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Microstructural observations of shear zones in sensitive clay

Anders Samstad Gylland [a,*], Håkon Rueslåtten [b], Hans Petter Jostad [a,c], Steinar Nordal [a]

[a] Division of Geotechnical Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[b] Lithicon, Trondheim, Norway
[c] Norwegian Geotechnical Institute, Oslo, Norway

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ABSTRACT

The present work assesses the structure and evolution of shear zones in sensitive 'quick' clays from the initiation to the well-established state. This assessment is done by utilizing laboratory and small scale field experiments combined with the analysis of thin sections in light microscopy and SEM. High resolution X-ray tomography ('micro-CT') is also applied. In combination, detailed 2D and 3D visualization of the shear zones is achieved. Shear zones are suggested to be formed in mm-thick continuous fields of displacement. With increasing shear displacement, sets of micron-sized minor shears develop within the main shear zone. These initiate, terminate and merge both in the plane and out-of-the-plane directions. The minor shears are characterized by distinct particle reorientation where the flaky clay particles and mica grains are aligned parallel to the direction of shear. A porosity reduction is observed in the minor shears. This is a direct observation of material contractancy and implies migration of water from the shear zone into the undisturbed matrix. The width of the main shear zone is considered to be related to the applied rate of shear while the minor shears have a width determined by the micro-texture of the sediment. The observed multi-scale structure of the shear zones, which is governed by complex inner mechanics, is challenging the 'smooth shear zone' concept that is commonly applied in numerical simulations. This is motivating a further improvement of such tools and the testing of other types of clay sediments.

1. Motivation and scope

Sensitive marine clays in Scandinavia are causing challenges when dealing with construction works and evaluation of slope stability. These clays display strain softening behaviour and have a remoulded shear strength that in extreme cases can be less than 0.1 kPa. Because of these properties, landslides in these clays tend to develop from a limited initial failure to cover large areas of terrain by a progressive failure development. The modelling of stability and failure evolution in these sediments requires input on the failed state of the material, including properties of the shear zones. In the simulations of Bernander and Olofsson (1981), Andresen and Jostad (2004) and Grimstad and Jostad (2012) the kinematics of the shear zone is assumed to be either a smooth shear band or a displacement discontinuity. Case records of slope failures in sensitive clays indicate that the final configuration of a shear zone at large deformations resembles a pure slip surface (e.g., Jakobson, 1952; Larsson and Jansson, 1982; Geertsema et al., 2006). The processes at hand in the stages of early development of a shear zone are to a less extent described.

The present work aims at providing deeper insight into the failure mechanisms of soft sensitive clay. The focus is placed on describing and analyzing shear zones from the initiation to a well-established state by utilizing microscopy techniques. This includes features like structure, thickness and evolution as well as sliding resistance. The study is performed as a combination of laboratory and small scale field experiments.

2. Sensitive clays and shear zones

2.1. Sensitive clays

During the last glaciation of Scandinavia about 10,000 years ago, the fast transportation of muddy melt water into a marine environment caused a separation of sediment particles according to their grain sizes. However, the silt and clay particles are flocculating in the salt water, which causes a poor sorting of these particle sizes. Thus, the silt and clay is deposited as extremely porous floccules and form sediments with high porosity (40–60%). The platy shaped phyllosilicates are strongly bonded in an edge to surface 'card house structure', stabilized by strong van der Waals forces. As a consequence of the rebound of the country when the glaciers melted away, the marine clays were exposed to meteoric water. The fresh water slowly infiltrated the clays and diluted the salt pore water. This caused an expansion of the 'diffuse double layer', whereby the repulsive electrostatic forces on the mineral surfaces finally counter-balanced the van der Waals attractive forces. In this situation, the clay is in a state which is referred to as 'quick'; i.e., just

* Corresponding author.
E-mail address: anders.gylland@ntnu.no (A.S. Gylland).

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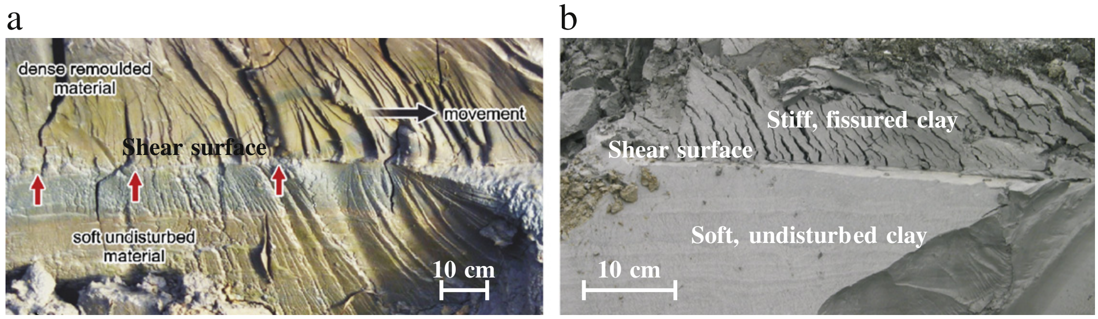

Fig. 1. Shear surfaces from (a) The Mink Creek landslide, Canada 1993 (reprinted from Geertsema et al., 2006, Copyright (2006), with permission from Elsevier); (b) a prehistoric landslide in Buvika, Norway (photo: Louise Hansen).

a small mechanical distortion can lead to a collapse of the 'card house structure' causing a liquefaction of the clay due to the excess pore water (Rosenqvist, 1953; van Olphen, 1977).

