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Øystein Lid Opsal

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Doctoral theses at NTNU, 2018:204

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Thesis for the degree of Philosophiae Doctor

Trondheim, June 2018

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Preface

The work leading to this PhD thesis has been performed from October 2013 to March 2018 by PhD candidate Øystein Lid Opsal at the Department of Geoscience and Petroleum (IGP), Faculty of Engineering (IV), Norwegian University of Science and Technology (NTNU). The PhD is a research project (no. 80197) initiated by the Norwegian Water Resources and Energy Directorate (NVE), where NVE has funded three years, while NTNU has funded one year. The candidate has been supervised by the project leader and main supervisor, Chief geologist at NVE and Associate Professor at NTNU-IGP, Terje Harald Bargel, in addition to two co-supervisors, Professor Bjørge Hermod Brattli and Associate Professor Randi Kalskin Ramstad at NTNU-IGP. Due to the retirement of Professor Brattli, Associate Professor Ramstad was appointed co-supervisor in May 2017.

In addition to the work directly related to the PhD project in this time period, the candidate has attended and passed eight courses (a total of 57 credits, where 39.5 credits are on PhD level) at NTNU to fulfil the mandatory PhD coursework (the minimum requirement is 30 credits, where at least 20 credits must be courses on PhD level). The candidate has also fulfilled the one year of full-time mandatory duty work for IGP, i.e., lecturing, student exercises, co-supervising master students, etc.

The PhD project resulted in two published journal articles, and this thesis consists of an introduction and a summary of the project, of which the main content of the articles are combined and presented. The journal articles provide both new and improved information on geological parameters and shear strength of dry tills from the southern half of Norway, as well as their relation to bedrock geology:

1. Opsal, Ø.L. 2017: Shear strength of dry tills from the southern half of Norway in relation to bedrock geology. *The Norwegian Journal of Geology 97(2)*, 145–169. https://dx.doi.org/10.17850/njg97-2/04.

2. Opsal, Ø.L. & Langeland, J.M. 2018: Geological parameters in relation to bedrock geology and shear strength of dry tills: samples from the southern half of Norway. *Bulletin of Engineering Geology and the Environment.* Published online 03 February, 12 pp. https://doi.org/10.1007/s10064-018-1236-3.

Øystein Lid Opsal
PhD candidate
Trondheim, March 2018

Acknowledgements

I would like to start by expressing my sincere appreciation to my main supervisor at NTNU-IGP, and Chief geologist at NVE, Associate Professor Terje Harald Bargel, for his support and encouragement during the entire project. You made this project possible, and I have really appreciated our many meetings and discussions. Thank you for your sharing of knowledge, guidance, contributions, and helpful comments. I would also like to express my gratitude to my co-supervisor at NTNU-IGP, Professor Bjørge Hermod Brattli for his help, guidance, contributions, and sharing of knowledge these years. Due to the retirement of Brattli, Associate Professor Randi Kalskin Ramstad at NTNU-IGP came to my aid as co-supervisor in May 2017. Thank you so much for stepping in for Bjørge at such a crucial time and for providing valuable contributions in the revisions of the papers and in this thesis. You have a keen eye for detail, so your contributions have really made improvements on the work. Many thanks to you all!

Furthermore, I would like to thank the now graduated Geologist, my field and laboratory assistant, and co-author on the second paper, Jørgen Mathias Langeland, for his contributions. Starting with our weeks on the road driving thousands of kilometres and working long and hard days for collecting the till samples. Those field trips resulted in many funny episodes and encounters with random people in remote areas wondering if we were 'digging for gold'. I also appreciated your help in the laboratory regarding the initial testing with the shear box apparatus, and your work with the particle size distributions. Your contributions as co-author were also very valuable. Moreover, I would like to express my gratitude to the now graduated Geologists, Marit Bakken Gjørva and Marte Bakka Stemland, who assisted me in the laboratory with both preparation of samples and the long days performing the shear box tests – you did an excellent job and I thank you for that.

In addition, I thank Chief engineer Gunnar Vistnes and Engineer Odd Corneliussen at the NTNU-IGP laboratory for training and helping us all in the laboratory. I also thank Senior engineer Laurentius Tijhuis at NTNU-IGP for his contribution with the XRD analysis, and Professor Stephen John Lippard at NTNU-IGP for his valuable contributions as proofreader for both the papers and this thesis. I also thank Assistant Professor Arnfinn Emdal at NTNU, Department of civil and environmental engineering, Geotechnical engineering, for his helpful comments on the first manuscript. Furthermore, I thank the journal reviewers, Senior adviser José Mauricio Cepeda and Director Anders Solheim at NGI, as well as the anonymous reviewers, for their valuable suggestions improving the papers.

Moreover, I would like to express my gratitude to NVE and NTNU-IGP for funding this project. I would especially like to thank the project leader at NVE, Aart Verhage, for his support and encouragement during the entire project. I also thank Professor Bjørn Nilsen at NTNU-IGP for his support in the final stage of this project.

I would also like to give many thanks to all my fellow PhD colleagues for being in the same boat and making these years joyful with interesting and amusing discussions, quizzes, movie nights, etc. I really appreciate these new friendships from all over the world, and I wish you the best of luck with the PhD and future work. I also thank the other employees for creating such a good work environment. It has been a pleasure working here at IGP.

Finally, I would like to express my heartfelt gratitude to my mother Edit Lid and my father Arnstein Opsal for their unlimited support. My mom's endless encouragement and good advices have been invaluable for me these years, and all the way back to my very first year at the university. My dad's 'never give up'-mentality in his work managing his own company in challenging construction work projects has truly been a source of inspiration for me as well these years – hard work, works! I also thank my stepmother Astrid Øye Opsal and my sisters Ingrid Øye Opsal and Oda Elise Øye Opsal, and the rest of my family and friends for all their support. Unfortunately, it is very sad that my stepfather Edvard (Eddie) Børretzen, who abruptly passed away in 2013, is not here to share this academic achievement with us. His academic profession as a Psychologist influenced and motivated me to begin at the university in the first place. Last, but not least, I would like to express my sincere appreciation to my beloved girlfriend Siri Marie Johannessen for her constant support and encouragement these years. Your unlimited love, wonderful sense of humor and good mood have truly been priceless – I now look forward to start our new adventures in Bergen.

I dedicate this thesis to my dear parents.

Abstract

When excluding floods, it is primarily slope stability issues such as landslides and avalanches, which count for the main geohazards in Norway. Till is the dominant Quaternary sediment, where the till deposits mostly originate from local rocks with a transport distance less than five kilometres. Consequently, debris slides and debris flows are among the main geohazards on till-covered valley slopes. In this context, the shear strength of tills is poorly studied. In addition, available documentation and data supporting so-called 'known relationships' of bedrock geology to geological parameters of till, such as particle size distribution, particle shape, and the mineralogical composition seem to be rather poor or based on outdated or non-standardised test methods. These geological parameters are also known to influence soil shear strength. To improve the knowledge on this subject, a set of 33 near-surface, genetically independent till samples were collected from various locations in the southern half of Norway to investigate the relationships between shear strength, geological parameters, and bedrock geology. The samples were categorised into six regional rock provinces, i.e., the Precambrian basement, the Oslo region, and four provinces in the Caledonian orogen, with five to seven samples in each. The mapped rock type(s) assumed to represent the origin of the till samples were based on their area of extent around the sample sites, and adjusted for by the late Weichselian ice-flow directions. Furthermore, the disturbed samples were sieved (<16 mm) and dried before they were tested in a large-scale direct shear box apparatus. Drying was done to exclude water as a variable, so that the results could be linked to the geological parameters of the material. In addition, a portion of riffled material from each sample was prepared and tested to determine the different geological parameters from six tests, i.e., particle size distribution, flakiness index, shape index, roundness, surface texture, and XRD analysis. The mutual correlations between the geological parameters and their correlations to dry till shear strength were investigated to display the potential relationships amongst the till samples and rock provinces.

Categorised by the rock provinces, named A/B–G, the results are generally in accordance with expectations regarding the relation of such geological parameters to the differences of bedrock geology amongst the provinces. For example, the Caledonian province of metamorphic and igneous rocks (E) had on average a higher fines content and a higher share of flaky/elongated particles than the Caledonian province of Precambrian rocks locally affected by the Caledonian orogeny (G). Rock provinces E and G are represented by rocks such as mica schist and phyllite, and various gneisses, respectively. In addition, the XRD analysis showed that province G was dominated by feldspars, while the Caledonian province of overthrust sheets of sandstone and schist (F), which is mainly represented by sandstones, was

dominated by quartz. The results also indicate that the dry till shear strength is not specifically governed by one geological parameter, but rather by an interaction of all the parameters combined. Particle size distribution and mineralogical composition were found to relate to the angle of friction, while particle shape is considered to influence the initial shear resistance and may thus be of special importance regarding the potential initiation of debris slides and flows in the respective provinces. On a province level, the study provides indications of a relation between dry till shear strength and bedrock geology with associated geological parameters. This suggests that some rock provinces may, solely on the basis of their associated geological parameters, be more prone to debris slides and flows than others. For this case, province G was found to be the 'strongest' province, while province F was found to be the 'weakest' province. The overall project objective is that the results of the study may improve the forecasts of the existing online Norwegian debris-slide warning system ('Jordskredvarsling'), which at the present does not directly include the investigated parameters.

However, it must be emphasised that the number of samples tested is relatively few, and they are geographically scattered. The samples were also collected without considerations of their genesis, which is known to influence several till characteristics. Moreover, the testing procedures and thus the results do not replicate individual field/in-situ conditions at the sample sites, as the samples were disturbed when collected and prepared for the purpose of achieving an equal comparison basis with a minimum of laboratory variables. In addition, it is important to emphasise that what makes an area prone to debris slides and flows depends on many other parameters, e.g., terrain characteristics, hydrological conditions, vegetation, etc.

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Minor typos have been corrected after submission of the thesis.

1. Introduction

1.1 Project background

Debris slides and debris flows cause significant damage in many parts of the world, especially in countries such as Norway where both relief and precipitation are high. This type of landslide may be sudden in its appearance and thereby poses a severe risk for settlement and infrastructure. In Norway, debris slides and flows usually occur in till-covered valley slopes, but also in, e.g., weathered material and former landslide deposits. A previous extensive Norwegian research project named 'GeoExtreme', was a multi-institutional project performed by researchers from the Geological Survey of Norway (NGU), the Norwegian Geotechnical Institute (NGI), Bjerknes Centre for Climate Research (BCCR), Center for International Climate and Environmental Research, Oslo (CICERO), and the Norwegian Meteorological Institute (MET). In the time period 2005–2009 this project performed investigations on several issues concerning climate and landslides in Norway, as well as performing future predictions (see, e.g., Jaedicke et al. (2008) for further information about the project). Due to limited knowledge on the topic, it was also desirable to include investigations on the potential relationships between bedrock geology and debris slides and flows in the project, but this was not performed. Therefore, the need for information on this topic still remained after the GeoExtreme project ended (Bargel, 2012).

