MEASURING STRENGTH INCREASE OF REMOULDED SENSITIVE CLAY FROM THE GJERDRUM LANDSLIDE, NORWAY

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KEYWORDS

Landslide, Sensitive clay, Undrained strength, Remoulded, Reconsolidation

ABSTRACT

The Gjerdrum landslide occurred in 2020 and involved highly sensitive clay (quick clay). After the landslide, a large deposit of slide material remained in the slide area. The remoulded clay initially had very low undrained shear strength, but strength increased due to consolidation, helped considerably by the installation of plastic vertical drains (PVDs). Determination of the strength of the remoulded slide material was vital to design the remediation measures. The objective of this work is to characterise the slide material and examine the changes in index properties over time.

The properties of the slide material are well documented; cone penetration testing (CPTu) and soil sampling were conducted in the slide material at two different times after the landslide. Undrained shear strengths based on fall cone tests and unconfined compression tests are reported in this paper. The undrained shear strength (c_u) increased with time for both testing methods.

1. INTRODUCTION

After the Gjerdrum landslide there remained a large volume of remoulded slide material in the slide area. The slide material in many places had extremely low remoulded strength (quick clay with c_u < 0.5 kPa [1,[2]) and responded to loading in a liquid like manner. This remoulded clay made it difficult to access the slide area and to start remediation measures.

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Given sufficient time and allowing for drainage of water, remoulded clay consolidates and gains strength. This increase in strength must be quantified to design the remediation measures.

This paper aims to characterise the Gjerdrum slide material and show the strength increase with time using results from standard index tests.

2. GJERDRUM LANDSLIDE

Landslide event

In the middle of the night on 30th December 2020, a quick clay landslide occurred at Ask. The town of Ask is located in the municipality of Gjerdrum, approximately 30 km northeast of Oslo, Norway. The landslide killed eleven people, destroyed several homes and significantly damaged local infrastructure.

The slide release area had a length of 630 m and a width of 240 m. In total, the release volume was estimated to be 1.35 million cubic meters. The run-out area of the slide extended 2 km to the south due to the presence of quick clay [3].

Cause of the landslide

The cause of the landslide was later investigated by an independent commission [4]. The landslide was found to have initiated in a tall, steep slope approximately 400 m south of the residential area (Figure 1) and was triggered by erosion in the stream. The initial slide was probably small and triggered a series of larger retrogressive slides that moved up the slope and developed northwards and sideways, eventually reaching the residential area. Much of the slide material consisted of quick clay, and the soil structure collapsed upon failure, becoming liquid flowing out of the slide area.

Mitigation measures

The first mitigation measure was unloading of slope by removing soil from the landslide scarp. When the landslide area was assessed as safe enough to enter and slide debris from houses etc. were removed, plastic vertical drains (PVD) were installed in the landslide area south of the residential neighbourhood. PVDs were installed over an area of approximately 23 000 m^2, depicted in Figure 2, between April to August 2022. The purpose of the PVDs was to speed up consolidation of the slide material.

After installation of PVDs in the landslide area staged counterfills, consisting of crushed stone and clay, were constructed in the landslide area, allowing time for the remoulded slide material to consolidate between stages.

