

BACK ANALYSIS OF A RAINFALL INDUCED LANDSLIDE, EIDSVOLL, NORWAY

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Landslides in Quaternary soils are common in Norway and constitute a substantial risk to society. Landslides can be of several types: Debris flows occur as the result of erosion and entrainment. Smaller local landslides described as rotational or translational slides are frequently released by infiltration from rainfall and snowmelt, including effects of ground water flow. Many landslides occur on steep slopes that depend on unsaturated conditions to remain stable. This paper presents a case study of one landslide occurring in the autumn of year 2000, during which Eastern Norway received unusual amounts of rainfall. Slopes in the area are stable for normal annual rainfall. For rainfall during the autumn of year 2000, with an estimated value of about 240 mm in 30 days based on gridded values from near-by metrological stations, infiltration of surface water resulted in a gradual decrease in slope stability, leading to slope failure. Long-term rainfall triggered numerous landslides in the region, most of them shallow, involving mostly intermediate soils (some shallow landslides were also observed in clay slopes). The case study involves ground investigations including soil sampling and laboratory testing of unsaturated soil properties, followed by stability analyses taking retention properties and unsaturated strength into account. Long-term infiltration is shown to gradually reduce the stability of the actual slope, until critical stability was reached.

Keywords: landslide, unsaturated, rainfall, infiltration, stability, water retention

1. Introduction

Geology in Eastern Norway is dominated by the Quaternary, resulting in varied types of deposits. Sediments may be of glacial, glaciofluvial, lacustrine, fluvial and marine, in addition to anthropogenic origin. In Eastern Norway, marine sediments are found up to ca. 200 m above sea level due to isostatic uplift after the last ice age. Geomorphological processes such as landslides and erosion are active in these deposits and produce colluvium of various origins and compositions. Landslide processes vary in these types of sediments due to differences in hydrogeologic response caused by different soil properties (e.g. retention properties, permeability). The landslide activity in areas with similar deposits varies with different climatic conditions, as annual rainfall changes rapidly from West to East across Norway. Most of the precipitation from Atlantic weather systems is left on the Western side of the mountain range following Norway from South to North, leaving areas East of the mountain range very dry (Heyerdahl and Høydal, 2017), but also vulnerable to intense scours and prolonged rainfall.

2. Stability of natural slopes

Natural slopes may be observed to exhibit larger slope gradients than the effective friction angle ϕ' allows (Heyerdahl, 2016), assuming that cohesion generally is minor in actual soil types. Typically, the upper part of slopes may have inclinations well above 45° indicating that some cohesion, either true or apparent (e.g. due to soil suction), must be present. Reinforcement by vegetation and roots in the top layer may also have a stabilizing effect (Meijer et al., 2015) but is not always an important factor. Documentation of cohesion, true or apparent, is often difficult in granular/intermediate soils, as sample disturbance may result from the chain of processes from soil sampling, transportation of samples to laboratory, extrusion of samples in the laboratory, and sample enclosure in the testing (e.g. triaxial or shear box) apparatus, similar to sample disturbance as described for soft clays (e.g. Lunne et al., 2006). True cohesion existing in the specimen in situ may thereby be destroyed.

3. Risk associated with landslides in intermediate soils

Landslides in intermediate soils are often triggered by infiltration and groundwater flow. Such landslides may have high mobility, and although normally moderately sized, may have energy to cause serious consequences when occasionally hitting vulnerable objects downslope. The mobility of one such slide is illustrated in Fig. 1. For transportation infrastructure, small landslides may often interrupt traffic and cause a direct hazard affecting safety on roads and railways. Occasionally, such landslides hit existing houses and, in some cases, have resulted in the death of persons. Landslide risk is handled differently for different types of infrastructure. For urban planning, safety criteria are based on non-exceedance of annual probability of landslides reaching buildings of different types, with probabilities from 1:100 per year for less exposed buildings, 1:1000 for normal dwellings (typical small houses) and 1:5000 for larger residential developments, schools etc. For roads and railroads, landslide risk is evaluated based on other criteria, such as road class/traffic density, landslide risk per km road etc. For railroads, reduced train speed is used for risk reduction in situations where high intensity rainfall is expected. Temporary road closures are also used, but mostly for roads exposed to snow avalanches. For all these

strategies, understanding release mechanisms for landslides in different geologic and geomorphologic settings, and for different soil types, is of importance.