Since 2009, the Norwegian Water Resources and Energy Directorate (NVE) has held the overall responsibility for governmental management tasks regarding the prevention of accidents due to landslides in Norway (NVE, 2018). Following the GeoExtreme project, in 2010 NVE initiated a new project aiming to establish methods for regional warnings of debris slides and flows throughout the country. Testing of the service started in 2012 in cooperation with MET, the Norwegian Public Roads Administration (SVV), and Bane NOR (previously the Norwegian National Rail Administration (JBV)). In 2013, the project launched a publically available website (http://www.varsom.no/flom-og-jordskredvarsling/) named in Norwegian 'Jordskredvarsling', i.e., 'debris-slide warning', which regularly publishes online national forecasts of debris-slide (and flood) warnings (NVE, n.d.). The overall purpose of the warning system is to prepare society for potential landslides to avoid loss of lives and to prevent damage on material values, and thereby to increase the safety and predictability in the society (NVE, 2017). However, this warning system is based on the correlation between past landslide incidents and both meteorological and hydrological variables (Boje et al., 2014), thus not directly including geological parameters. The lack of geological parameters, such as the particle size and shape, which are important in slope stability assessment due to their influence on soil shear strength (Cornforth, 1973; Yagiz, 2001), may therefore be considered as limitations in the present warning system.

In short, four main conditions must be met if one is to trigger a debris slide (see, e.g., Chatwin et al., 1994; Sidle & Ochiai, 2006; Sassa et al., 2007; Bargel et al., 2011):

1. Presence of a soil cover.
2. Sufficient slope steepness (usually above 30°, but 25° and even lower is also possible depending on the water content. Debris slides on slopes steeper than 45° are rare, mainly due to a reduced or non-existing soil cover).
3. Poor stability of the soil cover, which is dependent on many parameters:
    - Terrain characteristics and shape.
    - **Soil type and associated characteristics**.
    - Soil cover thickness.
    - Vegetation, etc.
4. Presence of a 'trigger':
    - Water is the main trigger in Norway (rainfall and/or snowmelt).
    - Earthquakes (a rare trigger in Norway).
    - Anthropogenic activities (e.g., slope excavation, blasting, etc.).
    - Rock falls onto the soil cover, etc.

As emboldened for no. 3 above, 'Soil type and associated characteristics' is the focus of this PhD, i.e., the geological parameters of the soil, which in this case is till. Internationally, geological parameters such as the size and shape of fragments (particles) in tills have been investigated for more than a hundred years (e.g., Hershey, 1897; Wentworth, 1921, 1936; Krumbein, 1933; Arneman & Wright, 1959; Holmes, 1960; Drake, 1971; Cammeraat & Rappol, 1987; Watabe et al., 2000). On this matter, it seems like a large part of the studies on Norwegian tills were performed in the 1970s and 1980s (e.g., Bergersen, 1970; Bergersen & Garnes, 1972; Garnes & Bergersen, 1977; Vorren, 1977; Haldorsen, 1981, 1982; Ballantyne, 1982). However, when excluding studies performed on, e.g., depositional processes, many studies on particle size and shape are in relation to construction work purposes, such as aggregates for asphalt or concrete (e.g., Erichsen et al., 2010; Bulevičius et al., 2013). Thus, although many studies have been performed on (Norwegian) tills, the relation of such geological parameters to the shear strength of tills is relatively poorly documented. In addition, available documentation and data supporting so-called 'known relationships' of Norwegian bedrock geology to such geological parameters of tills seem to be rather poor or based on outdated or non-standardised test methods. These so-called 'known relationships' may also be called 'self-evident truths', e.g., that tills originating from bedrock of schist should contain more flaky shaped particles than tills originating from harder rocks such as granite, which, in contrast, should contain more cubical shaped particles.

1.2 Project objectives

The motivation for NVE to initiate this PhD project (no. 80197) on the topic of debris slides was the present and future potential of such landslides in Norwegian till-covered slopes. The main idea of the project is that, on the basis of variations of bedrock geology, tills from different rock provinces should also have variations regarding geological parameters and (thus) shear strength. Therefore, the project aims to improve the rather poor documentation of shear strength and associated geological parameters for Norwegian tills in relation to bedrock geology. However, it must be emphasised that this project is not focusing on theoretical science regarding slope stability and debris slides per se. The project is applied science (empirical), where the main purpose is to do laboratory tests to provide a contribution in the form of improved or new information on geological parameters and shear strength of a variety of Norwegian tills. Furthermore, the project seeks to investigate the potential relationships between these individual parameters with regard to differences of bedrock geology to evaluate if some regional rock provinces may, solely on the basis of their associated geological parameters, be more prone to debris slides and flows than others. In turn, this contribution may be useful for, e.g., improving the debris-slide risk mapping and/or as input parameters for computer modelling of such landslides. The overall project objective is that the results of the study may be implemented in the national debris-slide warning system (Jordskredvarsling), thereby improving the forecasts. The actual processes of such implementations are, however, not within the project scope.

1.3 Note on contributions

This section provides detailed information about the roles and contributions of the PhD candidate and the other contributors in the project.

Table 1.1 *A list of the main contributors in this PhD project at NTNU-IGP.*

Name	Title/Role
Øystein Lid Opsal	PhD candidate/Lead author
Terje Harald Bargel	Associate Professor/Main supervisor (2013–2018)
Bjørge Hermod Brattli	Professor/Co-supervisor (2013–2017)
Randi Kalskin Ramstad	Associate Professor/Co-supervisor (2017–2018)
Jørgen Mathias Langeland	MSc student/Field and laboratory assistant/Co-author
Marit Bakken Gjørva	MSc student/Laboratory assistant
Marte Bakka Stemland	MSc student/Laboratory assistant
Laurentius Tijhuis	Senior engineer/Laboratory staff
Stephen John Lippard	Professor/Proofreader

1.3.1 Fieldwork

The candidate did the main part of the planning and performed the necessary preparations for the fieldwork, with input and approval from Bargel, Brattli, and Langeland. When in the field, the sampling areas were evaluated and agreed upon by the candidate and Langeland before collecting the till samples. Work tasks, such as driving, digging the sample pits, etc., were equally distributed, but the candidate was also responsible for taking notes and for photographing the sample sites.

Table 1.2 *An overview of the fieldwork regarding the sampling of the tills.*

Date	Sample no.	Contributors
23.10.2014	23*, 33	Opsal & Bargel
27.04.2015	1, 2	Opsal & Langeland
28.04.2015	3, 4, 5, 6	Opsal & Langeland
29.04.2015	7, 8	Opsal & Langeland
30.04.2015	9	Opsal & Langeland
24.08.2015	10, 11, 12	Opsal & Langeland
25.08.2015	13, 14, 15	Opsal & Langeland
26.08.2015	16, 17, 18	Opsal & Langeland
27.08.2015	19	Opsal & Langeland
01.09.2015	20, 21, 22, 23	Opsal & Langeland
02.09.2015	24, 25, 26, 27	Opsal & Langeland
03.09.2015	28, 29, 30, 31	Opsal & Langeland
04.09.2015	32	Opsal & Langeland

*No. 23 was a test sample.

1.3.2 Laboratory work

The methods for preparing and testing the till samples in the laboratory were as far as possible based on national and/or international standards, but the procedures were 'tailored' by the candidate when this was considered necessary. For instance, the candidate developed and made the two wooden tools (Fig. 3.9B) for a best possible equal leveling of the till material in the large-scale direct shear box apparatus. The suggested laboratory procedures were discussed with Bargel, Brattli, and Langeland, who contributed with valuable input. Initially, the candidate and Langeland performed several shear tests to evaluate and confirm that the test procedure was suitable for the purpose of the study. Chief engineer Gunnar Vistnes at the laboratory at NTNU-IGP trained the candidate and Langeland in using the shear box apparatus. Bargel and Brattli approved the final procedures for the laboratory work before execution. Two additional master students in geology at NTNU-IGP, Stemland and Gjørva, were hired as laboratory assistants in the project due to the heavy manual work needed for operating the shear box apparatus. Thus, all the following shear tests were done as a collaboration between the candidate and the two laboratory assistants. In addition, Stemland and Gjørva performed parts of the work regarding the preparation of the samples prior to the shear testing (Table 1.3). Engineer Odd Corneliussen at the laboratory at NTNU-IGP trained the candidate and Langeland in using other laboratory equipment for, e.g., the processes of wet and dry sieving.

Table 1.3 *An overview of the project contributions regarding the laboratory work performed on the 33 till samples.*

	Contributors			
Laboratory work	**Opsal**	**Langeland**	**Stemland**	**Gjørva**
Separating the samples	16 samples		12 samples	5 samples
Splitting the samples	33 samples			
Drying the samples	33 samples			
Shear box test	33 samples		16 samples	20 samples
Particle size distribution – wet sieving	1 sample	33 samples		
Particle size distribution – dry sieving	1 sample	33 samples		
Flakiness index test	33 samples			
Shape index test	33 samples			
Roundness test	33 samples	33 samples		
Surface texture test	33 samples	33 samples		
XRD test	33 samples*			

*The candidate prepared the samples for testing, while Tijhuis performed the test in the XRD apparatus and thereafter the interpretation of the results.

1.3.3 Journal articles

The PhD project has resulted in two peer-reviewed and published journal articles, where the contributions are summarised for each article:

Article 1

Opsal, Ø.L. 2017: *Shear strength of dry tills from the southern half of Norway in relation to bedrock geology*. Published in the Norwegian Journal of Geology.

Following the fieldwork and laboratory work, the candidate organised all the data/test results and performed all the subsequent analyses. The candidate wrote the entire article and made all tables and figures. Bargel, Brattli, and Ramstad provided valuable input on the manuscript, and controlled and approved the content. Assistant Professor Arnfinn Emdal at NTNU, Department of civil and environmental engineering, Geotechnical engineering, also provided helpful comments on the manuscript. Lippard performed proofreading of the manuscript. The journal reviewers were Senior adviser José Mauricio Cepeda and Director Anders Solheim from NGI, and an anonymous reviewer, who provided valuable suggestions and improvements to the manuscript.

Article 2

Opsal, Ø.L. & Langeland, J.M. 2018: *Geological parameters in relation to bedrock geology and shear strength of dry tills: samples from the southern half of Norway*. Published in Bulletin of Engineering Geology and the Environment.

Apart from the registration of the results of the particle size distribution, which was performed by Langeland, the candidate organised all the data/test results and performed all the subsequent analyses. The candidate wrote the entire article and made all the tables and figures, although Ramstad made a new and improved version of figure no. 8 as part of the revision process. Langeland contributed with discussions and comments on the results and the interpretation of these, as well as general input on the manuscript. Bargel and Ramstad also provided valuable input on the manuscript, and controlled and approved the content. Tijhuis performed the interpretation of the results from the XRD analysis, while Lippard performed proofreading of the manuscript. The journal reviewers were anonymous but provided valuable suggestions and improvements to the manuscript.