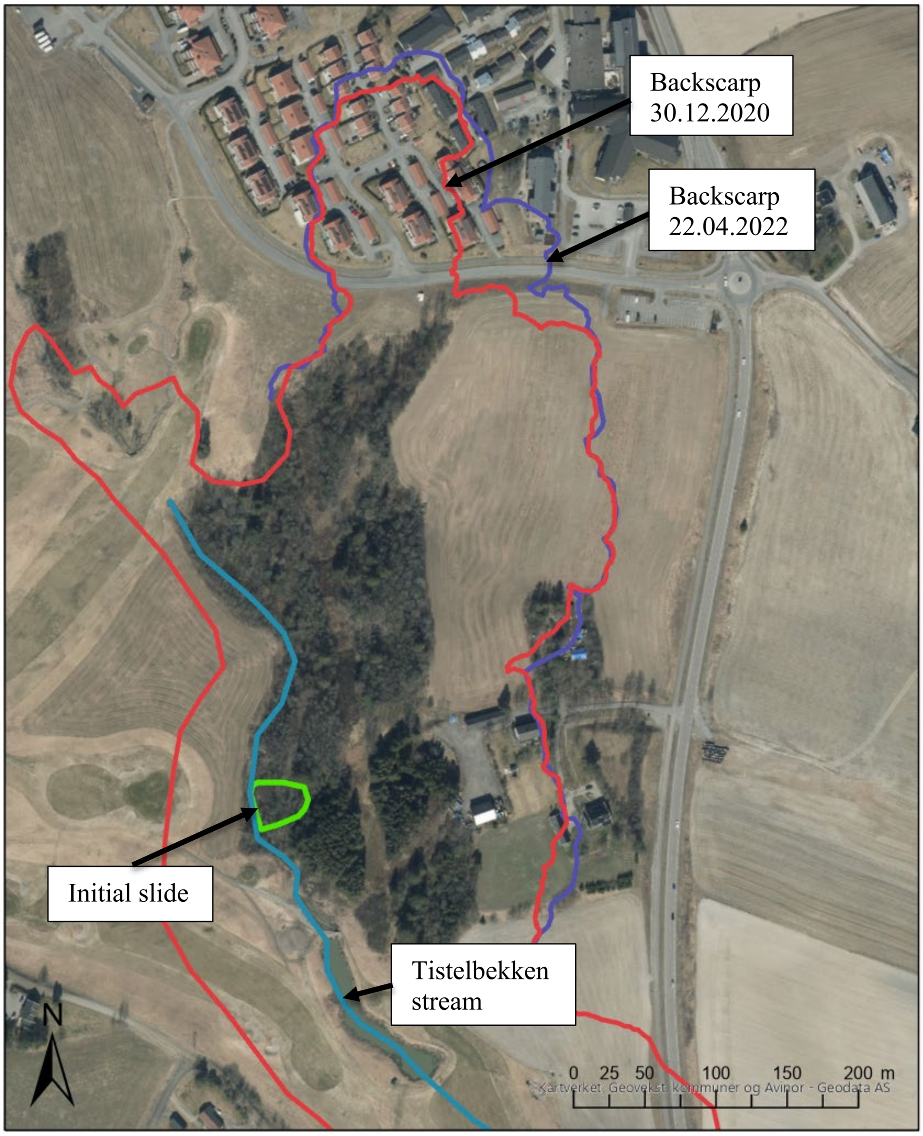

Figure 1. Aerial photograph of the landslide area in 2020 before the landslide occurred (source: Kartverket). The approximate location of the initial (triggering) slide is shown in green. The extent of the backscarp and run-out area on 5th January 2021 is shown in red, and the backscarp on 28th January 2022 is shown in blue. The runout area extends 2 km further to the south; thus, the full extent is not shown here.

Geotechnical site characterisation

The Ask area consists of a thick deposit of marine clay, with an upper layer of dry crust. Some areas have an upper layer of old fill material, either from levelling of farmland or due to the housing developments. Some limited site investigations (SI) had been conducted in the residential area prior to the landslide, but none were conducted in the slope where the landslide was triggered.

Figure 2 presents the area of SI results presented in this paper. Multiple rounds of SI have been conducted [5-[8], both in the surrounding vicinity and in the landslide area itself.

The slide material from the northern and eastern parts of the slide area were of most interest to engineers, as the landslide left tall scarps (up to 15 m) close to the remaining residential areas. The maximum thickness of the slide material in this area was around 10 meters.

