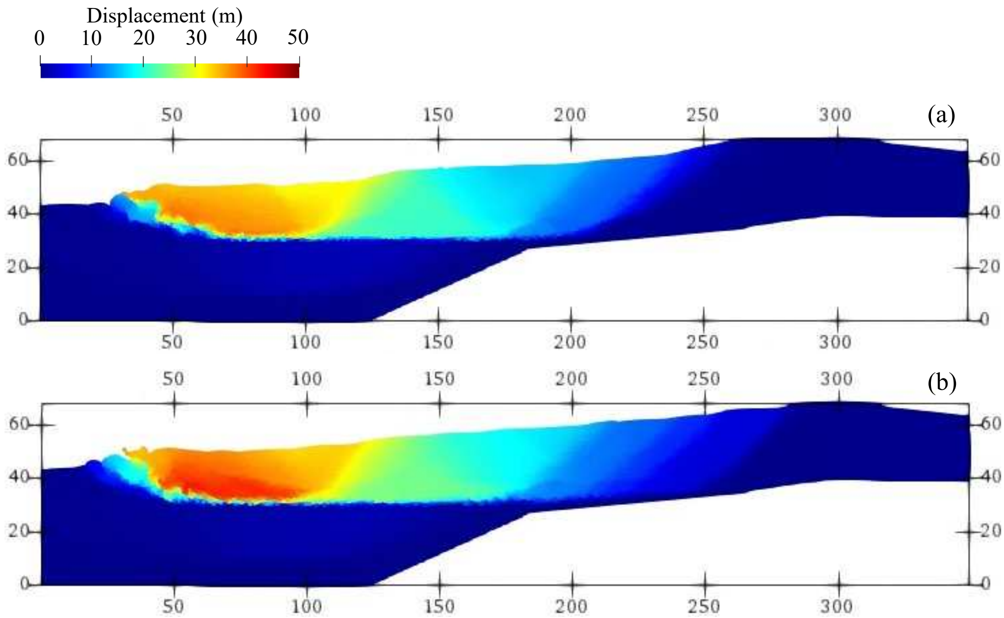

Figure 6. Displacement of the landslide at the physical time of 8 s for different softening parameters of quick clay: (a) 7, and (b) 20

4.2 *Effect of spatial variability of the undrained shear strength*

The in-situ CPTUs indicate that the undrained shear strength has a strong spatial variability both in the horizontal and vertical directions, depending on soil depth and overconsolidation ratio. Utilizing the CPTU results, the quick clay layer is divided into three layers for an improved simulation. The initial undrained shear strength in each of the three layers is constant with depth, with respectively 55, 60, and 65 kPa. The corresponding softening parameters were, respectively, 7, 4, and 1. Other conditions are the same as those in the previous simulation. Figure 7 compares the initial displacements of this simulation and the previous simulation (Figure 4(a)). It is observed that the calculated displacement from the previous simulation is larger. The location and shape of slip surfaces in these two simulations are also different. For further comparison, Figure 8 plots the developed shear bands in these two simulations. The shear band is shallower in the simulation case considering the strength variation, and the resulting runout distance is also smaller. This is mainly due to the lower soil layer having a higher shear strength, which reduces the spread of the landslide and raises the shear band location to the middle of the quick clay layer. The analysis matches the sliding surface interpreted from the in-situ CPTUs. These analyses illustrate that the spatial variability of the soil can affect the runout behaviour of the landslide.