2. Theory

2.1 Bedrock geology

The countries Sweden and Finland consist mainly and solely of Precambrian rocks, respectively (Oftedahl, 1981). In comparison, the Norwegian bedrock geology is highly variable, both in terms of formation (igneous, metamorphic, and sedimentary), as well as age, ranging from Precambrian (>542 Ma) to Permian (299–250 Ma) (Johnsen, 1995; Sigmond et al., 2013). In the Cambrian period (542–488 Ma) an ocean formed between Baltica (Northern Europe) and Laurentia (North America and Greenland), but within a 100 million years this proto-Atlantic ocean (Iapetus) closed as Scandinavia collided with Laurentia. The result of this collision was a mountain range named the Caledonian orogen, and no event has affected the Norwegian bedrock more than this collision as enormous rock massifs were moved hundreds of kilometres from the northwest to the southeast (Fossen et al., 2006). However, from being an impressive mountain range in the transition between Silurian (443–416 Ma) and Devonian (416–359 Ma), the Caledonian orogen weathered down throughout Devonian and Carboniferous (359–299 Ma) (Oftedahl, 1981). Thereafter, in the transition between Carboniferous and Permian, large-scale magmatic activity began in the southeastern part of Norway, which today is known as the Oslo region. This activity was closely linked to tectonic processes and events that lead to the making of a continental rift (graben) in this area (e.g., Prestvik, 2001).

In summary, regarding the Norwegian onshore bedrock area (Oftedahl, 1981):

- 67.9% is Precambrian, where 31.0% and 36.9% is outside or within the Caledonian orogen, respectively.
- 29.8% is Cambro-Silurian rocks.
- 1.9% is Permian eruptive rocks.
- 0.4% is Devonian sedimentary rocks, which is the youngest rocks deposited within the Caledonian orogen.

In addition to the Precambrian ‘Basement’, Caledonian rocks comprising overthrust sheets of both Precambrian rocks and sandstone and schist, metamorphic and igneous rocks, as well as Precambrian basement locally affected by the Caledonian orogeny, constitute the main part of the onshore Norwegian bedrock (Geological Survey of Norway (NGU), 2016a), see also Fig. 2.1. Consequently, due to this highly variable bedrock of Precambrian and Paleozoic rocks, the associated rock parameters, such as the mineralogical composition, hardness and strength, also vary in different geographical regions (rock provinces) throughout the country.

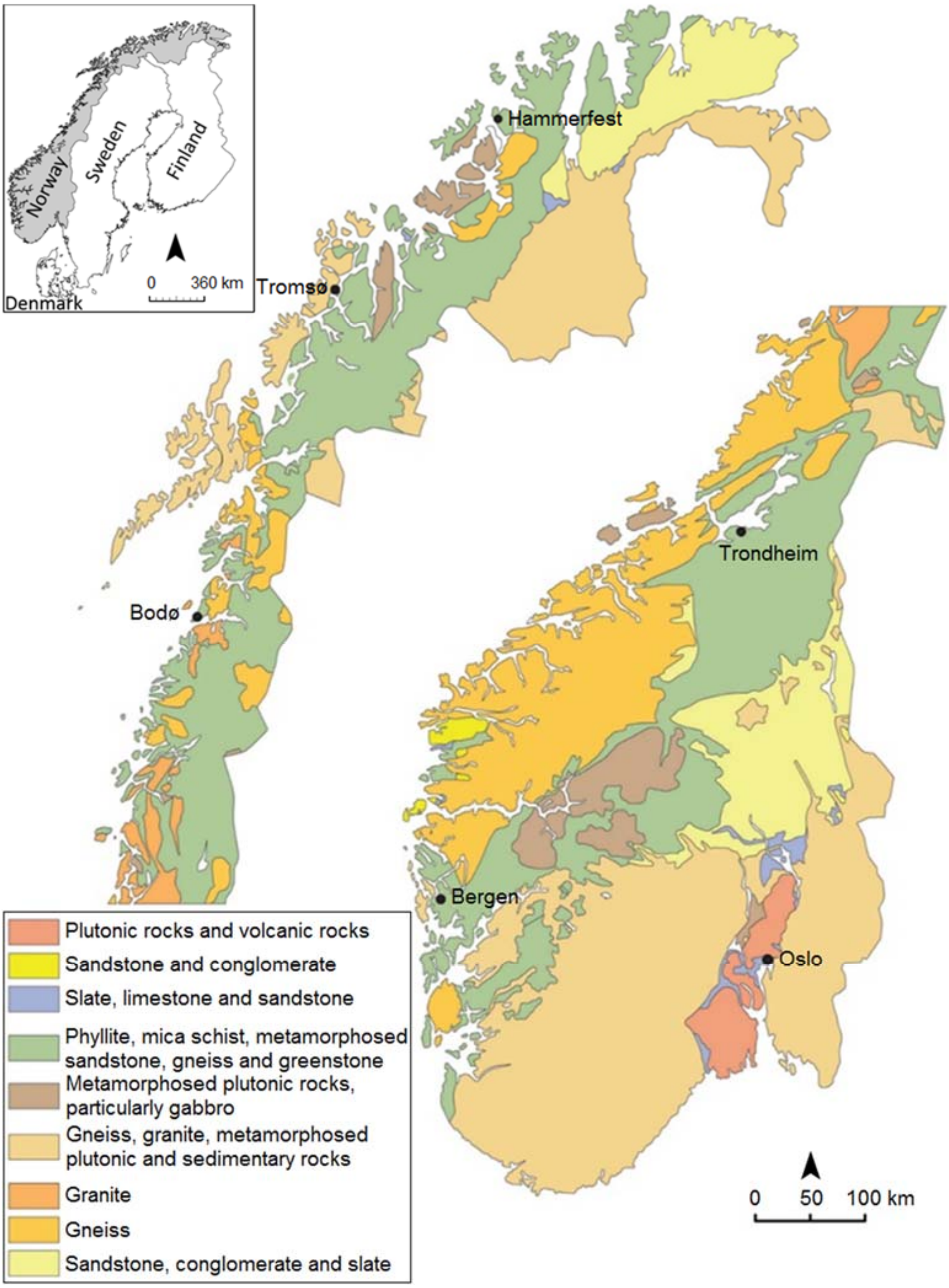

Figure 2.1 *A simplified bedrock geology map of Norway displaying various rock provinces, in addition to some typical rock types for each province. Modified figure, originally from Norsk Betongforening (1988), as cited by Haugen & Lindgård (2012).*

2.2 Quaternary geology: till

The Quaternary period, i.e., ca. 2.6 Ma (e.g., Sigmond et al., 2013), is primarily characterised by many and severe changes in the Earth's climate. The cold intervals in this period lead to more than 40 glaciations (e.g., Vorren & Mangerud, 2006), where glaciers were covering large parts of areas such as Northern Europe and North America (e.g., Sladen & Wrigley, 1983), see Fig. 2.2. The last (youngest) glaciation is termed Weichsel, between ca. 115–10 ka. The glaciations were a prerequisite for the formation of till (e.g., Thoresen, 2000). According to Evans (2017), the term 'till' was first used by the Scottish people to refer to rough and agriculturally impoverished ground conditions or stony clay, and then adopted as a geological term by geologist Archibald Geikie in 1863. The Till Work Group of the International Union for Quaternary Research (INQUA) Commission on Genesis and Lithology of Quaternary Deposits decided in 1980 the following definition of this material: '*Till is a sediment that has been transported and deposited by or from glacier ice, with little or no sorting by water*' (Dreimanis & Schlüchter, 1985, p. 8). The material till is therefore a glacial sediment, i.e., it is made by glaciers plucking, abrading, and crushing the underlying bedrock and soil (Fig. 2.3). This mixture of material ranges from small clay particles to large boulders (e.g., Thoresen, 2000), see Table 3.3. Since till may consist of a variable assortment of rock debris ranging from boulders to fine rock flour, one may also have extremes, e.g., tills mainly consisting of sand and gravel, or tills with an excess of clay (Culshaw et al., 1991). It is also characterised by being poorly sorted or unsorted, as well as being an unstratified deposit of unspecific origin. Although till does not make up substantial sediment thicknesses in the geologic record, it makes a discontinuous cover for as much as 30% of the Earth's continental landmasses (Easterbrook, 1982).

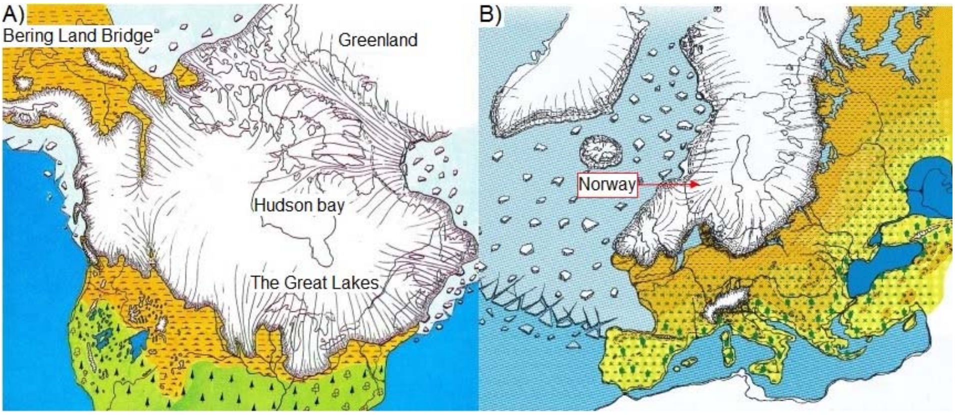

***Figure 2.2** Illustration of the ice sheets' greatest extension during the Weichselian glaciation, for A) North America, and B) Europe (Norway is marked with a red arrow). Modified from Andersen & Borns (1994), as cited by Jørgensen et al. (2013).*

Furthermore, regarding the formation of till, Boulton (1974) stated that the processes of crushing, plucking, and abrasion of rock masses depend largely on rock strength and hardness. The variation of rocks also affects the composition of till, as it is normally made by local rocks (Låg, 1948; Dreimanis et al., 1957). For this case, Ehlers (1983) pointed out that the Scandinavian tills closely reflect the composition of the local bedrock. In Norway, till is regarded as the dominant Quaternary sediment (Garnes, 1973; Haldorsen et al., 1983). For onshore areas, almost all Quaternary deposits are younger than 300 ka, and probably more than 90% of the present, remaining glacial deposits derive from the Weichselian glaciation, i.e., younger than 115 ka (Olsen et al., 2013). Although the till deposits may have thicknesses of 50–60 m in some limited areas (Thoresen, 2000), in higher relief areas the till cover is mostly discontinuous and its thickness only locally exceeds two meters (Haldorsen & Krüger, 1990). In general, a consistent layer of till is covering about 25% of the Norwegian mainland area (Thoresen, 2000; Olsen et al., 2013), see Fig. 2.6. Even though the transport distances of till may be several tens of kilometres (Clark, 1987), or even hundreds of kilometres (Dreimanis & Vagners, 1971), most of the Norwegian till material is transported a relatively short distance, i.e., less than five kilometres (Reite, 1990; Thoresen, 2000). Studies done in the neighboring countries, Sweden and Finland, have found similar results, concluding that the majority of tills are transported only a few kilometres (Perttunen, 1977).

Tills are said to be more variable than any other sediment known by a single name (Flint, 1971, as cited by Hambrey, 1994). This high variability stems from the variety of materials that are present in till, as well as from the variety of processes involved in its formation and deposition (Dreimanis & Schlüchter, 1985). Moreover, on material differences, it is known that the terminal size of comminution, as well as the shape of the broken product, are determined by the lithology (Goldthwait, 1971). Therefore, the origin of the rock has a strong influence determining the shape of the particles (Pellegrino, 1965). Former Norwegian studies by, e.g., Jørgensen (1977), have shown that parameters such as the particle size distribution of tills may vary significantly throughout the country.