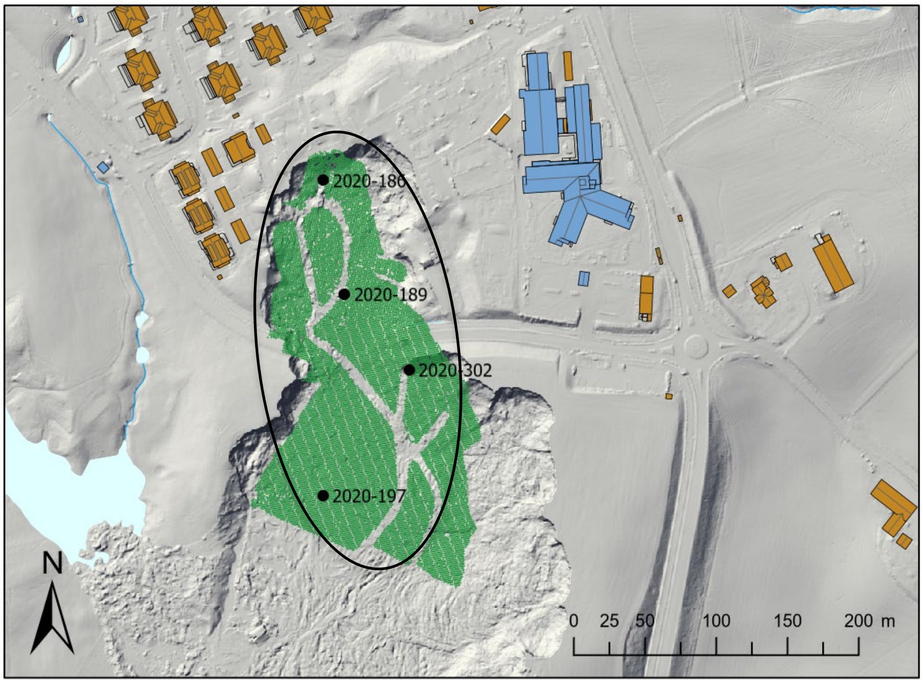

Figure 2. Digital terrain model created from laser scan conducted on 14th January 2021, two weeks after the landslide. The area with site investigation results included in this report is indicated with a black oval. Precise locations are provided for four specific boreholes that are discussed later in this article. Plastic vertical drains were installed in the green area in 2022.

In-situ testing and soil sampling within the slide area were conducted between August 2021 and February 2023. There are large inherent uncertainties in the response of slide material, e.g. how the properties of the remoulded material develops over time, as excess pore pressure dissipates. Changes in the properties of the slide material has been documented by conducting CPT and laboratory testing of the material at the same location at different times. The focus of this article is on the properties of the slide material and how they develop over time, documented with index testing. Results of advanced testing and CPTu will be presented in later publications.

For brevity, only results from slide material are reported in this paper, where slide material is defined as soil that has been moved or remoulded during the landslide event. The slide material is a heterogeneous material that consists of remoulded clay/quick clay, dry crust and some intact blocks of clay/dry crust. The number of site investigations in slide material, within the area indicated in Figure 2 are as follows: 15 total soundings, 26 rotary pressure soundings, 60 CPTu and 17 series of piston samples.

Soil description

Soil samples were described based on visual inspection. The slide material was most often described as:

- clay,
- consistency varies from very soft to firm,
- colour is dark grey,
- often described as silty,
- some samples have inclusions of dry crust (Figure 3a),
- some samples have silt layers or layers of fine sand,
- some samples are described as laminated (Figure 3b).

Figure 3. Piston samples. Examples of (a) dry crust intrusions, (b) laminated clay.

Only one analysis of particle size distribution was conducted for the slide material, where the material was classified as clay: 35 % clay sized particles and 65 % silt sized particles, as measured by the falling drop method.

Index parameters

In general, there is a large spread in the results for index parameters, which is attributed to the heterogeneity of the slide material. The trends for index parameters are summarised in Table 1.

Table 1. Summary of index parameters for slide material

Index parameter	**Figure number**	**Range**	**Comment**
Water content (*w*)	4 (a)	21-40.7%	Decreases with depth, large variation at same depth
Unit weight (γ)	4 (b)	15.9–21 kN/m^3	Increases with depth
Atterberg limits and Plasticity index	5	PL: 17-24 LL: 24-40 PI: 6-20	
Undrained shear strength from fall cone (FC) tests (c_{ufc} and c_{urfc}) *	7		Large spread in undisturbed strengths (c_{ufc}). Remoulded strengths (c_{urfc}): 4 samples had strengths lower than 2 kPa, and were classified as *brittle*†. Sensitivity varied between 1 -80.
Undrained shear strength from unconfined compression (UC) tests (c_{uuc})	6	7-73 kPa	Increases with depth‡.

Note:
* Fall cone tests were conducted in accordance with NS 8015 [1**Error! Reference source not found.**].
† Norwegian regulations define stain softening clays or silts, with brittle failure mechanism as “brittle”, these materials have c_{urfc}< 2 kPa [2].
‡ These results were affected by the dilatant response of the slide material; in about 60 % of tests “failure” was defined at 15 % axial strain, because the sample continued to dilate and increase in strength past this point.