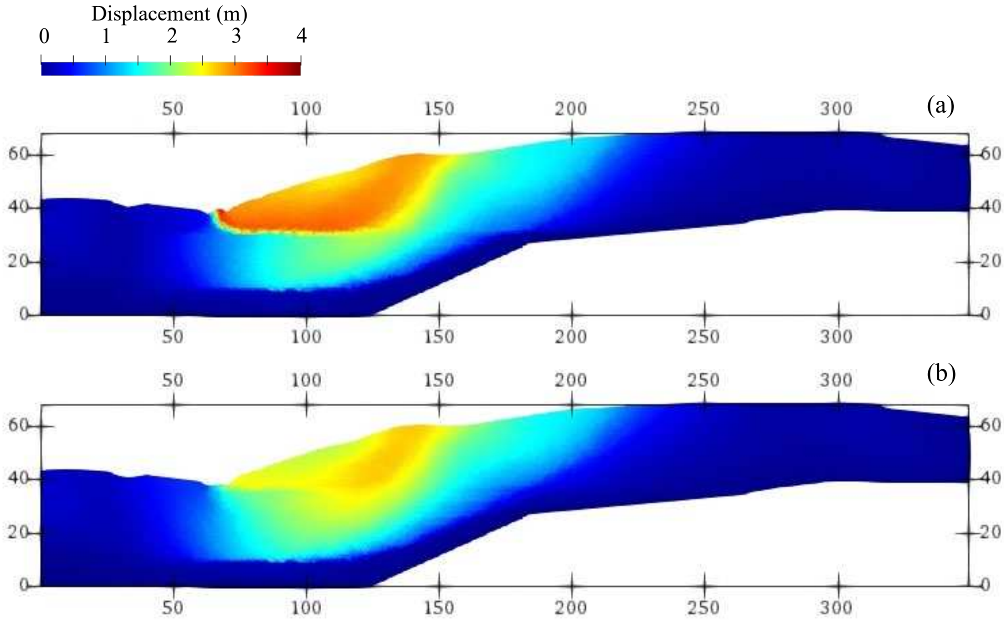

Figure 7. Initial displacement of the landslide for different distributions of undrained shear strength in the quick clay layer: (a) constant value, and (b) variation along the depth

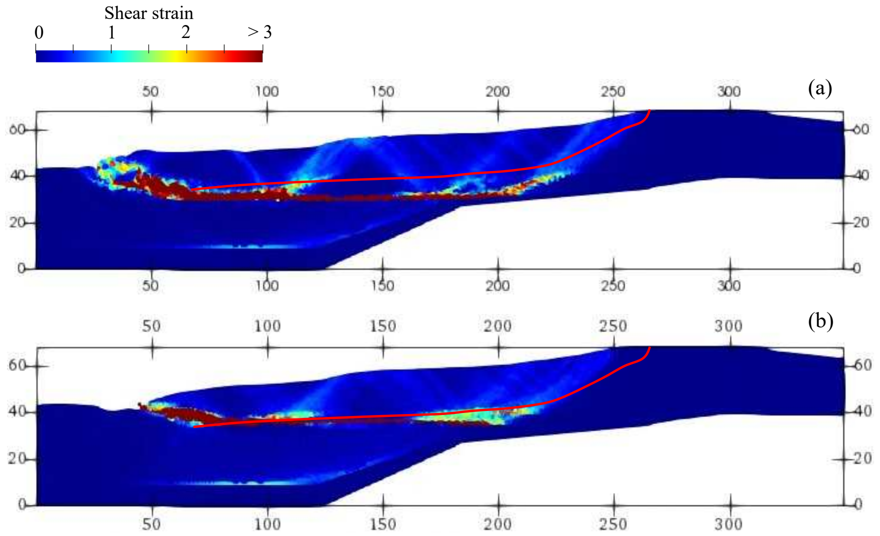

Figure 8. Shear band of the landslide for different distributions of undrained shear strength in the quick clay layer: (a) constant value, (b) variation of shear strength with depth. Red curve is the sliding surface interpreted from the in-situ CPTUs

5 CONCLUSIONS

The initiation and post-failure behaviour of landslides in sensitive clays is of great significance for the hazard zoning and for the risk management. The paper presents MPM-based simulations to back calculate the initiation and progressive failures of the Gjerdrum landslide.

The simulations gave a reasonably good back-calculation of the initiation and progressive failures for a cross-section of the Gjerdrum landslide. A larger value of the softening parameter in the Mohr-Coulomb softening model results in a larger runout extent of the landslide. The variation of the shear strength induces the change of the shear stress in the failure surface during the progressive failure and provide a more realistic sliding surface as observed in the field.

The application of the MPM for modelling the complete quick clay landslide already provides promising results. The challenge resides in finding the representative soil parameters (the peak and residual undrained shear strengths, the remoulding rate) to use in the numerical analyses, and also the spatial variation of these parameters. The strain rate dependency of the undrained shear strength is also a crucial factor for the prediction of progressive failures in sensitive clays.

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