Depositional genetic varieties of till may be classified by environment (terrestrial or subaquatic till), by position (ice-marginal, supraglacial, or subglacial till), or by process (primary till; lodgement till, melt-out till (including sublimation), and deformation till, in addition to secondary till; flow till) (Dreimanis, 1989, as cited by Evans, 2017), see Fig. 2.4. However, when in the field it is often considered difficult to distinguish between different types of till without performing detailed studies (Dreimanis, 1976; Haldorsen, 1982; Haldorsen & Krüger, 1990). To be able to distinguish tills one usually has to investigate, e.g., the orientation of elongated particles, potential sorted layers, and the degree of packing (Thoresen, 2000).

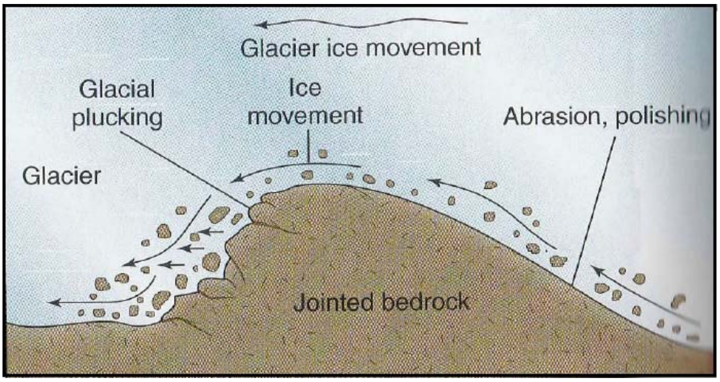

Figure 2.3 *Illustration of glacier ice movement on jointed bedrock, resulting in plucking, abrasion, and polishing, from Christopherson (2009).*

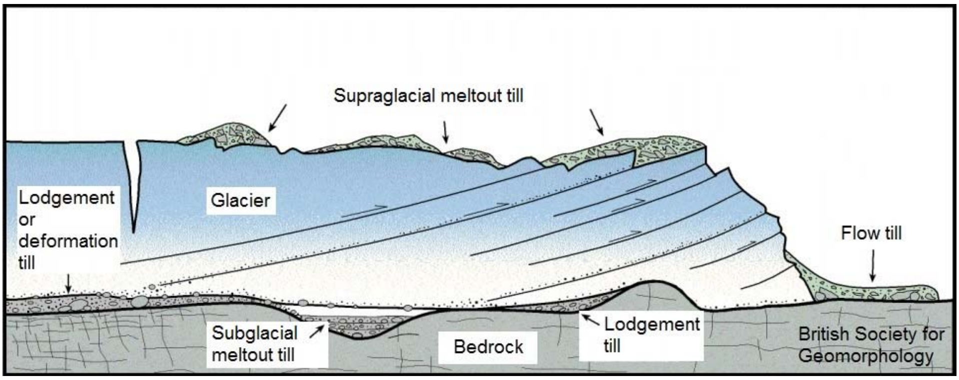

Figure 2.4 *Illustration of depositional settings for various types of till. Modified figure, originally from the British Society for Geomorphology.*

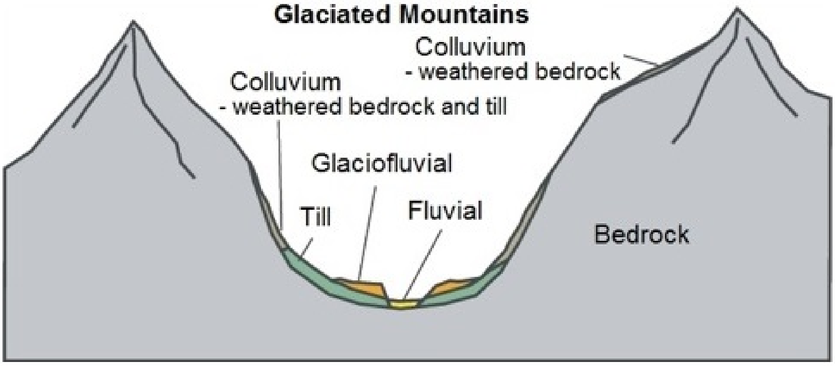

Figure 2.5 *Illustration of an idealised valley cross-section in mountainous terrain after glacial melting displaying the distribution of till and other sediments, modified from Yukon Geological Survey (2007).*

Fig. 2.5 gives a good illustration of Norwegian till-covered valleys, especially in the western part of the country where the relief is high. Due to natural construction work limitations regarding slope inclination, it is normally the lower and less inclined areas of the valleys containing till (and other) deposits that are used for settlement and infrastructure such as roads and railways. Typically, the upper part and surface of such Norwegian till deposits are more porous than the underlying, consolidated till due to processes such as weathering and biological activity (e.g., Norem & Sandersen, 2014) (Fig. 2.7). This may reduce the relative soil density (Dearman, 1991), which, in turn, may increase the permeability and water infiltration in the soil.

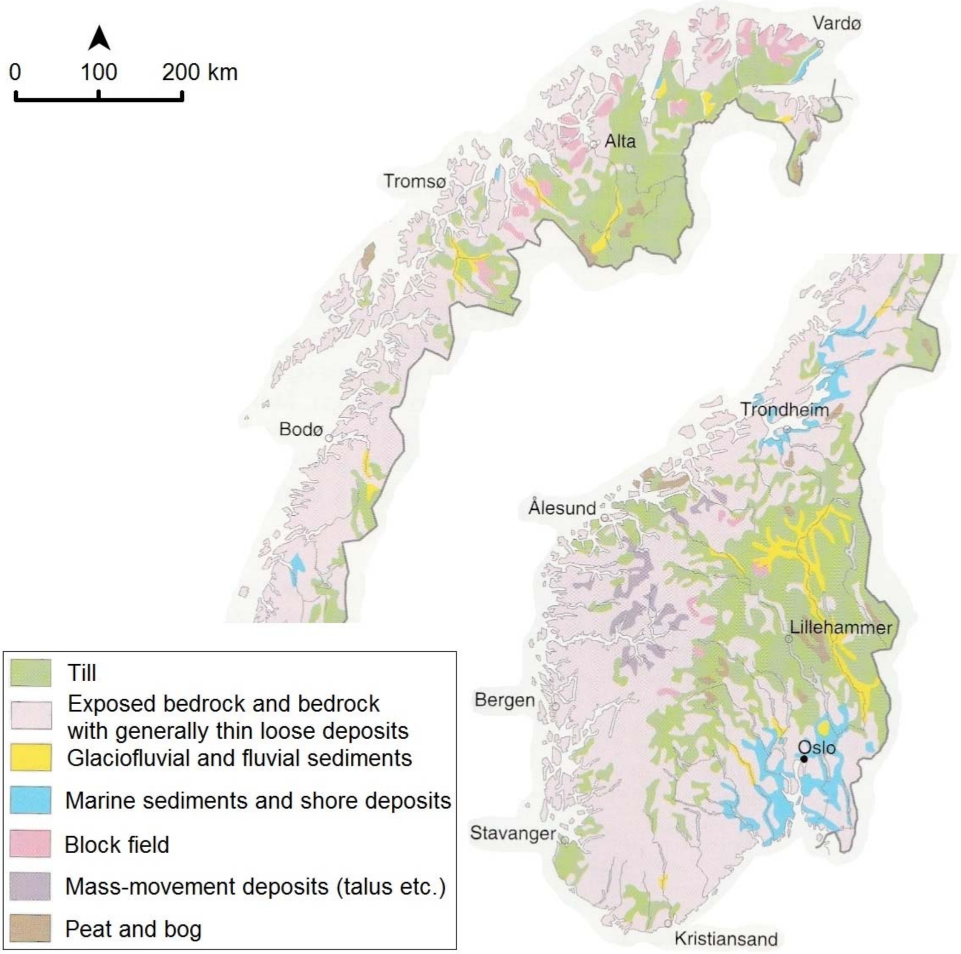

Figure 2.6 *A simplified Quaternary geology map of Norway. Modified figure, originally from Statens kartverk (1995), as cited by Rueslåtten (1995).*

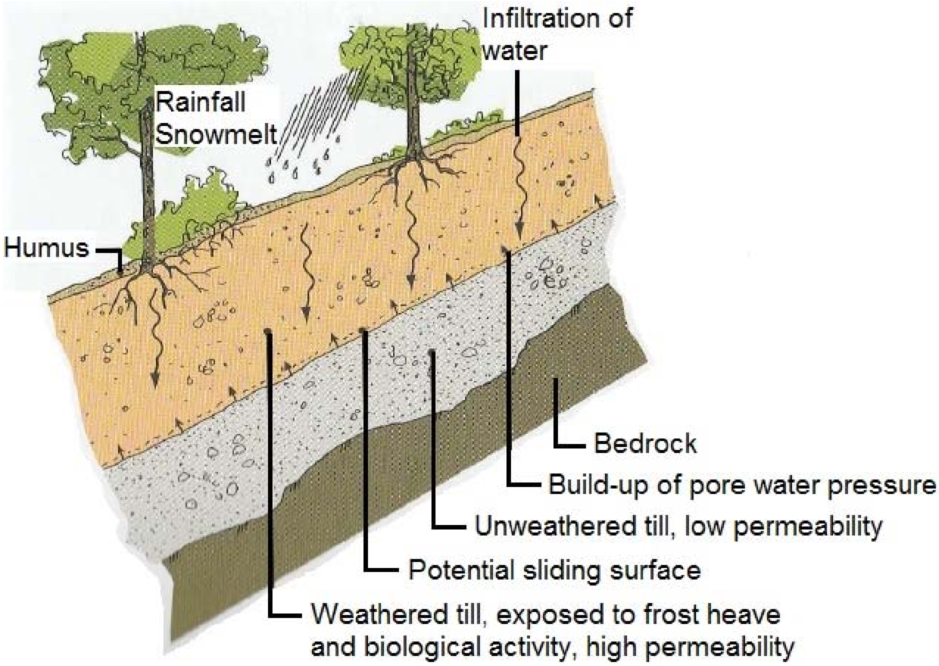

Figure 2.7 *Illustration of a till-covered valley slope, with weathered till upon a layer of unweathered till. The upper/surface layer (of weathered till) may, with a build-up of pore-water pressure on the potential sliding surface, be exposed for debris slides and flows. Modified figure, originally from Byggforskserien 311.135, as cited by Sandersen (2014).*

In geotechnical aspects, till is normally regarded as a 'good' foundation soil (Milligan, 1976), although the shearing resistance (shear strength) is essential in the analysis of soil stability problems such as slope stability (Fredlund & Rahardjo, 1993; Allred, 2000; Das, 2010).