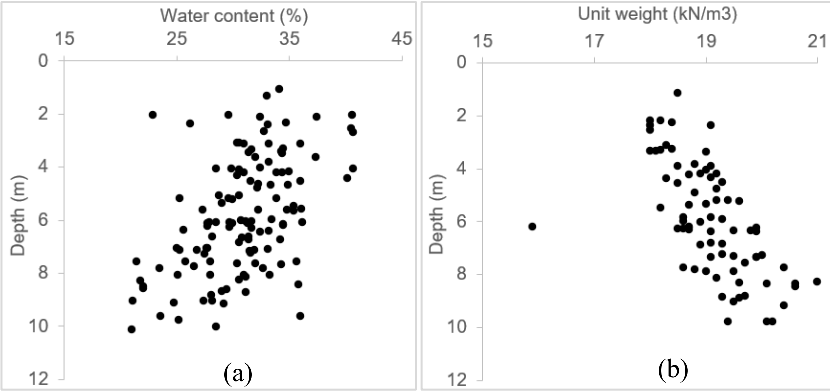

Figure 4. a) Water content (w) and b) unit weight (γ) for samples of slide material

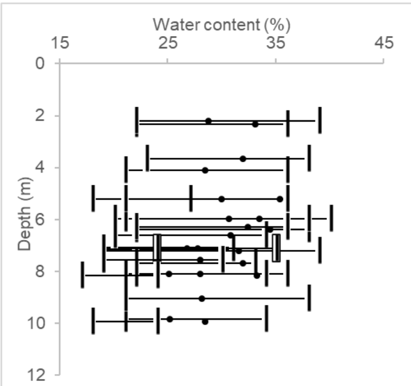

Figure 5. Atterberg limits and natural Water content for the slide material.

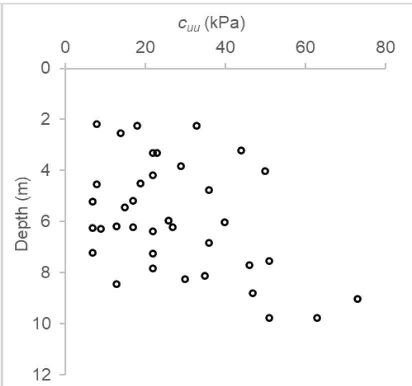

Figure 6. Unconfined compression test results (c_{uuc}) from the slide material.

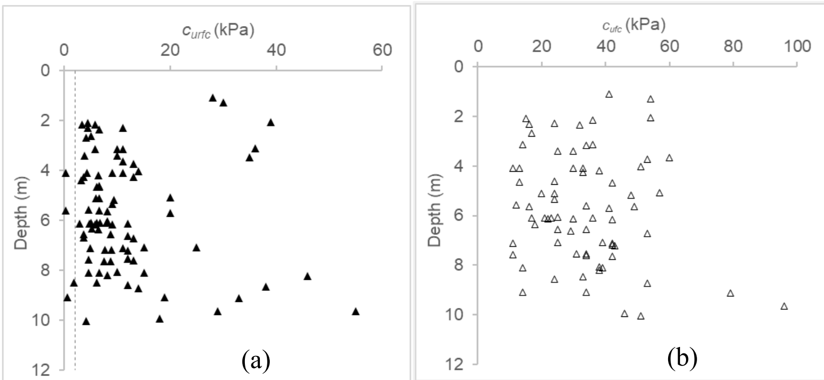

Figure 7. Undrained shear strength from fall cone tests in the slide material a) results for remoulded soil, b) results for undisturbed soil specimens in slide material. The dashed vertical line in a) represents the definition of "brittle" material in the Norwegian regulations (c_{urfc} <2 kPa).

3. METHODS

Determination of slide surface depth

To evaluate the properties of the slide material, it was first necessary to determine where the slide surface was located. It was possible to localise the transition between slide material and intact clay level by interpreting CPTu results. Figure 8 shows an example of interpreted layering, where the grey layer is interpreted as slide material. Only the pore pressure response (u_2) is shown, and from the figure it is clear that the intact clay has a higher excess pore water pressure response than the remoulded material. This pore pressure response was also reflected by a sudden increase in the pore pressure parameter, B_q. Similar interpretation of CPTu-data has been used to determine the interface between intact and remoulded material, e.g. [9].