4. A landslide case study

4.1. Landslide event

An extraordinary rainy autumn in Eastern Norway occurred in the autumn of year 2000 (Jaedicke and Kleven, 2008). The rainfall may be described as long-term, with daily scours for several months, but generally not characterized by extreme short-term scours. One of the many landslides that occurred in the autumn of year 2000, triggered on 21 November 2000, was used as a case study to increase knowledge of the role of unsaturated soil in the stability of natural slopes in Norway. The stabilizing effect of soil suction for a particular slope depends on infiltration and distribution of water content in the ground, because of rainfall intensity, soil layering, hydraulic parameters and effective friction parameters of the soils involved. Infiltration may originate from rainfall or snowmelt, or from surface water during flooding. In fact, not far from the landslide in year 2000 described herein, a sequence of landslides triggered by snowmelt took place in 2018, verifying that infiltration from rapid snowmelt may also release landslides in this region (Heyerdahl and Mathisen, 2025). A map of the landslide area is presented in Fig. 1, illustrating the large mobility of landslides in silty, sandy sediments. A picture is included in Fig. 3.

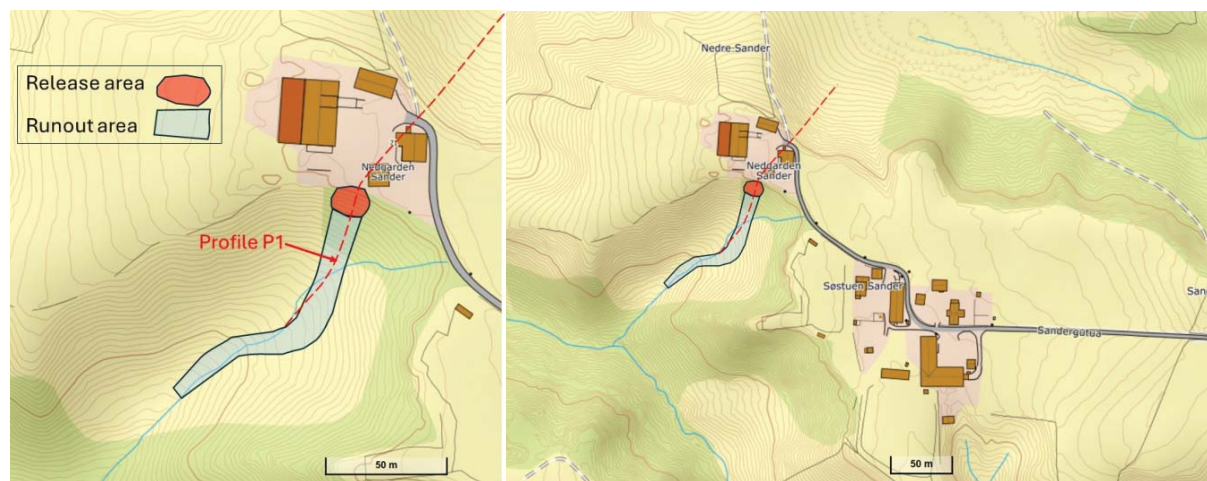


Fig. 1. Left: Detailed situation map with release and runout areas of the November 21 year 2000 landslide. Right: Overview map, showing plateau east of the landslide release area. Position of profile P1 (Fig. 2) shown in red dashed line.

4.2. Laboratory investigation of unsaturated parameters

Water retention of typical layers (sandy silt, silty sand) was thoroughly investigated and unsaturated direct shear tests were performed. Retention curves were measured for specimens of sandy silt and silty sand (Heyerdahl and Pabst (2017)). Direct multi-stage shear tests on intact specimens of silty sand were performed (Heyerdahl, 2016), finding a friction angle φ' equal to 41° . For intact specimens of sandy silt from the landslide area (Heyerdahl and Pabst, 2017), φ' as high as 36.9° was found (Heyerdahl et al, in prep.), while φ' of at least 35° was found in triaxial testing of an intact specimen consisting of 60 % silt, 30 % sand and 10 % clay from the same region (Heyerdahl et al., 2018). These comparatively high values, together with high cohesion determined for investigated samples, in part explain stability of steep slopes under “normal” conditions with suction in shallow soil layers. However, for increasing saturation, slope stability may still reach a critical situation and slope failure can occur.

For unsaturated soils, shear strength depends on soil suction and saturation. Soil suction acts isotropically and thereby gives an addendum to effective stress independent on inclination of shear planes, different than vertical surcharge, where horizontal effective stress is generally only a portion of the vertical stress. Eq. (1) shows how Bishop's effective stress formulation (Bishop, 1959, Bishop and Blight, 1963) incorporates matric suction in Terzaghi's classical effective stress formulation (Terzaghi, 1925).