2.3 Shear strength

Shear strength is known as the property that enables a material to remain in equilibrium when its surface is not level. Soils in liquid form have virtually no shear strength, and even when solid their shear strengths are of relatively small magnitudes compared with those exhibited by human-made materials like concrete or steel. Over the years, various yield theories have been proposed for soils, such as the Mohr-Coulomb theory. The Mohr-Coulomb theory does not consider the effects of strains or volume changes that a soil experiences on its way to failure. Nor does it consider the effect of intermediate principal stress. Nevertheless, as it is simple to apply and satisfactory predictions of soil strength are obtained, the Mohr-Coulomb theory is widely used in the analysis of most practical problems involving soil strength (Smith, 2014). The functional relationship between normal stress, σ, and shear stress on a failure plane, τ_f, can be expressed in the form of (Das, 2010):

$$\tau_f = f(\sigma) \qquad [1]$$

The failure envelope defined by Eq. [1] above is a curved line, while for most soil mechanics problems it is sufficient to approximate the shear stress on the failure plane as a linear function of the normal stress, which can be written as (Das, 2010; Smith, 2014):

$$\tau_f = c + \sigma \tan \phi \qquad [2]$$

where:
τ_f = shear stress at failure, i.e., shear strength.
c = cohesion.
σ = total normal stress on the failure plane.
ϕ = angle of shearing resistance, i.e., angle of internal friction.

Eq. [2] is termed the 'Mohr-Coulomb failure criterion'. However, in saturated soil, the total normal stress at a point is the sum of the effective stress and the pore-water pressure, i.e., σ' and u, respectively. The effective stress, σ', is thereby carried by the solids of the soil (the 'soil skeleton') (Das, 2010):

$$\sigma = \sigma' + u \qquad [3]$$

As the shear strength depends upon effective stress and not total stress, Eq. [2] can be expressed as (Smith, 2014):

$$\tau_f = c' + \sigma' \tan \phi' \qquad [4]$$

where: c' = cohesion and ϕ' = friction angle, based on effective stress (Das, 2010).

Regarding slope stability assessment, Das (2010, p. 365) defines the soil mass shear strength as '*the internal resistance per unit area that the soil mass can offer to resist failure and sliding along any plane inside it*'. Controlled shear tests have been a method to measure the shear strength of soils since the 1930s (Bishop & Eldin, 1950). The direct shear test is the oldest and simplest form of shear test arrangement for determining the shear strength parameters, i.e., c, c', ϕ, and ϕ' (Das, 2010). However, as also indicated by Thermann et al. (2006), it seems that homogeneous soils consisting of one or a few closely related fractions such as clay, as well as non-cohesive soils, such as sand, have been the most often used material for shear strength tests (e.g., Donald, 1956; Bjerrum & Landva, 1966; Palmeira, 1987; Miller

& Hamid, 2007; Schnellmann et al., 2013). In comparison, it seems that fewer studies have been done on heterogeneous soils consisting of multiple fractions such as till or colluvium (e.g., Gan et al., 1988; Iverson et al., 1994; Vanapalli et al., 1996; Fannin et al., 2005; Thermann et al., 2006). Apart from limited and local studies such as construction projects and master theses (e.g., Lund, 2013; Langåker, 2014; Langeland, 2016), the shear strength of Norwegian tills is rather poorly documented.

For cohesionless materials, the shear strength is usually expressed in terms of the so-called angle of internal friction, see also Table 2.1. On this matter, the shear stress-deformation relations are largely influenced by the initial soil density. For densely packed soils, this is visualised by a significant peak in the shear stress-deformation curve due to dilatancy, before levelling out horizontally in an 'ultimate steady state condition'. In contrast, loose to medium packed soils show none or only a minor peak in the curve before reaching the ultimate, horizontal level (Kaniraj, 1988; Ishibashi & Hazarika, 2015). According to Simoni & Houlsby (2006) this critical (ultimate) shear strength represents the minimum shear strength that the soil can display in a shear test (Figs. 2.8–2.10).

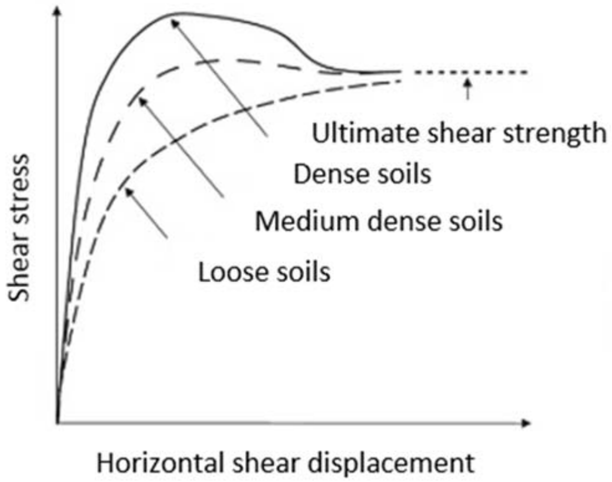

Figure 2.8 *Illustrations of shear stress-displacement relationships for loose, medium dense, and dense soils. Modified figure, originally from Kaniraj (1988) and Ishibashi & Hazarika (2015).*

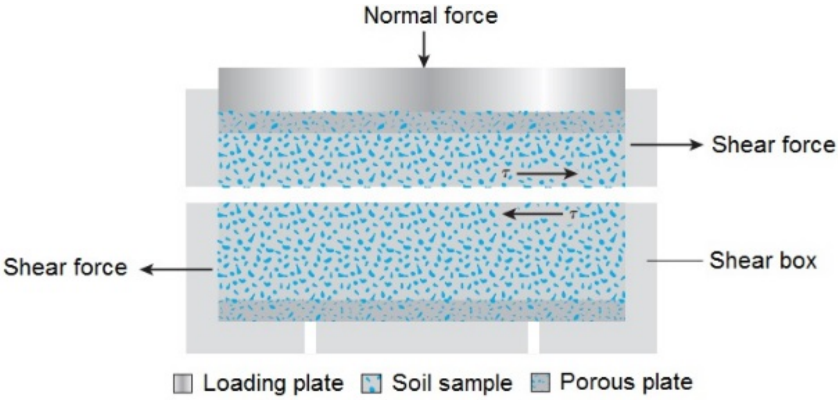

Figure 2.9 *A cross-section illustrating the principle of a direct shear box apparatus, which consists of two (metal) box halves split horizontally at the middle of the soil sample, where one half has a fixed position. If the sample is containing water, porous plates may be placed on top and in the bottom of the sample, thereby allowing the sample to drain. A vertical load is applied to the top of the sample, and as the shear plane is predetermined in the horizontal direction the vertical load is also the normal load on the plane of failure. Having applied the required normal force, shear force is exerted on the box. Modified from Das (2010).*

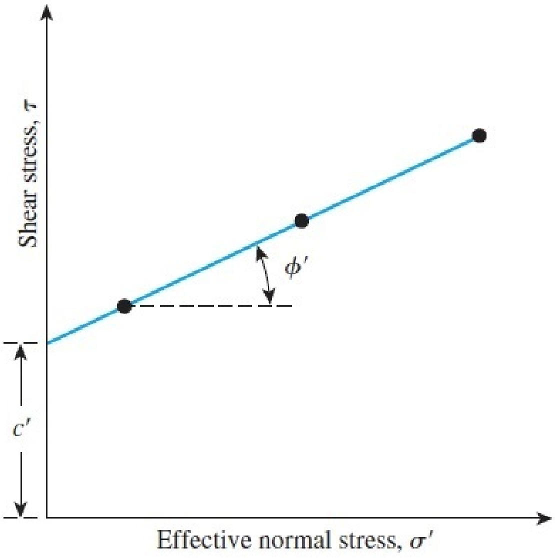

Figure 2.10 *The Mohr-Coulomb failure criterion, modified from Das (2010). In the shear box test both the normal and shear stresses at failure are known, so there is no need to draw stress circles and the failure points (three in this illustration) may be plotted directly. As these points must lie on the strength envelope, it will be established by the best straight line through the points, from which one obtains the cohesion, c', and angle of friction, ϕ' (Smith, 2014).*

Table 2.1 *Typical values of drained angle of friction for some soil types with various degree of packing, from Das (2010) and Koloski et al. (1989)*.*

Soil type	**ϕ' (°)**
Sand: Rounded particles	
Loose	27–30
Medium	30–35
Dense	35–38
Sand: Angular particles	
Loose	30–35
Medium	35–40
Dense	40–45
Gravel with some sand	34–48
Silts	26–35
Tills*	35–45

Geological parameters, such as the particle size distribution and particle shape, including particle angularity (Shin & Santamarina, 2013) and particle strength and surface roughness (Duncan et al., 2014), as well as mineralogy (Bolton, 1986; Fannin et al., 2005), are known to have an influence on soil shear strength (e.g., Yagiz, 2001). Furthermore, on the influence of geological parameters on soil shear strength, the angle of shearing resistance is generally increasing with increasing median particle diameter (Li, 2013; Wang et al., 2013). Even though it is recognised that particle shape affects soil behaviour, the geotechnical soil classification systems do not take particle shape into consideration and, consequently, the role of particle shape on soil response is therefore vague (Cho et al., 2006). However, in the context of shear strength, a decreasing particle sphericity is known to cause particle interlocking of different degrees, which, in turn, restrains slip and rotation (Rong et al., 2013). According to Cho et al. (2006), such decrease in the particle sphericity leads to an increase in the constant volume critical state friction angle. Li et al. (2013) found that increasing convexity increased peak friction angle, but decreased constant volume friction angle, while increasing elongation increased constant volume friction angle, but decreased peak friction angle. Moreover, according to Shin & Santamarina (2013), the presence of angular particles hinders particle mobility, which leads to a higher angle of friction. Shinohara et al. (2000) and Sukumaran & Ashmawy (2001) found that the angle of internal friction increased with increasing particle angularity, i.e., angular-shaped particles usually result in higher shear strength than rounded particles (Chan & Page, 1997; Guo & Su, 2007).

In addition, the interparticle friction generally varies with particle texture (or roughness), which refers to the small asperities present on the surface of the particles (Guo & Su, 2007). This microroughness is related to the hardness, texture, and strength of the surface, which are determined by the crystal structure of the minerals and intercrystalline bonding (Terzaghi et al., 1996). Therefore, the interparticle friction increases with surface roughness due to the process of particle slippage, as this is controlled by surface roughness (Santamarina & Cascante, 1998). Consequently, the angle of friction at critical state of cohesionless soils depends on the particle size distribution, particle shape, and mineralogy (Leroueil & Hight, 2003).

2.4 Landslides in Norway

When excluding floods, it is primarily slope stability issues, such as avalanches and landslides, which count for the main geohazards in Norway. Historically, landslides and avalanches in snow, rock and clay are the main causes of fatalities (Jaedicke et al., 2008). However, there have also been tragic outcomes of debris slides and flows, e.g., Hatlestad terrasse in 2005 in Bergen municipality (Fig. 2.11A), which resulted in three fatalities and seven wounded persons as the debris slide hit the houses (Granli, 2010). Although debris slides and flows seldom result in human fatalities, they often cause damage to buildings and infrastructure such as roads and railways, thus resulting in potentially high economic losses. In fact, about 1/3 of the roads and railways in Norway are exposed to potential landslides, and merely the closure of roads due to landslide incidents cost in total over 100 million NOK per year (Transportøkonomisk institutt, 2013). It is the western and coastal parts of Norway that are most exposed to landslides (Figs. 2.12–2.14). Valley slopes that are mostly covered in till are, consequently, prone to debris slides and flows (Bargel et al., 2011). In addition, due to the predicted future climate change, the frequency of debris slides is assumed to increase in many regions of Norway (Figs. 2.15 & 2.16) (Kronholm et al., 2007; Norem & Sandersen, 2014; Sandersen, 2014).

