#115 Slope instrumentation and unsaturated stability evaluation for steep natural slope close to railway line

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Introduction

- An IC railway project in Eastern Norway involves a new track next to an existing line (Fig. 1). West of the track, the natural slope is steep, in part >45˚.
- The area west of the slope contains cultural heritage objects as church, old graveyard etc. Physical slope stabilizing measures should preferably be avoided!
- Safety requirements for new railways are given as nominal safety factors (e.g. FS≥1.4). For natural slopes, probability of failure could be more relevant.

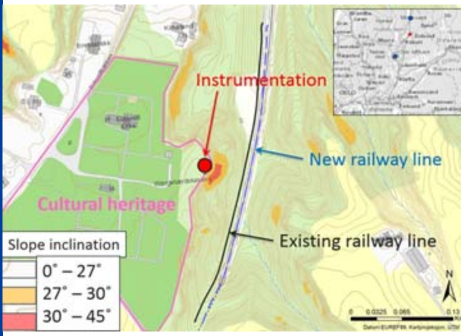


Figure 1: Study area. A new track is planned east of the existing line. The natural slope west of the existing track must still be considered

Ground conditions

- A ~10 m layer of sand/silt lies on top of firm marine clay extending to large depth (Fig. 2). The slope is 25-30 m high. The upper slope (the sand/silt layer) is the concern of this paper. Deep-seated failure modes in clay are not discussed.

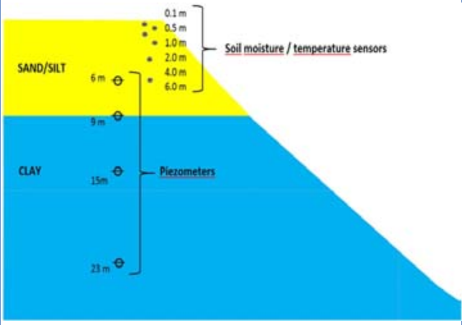


Figure 2: Main soil layering. Silt/sand above marine clay. Slope instrumentation indicated

- GSD analysis was performed for representative samples from the sand/silt layer (Fig. 3). Gradual change in main grain size fractions gives challenges with characterizing the slope for modelling purposes.
- Water content during sample opening was measured, and increases with depth. Gravimetric water contents close to 30% from 7 m depth indicate that the soil here is fully saturated (Fig. 3).

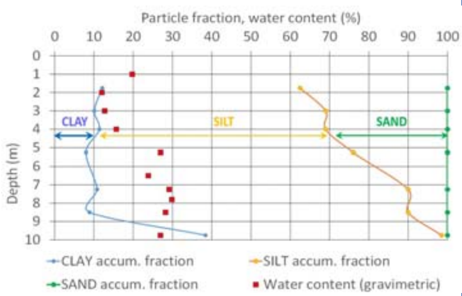


Figure 3: Grain size distribution (GSD) analysis and water content at sample opening for samples from the sand and silt layer

Retention curves and shear strength properties

- Main drying retention curves were measured on compacted specimens in a pressure plate apparatus. Suction was applied by axis translation (Hilf, 1956).
- Curve-fitting (van Genuchten, 1980) was used to produce continuous retention curves (Fig. 4).
- Although GSD changes gradually with depth (Fig. 3), retention curves for Batch1-3 (depths 1.5-6 m) are comparatively equal. For Batch4 (6-7 m) the curve shifts to larger water content at given suction values.
- The sand/silt layer was consequently simplified as two distinct soil layers in the seepage analyses.

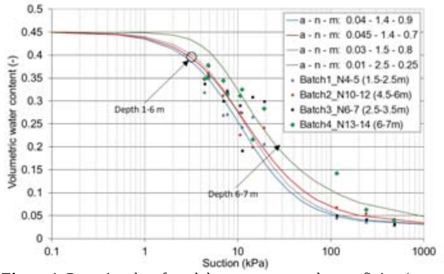


Figure 4: Retention data from laboratory tests and curve fitting (van Genuchten, 1980)

- One saturated triaxial test (intact specimen) was performed (Fig. 5), and dilated heavily during shearing. Effective friction parameters of $\phi' \geq 35°$ and $c' \sim$ 8-10 kPa seem appropriate, but are not easily determined from only one test.
- Saturated hydraulic conductivity k_{sat} = 2.4E-06 m/s.
- Two constant water content triaxial tests were performed (w = 20 and 21.5%, equal void ratio as intact test; w_{sat} = 30.5%). Results (Fig. 5) indicate increased shear strength for unsaturated tests.
- Baded on the retention curve (Fig. 4), Vanapalli (1990) gives an estimated increased unsaturated shear strength of approx. 5 kPa for $w \sim$ 20 %.