$$\sigma' = \sigma - u_a - \chi (u_a - u_w) \quad (1)$$

In which σ is the total stress, σ' is effective (Bishop) stress, u_a is air pressure, u_w is pore-water pressure, and χ is a parameter varying with saturation rate. For fully saturated soil, including suction up to the air entry value where water starts to exit the pores, χ is equal to 1, while χ will generally be lower than 1 for partial saturation. As an approximation, χ may be assumed equal to the saturation rate, with a zero value for dry soils. The expression

thereby collapses to Terzaghi's effective stress formulation. When increasing soil suction gradually from a saturated state, a shear strength prediction is based on "Vanapalli's 1st method" in Eq. (2) (Vanapalli et al, 1996).

$$\tau_{peak} = c' + \tan \phi' \cdot (\sigma_v - u_a) + \Theta^{\kappa} \cdot (u_a - u_w) \quad (2)$$

In which τ_{peak} is the shear strength for a set of parameters, σ_v is total vertical stress, $(\sigma_v - u_a)$ is vertical net stress, Θ is normalized water content (between 0 and 1), and κ is an exponent (chosen equal to 2.5). The expression is coherent with Bishop's stress formulation, as effects of soil suction disappear for saturated and dry soil. A shear strength prediction based on Eq. (2) indicates an increase in shear strength by a maximum value of ca. 4 kPa in layers of silty sand at the landslide site, which matches well with the results from laboratory tests (Heyerdahl, 2016). The effect of increased shear stress due to soil suction however drops after the peak value, which is attributed to gradually reduced saturation rate at higher suction. Peak shear strength comes for the maximum value of the product $\Theta^{\kappa} \cdot (u_a - u_w)$ in Eq. (2), i.e. the product of saturation rate (with exponent) and matric suction.

4.3 Slope stability during long-term rainfall

An attempt was made to backcalculate the evaluation of slope stability during the rainy autumn of the year 2000. The daily rainfall was about 8 mm during a period of 30 days prior to the landslide. Rainfall was applied as a boundary condition with stepwise unsaturated infiltration analysis and LEM stability calculations in Seep/w and Slope/w (Seequent, 2025). The calculation profile crosses a terrace (Fig. 1). The soil layering is shown in Fig. 2 together with geotechnical input parameters. For stability analysis, ground water flow from the plateau East of the landslide area is assumed to have minor influence on ground-water level locally where the landslide occurred, as the hydraulic gradient will result in ground water flow towards the steep slopes North/South of the terrace where the landslide occurred. Symmetric groundwater flow across the plateau's centerline is therefore assumed. In the model slope, only half the plateau is therefore modelled, with a vertical no-flow boundary at the model's left edge (Fig. 3). The retention curve's wetting branch for silt was modelled with Eq. (3) (van Genuchten, 1985).

$$\Theta = [1 / (1 + (ah)^n)]^m \quad (3)$$

In which n , m and α are curve parameters ($n=3.513$, $m=0.2936$, $\alpha=0.0819$), Θ is 0.4374 and h is pressure head.

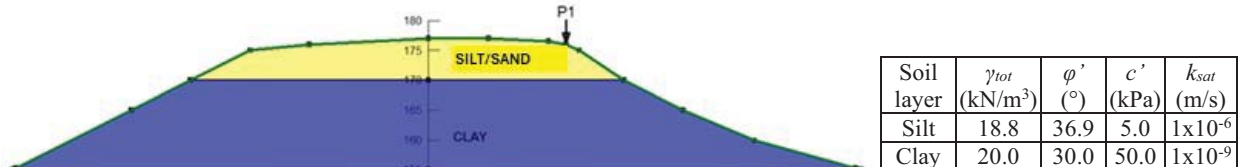


Fig. 2. Model slope and geotechnical input parameters. The top layer consists of silty sand/sandy silt, situated on top of a thick marine clay layer. The position of the landslide 21 Nov. 2000 is indicated in Fig. 1.

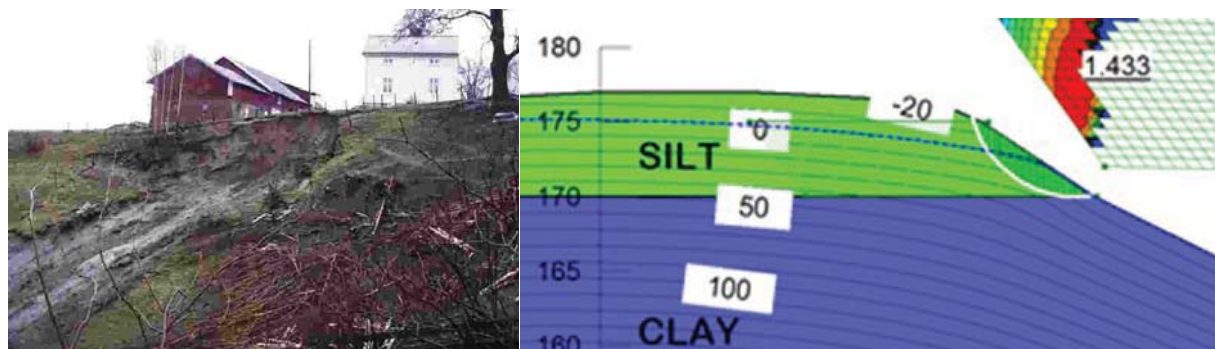


Fig. 3. Left: Landslide 21. Nov. 2000. Right: Calculated stability, profile P1 for initial situation (at start of rainfall).