Figure 2.11 *Examples of debris slides and flows in Norway. (A) Hatlestad terrasse in Bergen, 2005, Hordaland county (Granli, 2010). (B) Oldedalen in Yri, 2013, Sogn og Fjordane county (Hotvedt, 2013). (C) Årset in Ørsta, 2013, Møre og Romsdal county (NGU, 2015a). (D) Signaldalen, 2008, Troms county (NGU, 2015b).*

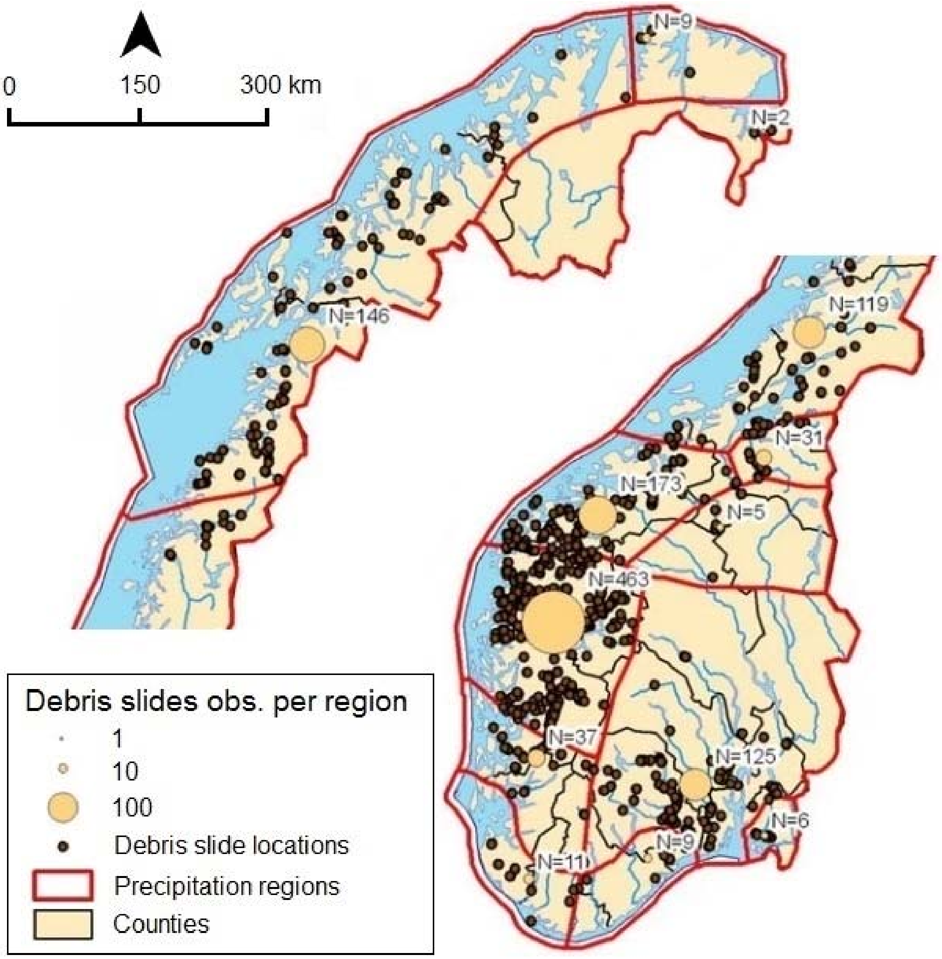

Figure 2.12 *The figure shows the number of registered debris slides in the period 1905–2006 categorised by precipitation regions, modified from Kronholm et al. (2007). As can be seen, the western and coastal parts of Norway have the most registrations of debris slides, although they seldom result in fatalities.*

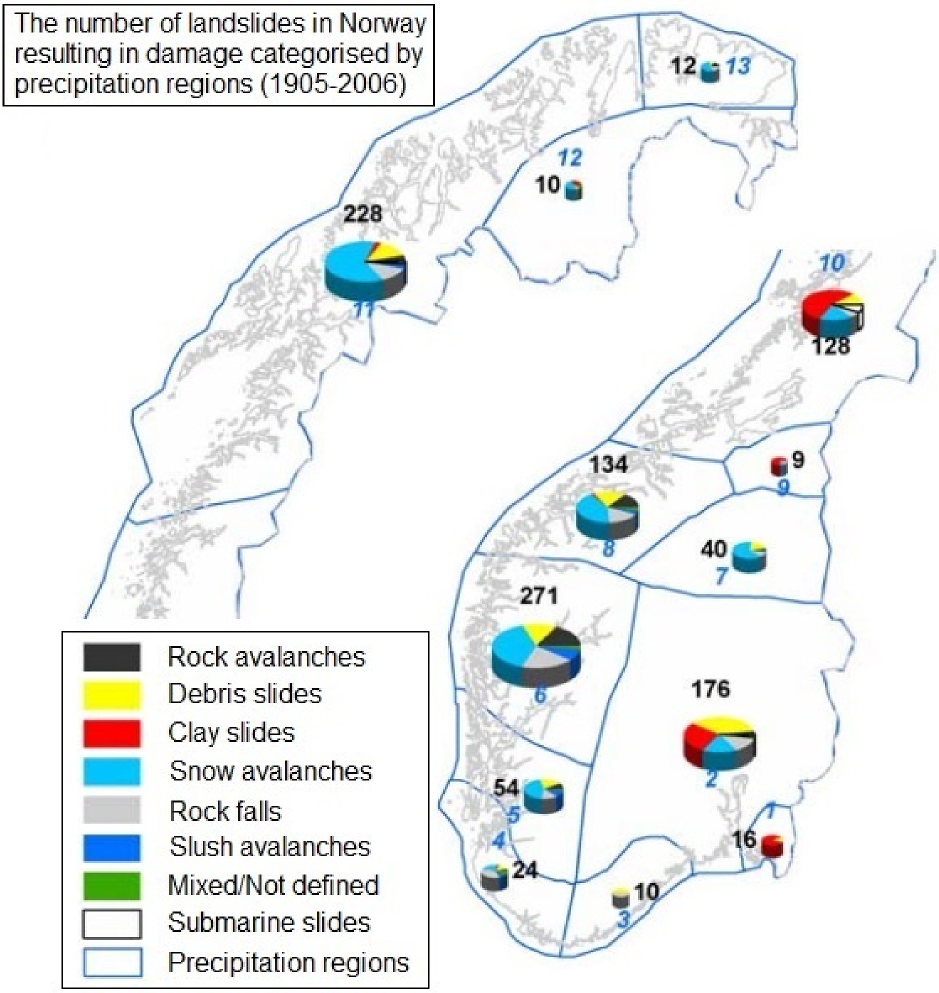

Figure 2.13 *The figure shows statistics of past damaging landslides in Norway in the period 1905–2006 categorised by precipitation regions and the type of landslides, modified from Kronholm et al. (2007). As can be seen, the western and coastal parts of Norway are the most exposed areas of landslides (regions 6, 8, and 11). In general, snow avalanches are highly represented, in addition to rock falls and rock avalanches, although debris slides are also common in most regions. In fact, the debris slides category has a very high share in region no. 2. Clay slides (quick clay slides) are most common in the southeastern and middle parts of Norway (regions 2 and 10), which contain a high share of marine sediments (Fig. 2.6).*

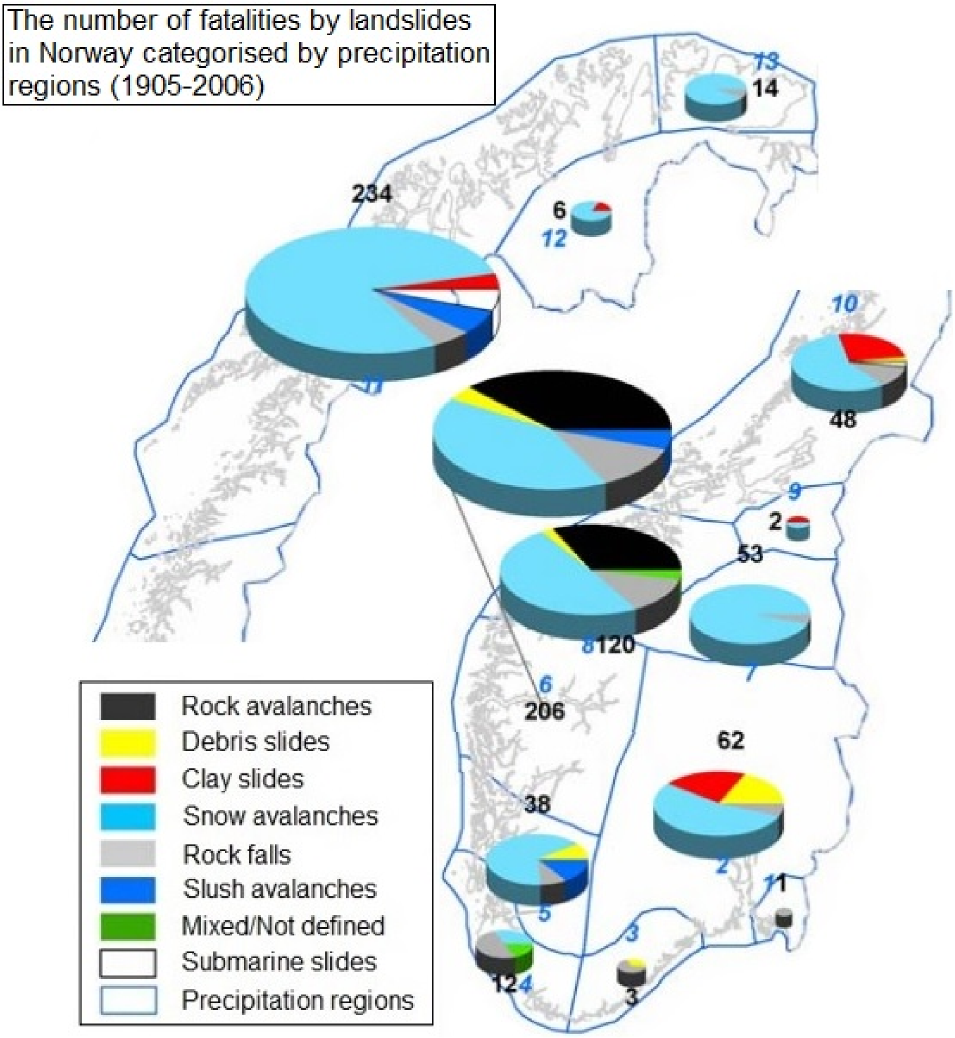

Figure 2.14 *The figure shows statistics of the number of fatalities by landslides in Norway in the period 1905–2006 categorised by precipitation regions and the type of landslides, modified from Kronholm et al. (2007). As can be seen, the western and coastal parts of Norway have the most fatalities (regions 6, 8, and 11). The category of snow avalanches has the most fatalities, but rock avalanches and rock falls are also highly represented. In regions 2 and 10, (quick) clay slides are also the cause of many fatalities. In comparison, the share of fatalities due to debris slides is relatively low, except for region 2.*