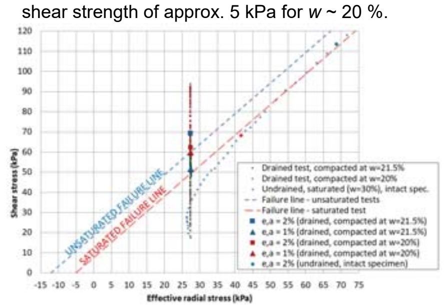


Figure 5: Failure lines interpreted from triaxial test results on saturated and unsaturated specimens

In situ slope instrumentation

- Hydrogeological conditions were investigated by soil moisture and ground temperature sensors installed in the sand/silt layer at 6 depths from 0.1 m to 6 m in early June 2016 (Fig. 2). Data were compared with infiltration data from rainfall and snowmelt.
- Piezometers were installed at depths 6 m, 9 m, 15 m and 23 m. The two deepest piezometers are within the clay layer, while the two upper piezometers are in the sand/silt layer.

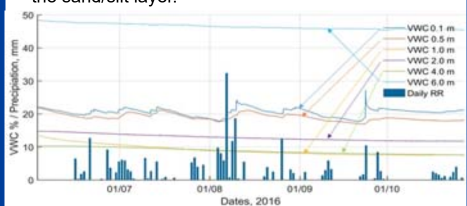


Figure 6: Volumetric water content and daily rainfall, Jun-Oct 2016

- Soil moisture down to 4 m lies far below saturated water content values (V_{sat} ~ 50 %). The slope responds very little to rainfall scours, except for the two upper sensors (Fig. 6).
- At 6 m the soil is close to saturation, which is verified by piezometer measurements (Fig. 7). At 6 m the piezometer measured a small suction (< 10kPa).

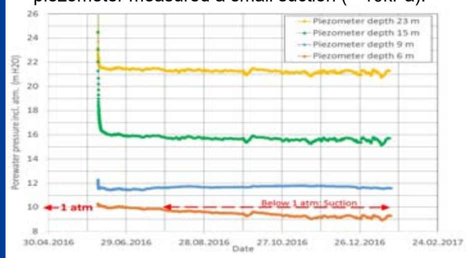
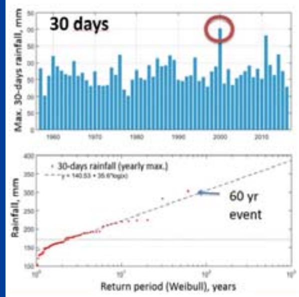


Figure 7: Piezometer data, Apr 2016 – Feb 2017

Rainfall and slope stability

- Critical rainfall was based on weather statistics from nearby meteorological stations (Fig. 8). The highest monthly rainfall occurred in year 2000.



Date	mm
27-11-2000	303.1
06-09-2011	282.4
03-11-2014	224.6
13-11-1976	223.5
11-09-1988	221.8
27-07-1960	219.9
12-09-1994	215.6
05-09-1985	213.2
25-08-1989	209.6

Figure 8: Frequency analysis, 30 days duration of rainfall for the 60-year period 1957-2016

- Slope stability analysis was performed for normal rainfall conditions (Fig. 9). The same geometry was analysed for daily rainfall data from year 2000. Through 73 days of rainfall, the theoretical safety factor was reduced to FS = 0.97, i.e. a reduction of approx. 10 %. However, the slope did not fail in year 2000, in the most critical year ever recorded.

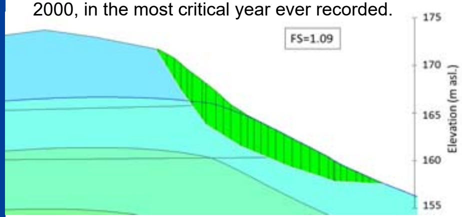


Figure 9: Slope stability results

Conclusions

1. The study indicated, through combined use of in situ instrumentation, laboratory results, slope stability analysis and historic rainfall data, that the assumed risk of slope failure is low (P < 1/100 pr. year).
2. Physical slope stability measures in the upper slope were therefore not considered necessary, and partial destruction of the cultural heritage site was avoided.

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