The soil profile consists of a 5-6 m layer of silty/sandy deposits on top of marine clay that continues to large depth. Assuming silt properties in the top layer, the safety factor (FoS) in profile P2 was calculated for a continuous rainfall of 30 days. The situation at the start of the rainfall is based on average yearly rainfall (ca. 800 mm), distributed over the year. This results in a groundwater surface 2-3 m above the clay layer with suctions up to 20 kPa and FoS equal to 1.43 (Fig. 3, right). From the initial situation, infiltration gradually increases porewater pressure (i.e., reduces suction) in the ground (Fig 4). The FoS drops gradually to a critical value (1.02) in 18 days (Fig. 5). At this moment, the slope is fully saturated, and the stability does not change further for continued rainfall.

4.4. Discussion

The FoS drops from >1.4 to a critical value (1.02) in 18 days from the start of the rainfall, i.e. a little quicker than the landslide was triggered. It should be considered that soil types vary with depth and laterally on the plateau, and the groundwater regime also. A similar analysis to the one above, assuming a top layer of only sand, resulted in the slope still being stable after 30 days of rainfall (Heyerdahl et al, in prep.). This indicates that averaging sand and silt properties may be representative for the slope. Ground investigations in the landslide area show that soils have varying sand/silt fractions and some clay content that may influence retention capacity and hydraulic permeability. Exact geometry of the failed slope is not exactly known (old maps has 1 m grid lines; real geometry before slope failure may have been worse than assumed). With uncertainties as mentioned, the study demonstrates how long-term rainfall resulted in a drastic worsening of the slope stability, where unsaturated parameters play an important role. The key to apply such studies will be to expand the database for soil properties, particularly for unsaturated behaviour, as background for prediction of slope behaviour during rainfall and eventually utilise the knowledge in landslide mapping, landslide warning and risk reduction.

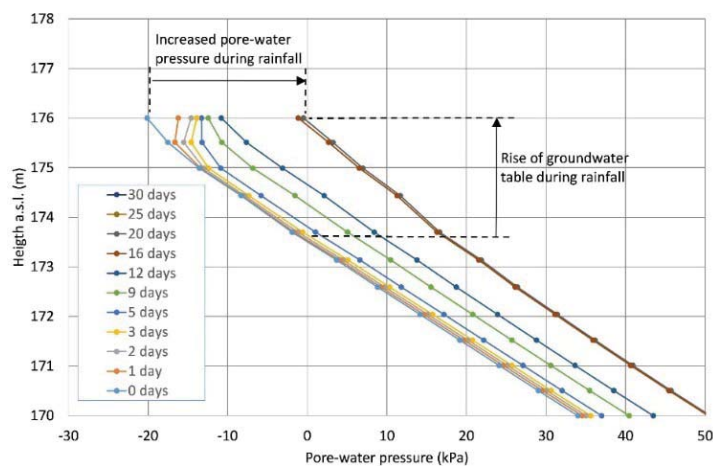


Fig. 4. Porewater development at the top of profile P1. Silt properties assumed for toplayer.

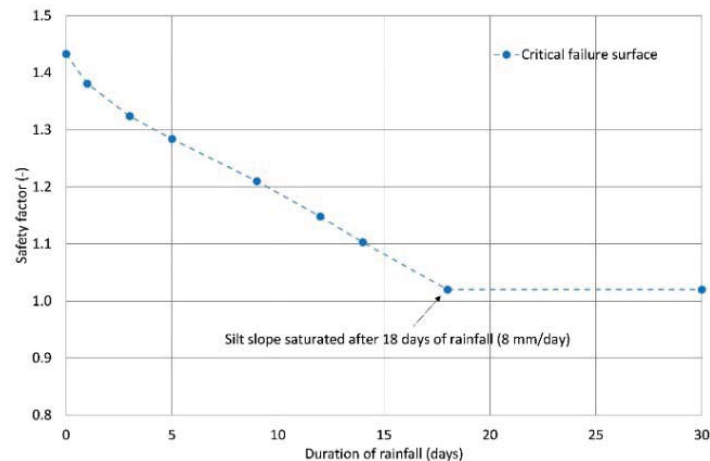


Fig. 5. Right: Development of FoS during the 30 days rainfall.

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