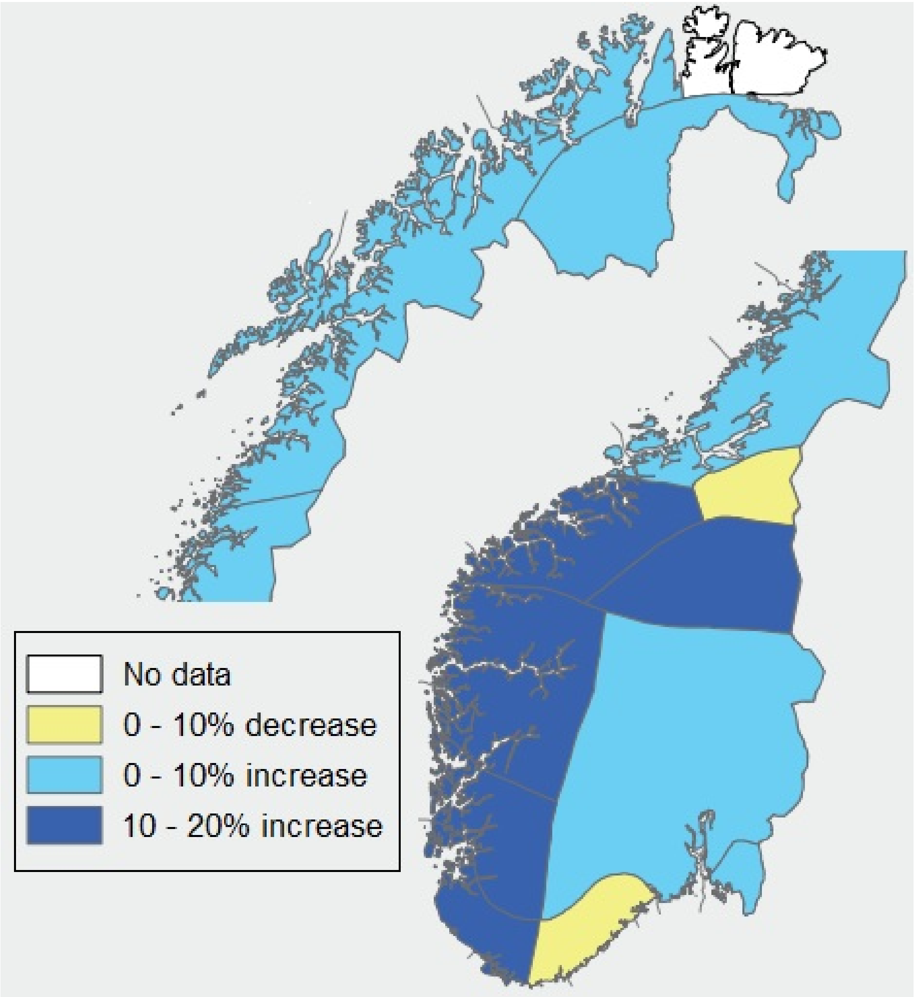

Figure 2.15 *The figure shows the assumed change in the number of days with extreme precipitation in the period 1990–2050, modified from GeoExtreme (n.d.). As can be seen, an increase is assumed for most regions, especially in the western part of the southern half of Norway.*

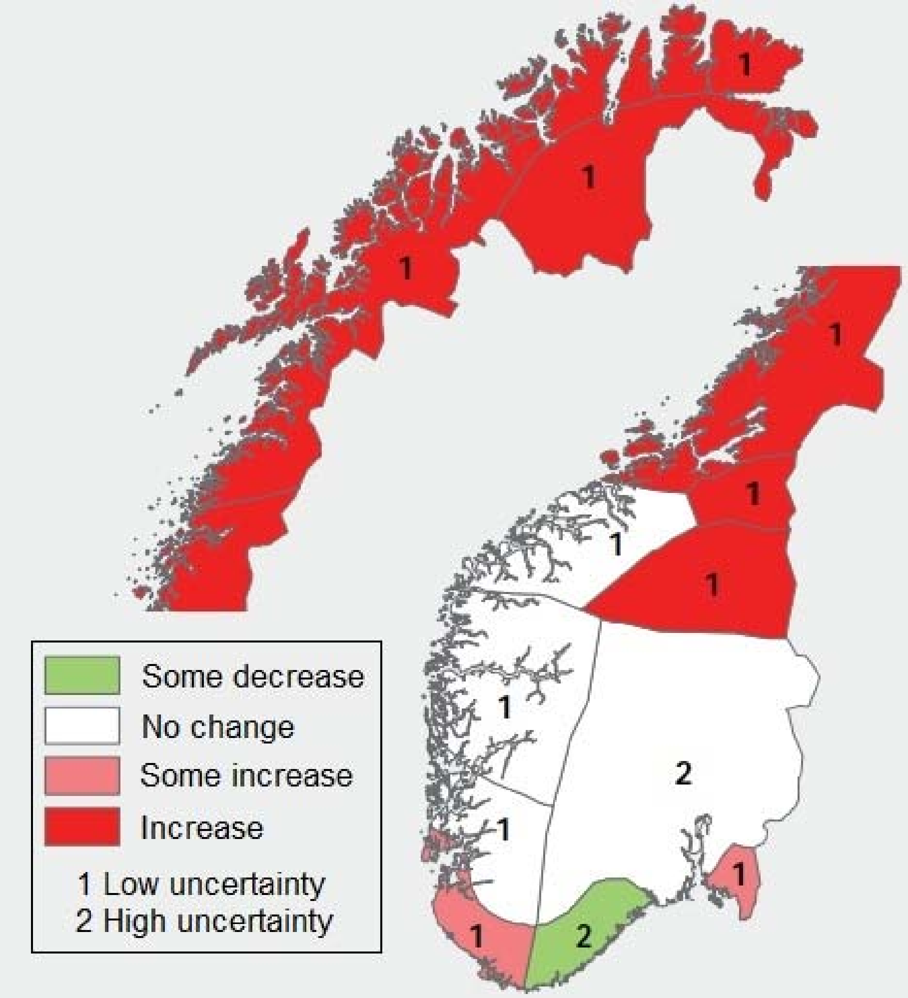

Figure 2.16 *The figure shows assumed changes in relative frequency of debris slides due to future climate change, modified from GeoExtreme (n.d.). As can be seen, an increase of debris slides is assumed in many regions of Norway, especially in the middle and northern parts of the country.*

3. Methods

The planning and execution of the field and laboratory work, as well as the subsequent work, such as processing the results, have been a main part of this PhD project. For the fieldwork, this included a three-week field trip driving nearly 5800 kilometres across the southern half of Norway, which in total resulted in about 2500 kg of sampled till material from 33 locations in 29 municipalities divided between 11 counties. The work procedures are mostly based on national and/or international standards. However, due to the rather limited documentation of previous Norwegian studies on till shear strength and associated geological parameters, some of the work procedures have been 'tailored' for this project when considered necessary. The following procedures for the field and laboratory work are therefore thoroughly described and illustrated with photographs. This description is thus more comprehensive than the method parts given in the two published papers. It also includes some plans, test procedures and experiences that after trial were changed or discarded, such as shear testing in saturated conditions. The reason for including this information is due to the mentioned limited documentation of previous Norwegian work on this topic, where such information and experiences may be useful for researchers in potential future work.

Note that the main parts of the text, tables and figures presented in this thesis are from the publications Opsal (2017) and Opsal & Langeland (2018). In addition, all photographs are taken by Opsal or Langeland. This thesis has used the referencing style of the Norwegian Journal of Geology.

3.1 Preliminary work

Before the fieldwork could begin, it was necessary to do a systematic investigation, evaluation, and planning of the best possible locations for sampling the tills. Due to natural project limitations and the greater variety of bedrock geology in the southern half of Norway (NGU, 2016a), the northern half of Norway was excluded from the study. When concentrating on the southern half, the study focused on collecting till samples from a variety of locations, aiming to collect at least five samples from each of the major rock provinces in this part of Norway (Fig. 2.1). First, geological maps, i.e., bedrock geology and Quaternary geology (NGU, 2016b, c), were studied to locate potential sampling areas. Since the overall topic of the PhD project is with regard to debris slides, the initial plan was to collect samples from locations with relatively recent and registered debris-slide incidents, preferably from the actual zone of initial failure. Such pin-pointed debris-slide locations were thought to be of special interest, as one could then investigate both the material at site that had failed, as well as its potential relationship to nearby registered meteorological data (e.g., temperature and precipitation) around the time of slope failure. A national publically available online map ('Skredhendelser') from NVE (2015) was therefore investigated, as this map service contains registered landslides all over Norway. Thus, maps of bedrock geology, Quaternary geology, road maps, in addition to maps of debris-slide incidents were printed and used in the fieldwork for locating potential sampling sites of till. These printed maps were thought to be especially useful in remote areas where the mobile internet coverage was too poor for the use of online map services. However, the plan of choosing debris-slide sites was initially considered difficult and finally discarded in the field, as it was very challenging due to:

- The number of samples needed.
- The weight of the samples.
- The need for accessibility by car to the sampling sites due to sample weight. The zone of failure is usually higher up in the terrain and thereby not reachable by car nor on foot, especially if one has to carry the sample material over long distances in difficult terrain.
- Difficulty of finding the actual debris-slide sites, as the landslide map mainly shows the registered locations where they have hit the roads or railways.
- Difficulty of finding the zone of failure of the debris slides, as these are often partly or completely revegetated.

From this, it became clear that the accessibility by car to the potential sampling sites was of key importance, and in this context the (forest) road maps were thoroughly investigated. This planning also included considerations on time consumption and cost regarding accommodation, ferries, toll bars, car type, transport regulations (total legal weight of samples per tour), etc. In turn, this largely determined the final number of samples that could be collected and later tested in the laboratory.

It also became clear that, when compared to the inland areas, the outermost coastal areas have relatively few accessible areas with substantial amounts of till deposits. Thus, the focus of sampling was drawn more to inland areas. In addition, it was decided to avoid sampling sites below the marine limit, as the tills in such areas could have been altered, e.g., changes in the particle size distribution due to wave washing and water currents (Reite, 1990). Furthermore, as this sampling was to be performed manually, an evaluation was also needed on the necessary equipment for the fieldwork, such as shovel, storage barrels, spring scale, Global Positioning System (GPS), etc. In summary, this desk study was a substantial part of the project, as it included an evaluation of several factors.

Figure 3.1 *Printed folders with a selection of maps, i.e., roads, bedrock geology, Quaternary geology, and historical debris-slide incidents, used in the fieldwork.*

3.2 Fieldwork

After the preliminary work/desk studies, the fieldwork was initiated. As mentioned, it is often difficult to distinguish between different types of till in the field without performing detailed investigations (e.g., Dreimanis, 1976). Thus, for simplicity, the tills were sampled in this study independently of their genesis, i.e., no distinction between subglacial till and supraglacial till was made. When in the field, the sampling of the tills was done manually with the use of a shovel and bucket. For practical reasons, the sample locations were therefore chosen in natural or man-made slope cuts with minimal vegetation cover, preferably along side slopes to forest roads (Fig. 3.2A–C). In this context, remote areas along forest roads with as little human impact as possible were preferable as sample sites. As anticipated in the preliminary work, the mobile internet coverage in such remote areas was often poor or non-existing, so the printed maps (Fig. 3.1) turned out to be very useful for their intended purpose. The actual sampling sites were chosen from field investigations at site.