Sensitive clay displays strain softening behaviour which is not mainly attributed to a change in material properties like friction angle and cohesion. Instead, the mechanisms are related to compaction or contraction. The material is loosely packed and upon shear failure the particle texture starts to collapse with a simultaneous reduction in porosity. This generates increased pore pressure in the excess pore water, which for undrained conditions reduces the shearing resistance of the clay as the effective stress state is forced to move down along the Mohr–Coulomb failure line. Section 3.1 includes experimental examples of this behaviour.

2.2. Shear zone formation in sensitive clays

Shear zone formation in sensitive clays is related to material instability and strain localization caused by the strain softening behaviour. Strain localization is a topic of comprehensive research where some of the classic work includes Drucker (1951), Hill (1958), Thomas (1961), Mandel (1964) and Rudnicki and Rice (1975). Upon strain localization, the shear zone is presumably where the structure collapses and where the excess pore pressure develops. The outside material unloads elastically with no pore pressure generation. This situation holds a potential to cause internal gradients of pore pressure. The corresponding local consolidation process in the vicinity of the shear zone is seen to have an impact on the global softening behaviour of the material; increased brittleness for increased rate (Gylland et al., accepted for publication). Hence it is important to understand the process of structural change and pore pressure generation in the shear band to properly model the material response of sensitive clay in the post-peak range.

2.3. Available laboratory studies of shear zones in clays

Several researchers have studied shear zones in various laboratory setups on non-sensitive clay. Morgenstern and Tchalenko (1967a) utilized a thin sectioning technique to study the evolution of shear fractures in reconstituted kaolin using a direct shear box. A set of simple clay-cake experiments were performed by Wilcox et al. (1973) to study the evolution of shear features along faults in the context of wrench tectonics. Mandl et al. (1977) examined shear zones in a large span of granular materials using a ring shear device and thin sections. The use and applicability of various fabric viewing techniques such as Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM) and thin sections in a polarized light microscope for studying shear features in reconstituted clay were discussed and compared by McKyes and Yong (1971). The same span of techniques was applied by Hicher et al. (1994) to study shear bands in reconstituted kaolin and bentonite.

Concerning laboratory studies of sensitive clay, Pusch (1970) examined shear bands in Swedish quick clay using TEM. He found distinct particle reorientation and breakage of inter-particle links in the main shear zone. Outside, the structure was mainly preserved only with limited link distortions. A set of biaxial tests on Norwegian quick clay from the same site as used herein was performed by Thakur (2007). The work focus on the issues of strain localization and a shear zone thickness in the range of 2–3 mm is reported.

2.4. Field observations of shear zones in clays

When it comes to field observations of shear zones in sensitive clays, there are some direct and indirect observations available. The report from the Surte quick clay landslide in Sweden, 1950 (Jakobson, 1952), showed a reduction in shear vane resistance in a distance ± 1 m from the assumed sliding plane and increased pore pressures ± 3 m from the same plane. Similar observations were made after the Bekkelaget quick clay landslide, 1953 Norway (Eide and Bjerrum, 1954) and the Båstad quick clay landslide, 1974 Norway (Gregersen and Løken, 1979). Another interesting observation from the Surte investigation was the presence of a highly disturbed zone of about 15 cm thickness in one of the piston core clay samples taken at the assumed failure plane. Lefebvre (1981) measured a reduction in water content of the failure surface from a landslide in Canadian sensitive clay. Geertsema et al. (2006) studied the Mink Creek quick clay landslide, 1993 British Columbia, Canada. The shear surface was visible at several locations and its thickness varied in size. A picture from a thin sliding surface from this landslide is included in Fig. 1a. Studies of clay slide deposits in Norway were performed by Hansen et al. (2007) and Solberg et al. (2008). They showed amongst others several examples of possible shear zones associated with large relative deformations. The thickness and structure of these were in mm-scale or cm-scale depending on sediment characteristics and failure mechanism. An example from a sliding surface as observed in Buvika, Norway, is included in Fig. 1b. The field data available from shear zones in stiff clay suggests a shear zone thickness in the order of 5–15 mm (Morgenstern and Tchalenko, 1967b; Skempton and Petley, 1967).

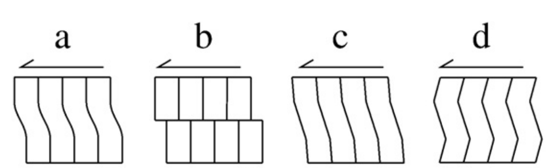

Fig. 2. (a) Smooth shear band; (b) Displacement discontinuity; (c) Normal kink band; (d) Reverse kink band.
Adapted from Morgenstern and Tchalenko, 1967a.