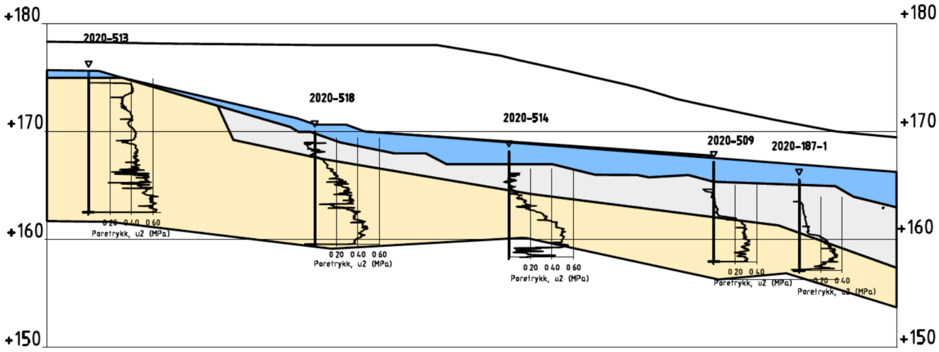

Figure 8. Example of terrain profile in the slide area. The yellow layer is clay (not quick clay, but still sensitive). The grey layer is the slide material. The blue layer is either counterfill or intact dry crust.

Interpretation of undrained strength

Interpretation of the pore water regime and the in-site effective stresses were necessary for the interpretation of CPTu. The on-site effective stresses were calculated based upon the closed available piezometer station, or a station at a similar elevation.

4. RESULTS AND DISCUSSION

The results for boreholes that have multiple rounds of sampling in the slide material are presented and discussed in this section. Suffixes to the borehole name signify a new round of site investigations and that the terrain level has changed, due to stabilisation measures such as the addition of counterfill. Locations of the boreholes are presented in Figure 2, whilst more information about the change in terrain level and date of installation of PVD is provided in Table 2.

Water content decrease with time

A decrease in water content is apparent in borehole 2020-186 (Figure 9a). This decrease in water content is expected, as the slide material consolidates, and excess pore water pressure dissipates. The other locations with repeat sampling, boreholes 2020-189, 2020-197 and 2020-302 (Figure 9b-d), do not exhibit a consistent reduction in water content. The most probable reason for this difference is the installation of PVD: only borehole 2020-186 had samples taken prior to installation of PVD, and thus the material in borehole 2020-189 was still under-consolidated for the samples in July 2022. For the remaining boreholes, the PVD have sped up consolidation, and by the time of the first round of sampling, primary consolidation was most likely already well underway or completed.

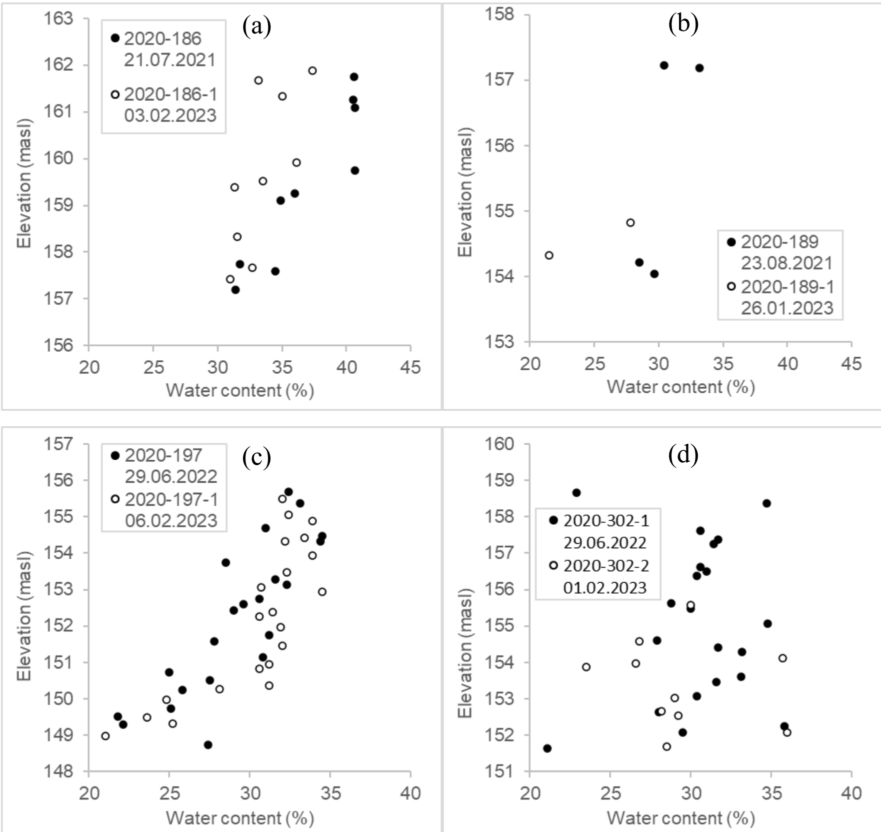

Figure 9. Change in water content with time for four borehole locations: a) 2020-186, b) 2020-189, c) 2020-197, d) 2020-302. The date of sampling is indicated for each sample.

Strength increase with time

The results of unconsolidated undrained (UC) tests are examined to check the increase in undrained strength with time. Repeat data was available at three boreholes: Figure 10.

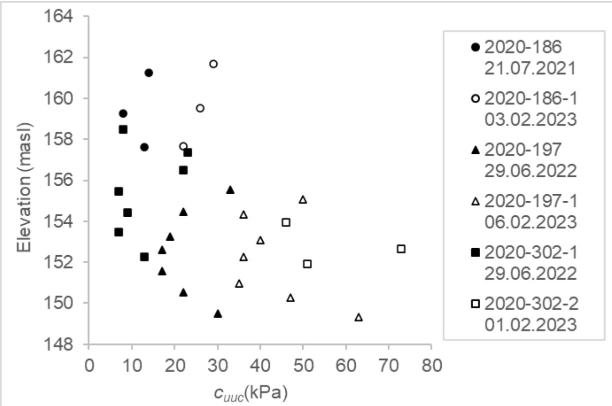

Figure 10. Undrained shear strength from unconsolidated, undrained tests on slide material against elevation. The date of sampling is indicated for each sample.

All samples displayed a strength increase of at least 10 kPa over time. Surprisingly, the samples with the longest time between samples (sampled at borehole 2020-186) resulted in smaller changes in undrained shear strength than samples with a longer time interval. Samples from borehole 2020-186 had a clear reduction in water content during this time period (Figure 9a), therefore it is unexpected that they exhibited the lowest increase in undrained shear strength. Possible reasons are a shorter time period with PVD, later application of the counterfill or differences in material type.

The change in undrained strength for boreholes 2020-197 and 2020-302 were larger, even though the time interval between sampling was smaller. These boreholes were located further south in the slide area and had the PVD installed earlier. Borehole 2020-302 also had a larger counterfill applied before the second round of sampling (Table 2). This indicates that the effective stress conditions should also be considered, and this hypothesis could be further strengthened by assessment of the pore pressure measurements at the time of sampling, and investigating when each counterfill was placed. Note also that borehole 2020-197 is the only borehole that is totally surrounded by PVD. Other boreholes were located on the edge of construction roads, where it was not suited to install PVDs.

Table 2. Changes in terrain level between sampling dates, and date of installation of PVDs in the vicinity of each borehole.

Borehole number	Difference in terrain elevation between sampling dates (m)	Approximate date of PVD installation
2020-186 to 2020-186-1	1.10	29.08.2022
2020-189 to 2020-189-1	1.60	02.07.2022
2020-197 to 2020-197-1	1.30	04.05.2022
2020-302-1 to 2020-302-2	2.40	11.06.2022

5. CONCLUSIONS

This paper presented results for index tests conducted on slide material from the quick clay landslide at Ask, Gjerdrum. The soil samples demonstrated that the slide material was quite heterogeneous and varied between boreholes. The samples consisted mostly of clays, with some few samples having inclusions of dry crust. There were also some unexpectedly high fall cone (c_{ufc}) results: which indicated the presence of intact and undisturbed "blocks" within the otherwise remoulded quick clay. Only four samples displayed a typical quick clay response, with remoulded fall cone strengths (c_{urfc}) under 2 kPa. Whilst the slide material had a liquid-like response immediately post-slide, the remoulded slide material was no longer very brittle after reconsolidation.

Closer analyses of tests conducted at the same elevation and borehole, at differ times indicated that all samples displayed an increase in undrained shear strength (c_{uuc}). Although the unconfined compression (UC) tests dilated, the UC tests are fast and cheap, and carried out on all piston samples, therefore it is fast and readily available way to assess the undrained shear strength. Probably the largest changes in water content occurred prior to, and just after the installation of the plastic vertical drains (PVD): only the borehole with samples taken prior to the installation of PVD exhibited a clear decrease in water content between different sampling periods.

This paper presents a small portion of the site investigation data gathered from the slide material at Gjerdrum. Future publications will include results from advanced laboratory testing and interpretation of CPTu.

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