The samples were collected from till deposits within roughly 1.5 m beneath the base of the organic top soil. This was done intentionally so that all samples were somewhat from the same depth and therefore relatively similar concerning their possible exposure to processes such as weathering, regardless of the total till cover thickness. However, about 15 cm of the uppermost till cover was removed before sampling was done further into the deposit. This was done to prevent the mixing of other potentially non-local material, such as sand from winter road maintenance. Note that the samples collected are disturbed and do not represent the original in-situ/field conditions. This was acceptable, as it is considered nearly impossible to obtain undisturbed samples in this type of material (Andresen, 1979; Hencher, 2012).

Likewise, due to the well-known range in size of solids forming a till, from clay size particles to boulders (e.g., Clarke, 1987), it was not practically possible to sample nor examine the larger fractions such as cobbles and boulders in the laboratory. According to recommendations in BS 1377-7 (1990) one should not include particles larger than 20 mm in the shear box apparatus. Since the shear box test was a major part of the project, it was decided to follow this recommendation of maximum particle size. Consequently, and by visual inspection, particles with a diameter clearly larger than 20 mm were manually sorted out at site and not included in the sampling. Organic material such as roots, leaves and insects were also as far as possible manually removed during sampling.

Furthermore, from NS–EN 932-1 (1996), the samples were weighed on site with a spring scale (Fig. 3.2D) to follow the given standard mass recommendations for a sample with maximum particle size of 20 mm, i.e., minimum 53 kg per sample. Due to the varying moisture content in the material when sampled, as well as the rather approximate weight measurements done by the spring scale, it was decided to collect significantly more material than the recommended standard minimum. Thus, most collected samples were, in fact, around 70 kg. The collected samples were put in individual plastic barrels (50 litres) and sealed to prevent any mixing of the material during transport (Fig. 3.2E). For the same reason, both the shovel and bucket were cleaned after each sampling.

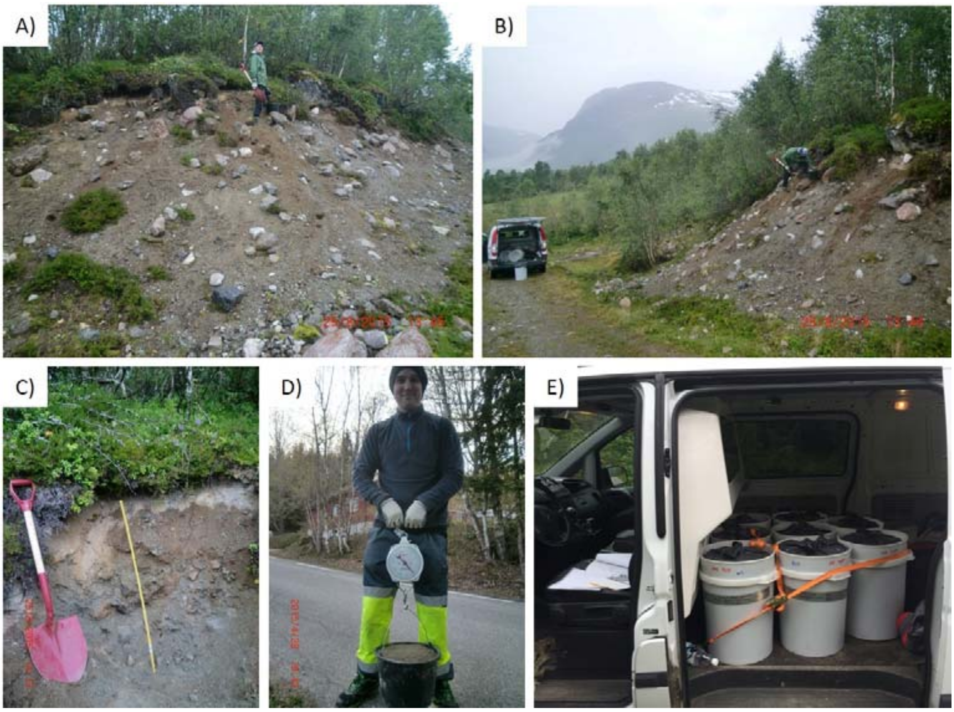

Figure 3.2 *(A & B) show a typical till sampling site (sample no. 14, province D) in a non-vegetated slope cut reachable by car, while (C) shows the excavation of the sample pit (the carpenter's ruler is 1 m). (D) Shows the use of a spring scale to collect the recommended amount of material per sample, i.e., minimum 53 kg. (E) Shows how the samples were transported by car in individual, sealed plastic 50 litres barrels, i.e., one sample per barrel. See also appendix 1 and 2 for coordinates and photographs of each sample site. (B & C) are from Opsal (2017).*

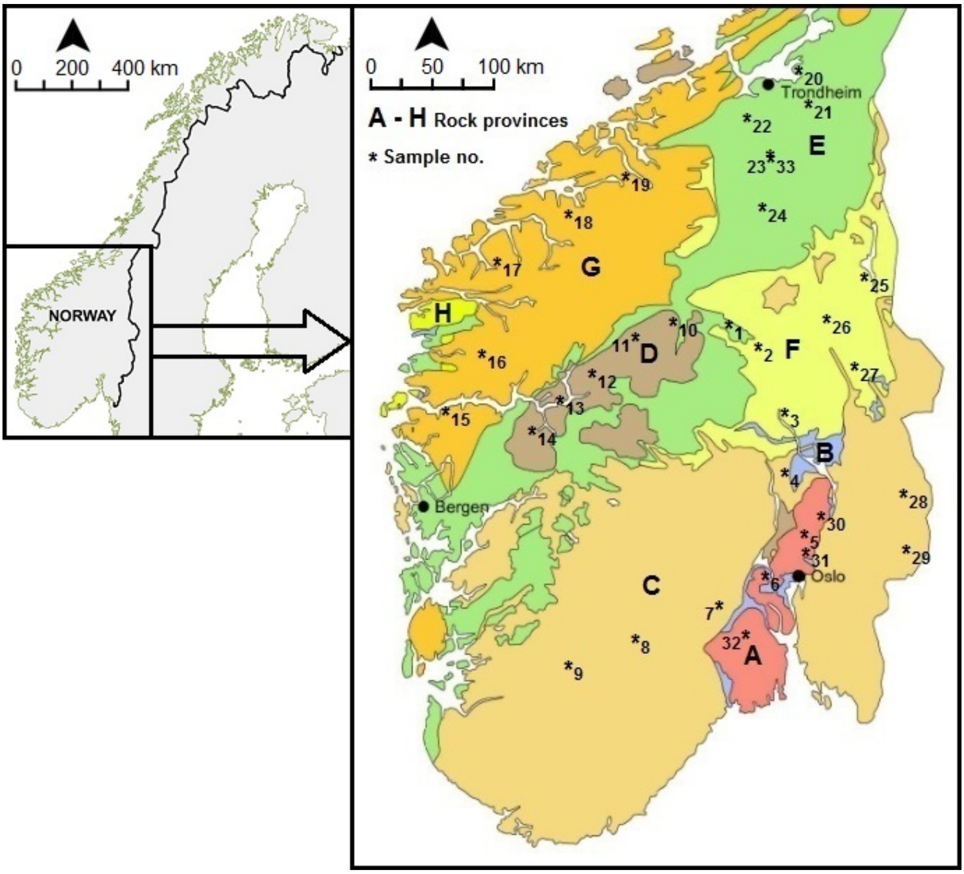

Figure 3.3 *A simplified bedrock geology map of the southern half of Norway illustrating the major rock provinces (named here as A–H) listed and described in Table 3.1, and the locations of the 33 collected till samples listed in Table 3.2. The figure is a modified version of Fig. 2.1 from Haugen & Lindgård (2012), as cited by Opsal (2017).*

Table 3.1 *A brief description of the major rock provinces (named here as A–H) in Norway, as illustrated on the map in Fig. 3.3 (Opsal, 2017).*

Rock province	Description
A	Extrusive and plutonic rocks in the Oslo region; mainly syenite, granite, monzonite and rhomb-porphyry
B	Sedimentary rocks in the Oslo region; mainly slate, limestone and sandstone
C	Precambrian basement; mainly gneiss, granite, metamorphosed volcanic and sedimentary rocks
	Caledonian rocks
D	Overthrust sheets of Precambrian rocks; mainly metamorphosed plutonic rocks, significantly gabbro
E	Metamorphic and igneous rocks; mainly phyllite, mica schist, metamorphosed sandstone, gneiss and greenstone
F	Overthrust sheets of sandstone and schist; mainly sandstone, conglomerate and slate
G	Precambrian basement, locally affected by the Caledonian orogeny; mainly gneiss
H	Sedimentary rocks; mainly sandstone and conglomerate

Table 3.2 *Overview of the locations of 33 collected till samples from 29 municipalities in 11 counties in the southern half of Norway, also distributed by the rock provinces as visualised in Fig. 3.3 (Opsal, 2017). See also appendix 1 and 2.*

Sample no.	Location	Municipality	County	Rock province
1	Kvam	Nord-Fron	Oppland	E
2	Fosse	Sør-Fron	Oppland	F
3	Sustad	Lillehammer	Oppland	F
4	Raufoss	Vestre Toten	Oppland	C
5	Harestua	Lunner	Oppland	A/B
6	Røyne	Lier	Buskerud	A/B
7	Jondalen	Kongsberg	Buskerud	C
8	Brunkeberg	Kviteseid	Telemark	C
9	Valle	Valle	Aust-Agder	C
10	Heranostangen	Lom	Oppland	D
11	Leirvassbu	Lom	Oppland	D
12	Murane	Årdal	Sogn og Fjordane	D
13	Kaupanger	Sogndal	Sogn og Fjordane	D
14	Jordalen	Voss	Hordaland	D
15	Indre Oppedal	Gulen	Sogn og Fjordane	G
16	Vassenden	Jølster	Sogn og Fjordane	G
17	Tunga	Volda	Møre og Romsdal	G
18	Voll	Rauma	Møre og Romsdal	G
19	Meisalstranda	Nesset	Møre og Romsdal	G
20	Skatval	Stjørdal	Nord-Trøndelag	E
21	Tømra	Selbu	Sør-Trøndelag	E
22	Korsvegen	Melhus	Sør-Trøndelag	E
23	Budalen	Midtre Gauldal	Sør-Trøndelag	E
24	Yset	Tynset	Hedmark	E
25	Åkerådalen	Rendalen	Hedmark	F
26	Steinbekkbua	Stor-Elvdal	Hedmark	F
27	Opphus	Stor-Elvdal	Hedmark	F
28	Flisa	Åsnes	Hedmark	C
29	Sørli	Kongsvinger	Hedmark	C
30	Sandsnessætra	Nannestad	Akershus	A/B
31	Hakadal	Nittedal	Akershus	A/B
32	Passebekk	Kongsberg	Buskerud	A/B
33	Enodden	Midtre Gauldal	Sør-Trøndelag	E

3.3 Laboratory work

All the laboratory work was performed at the Department of Geoscience and Petroleum at the Norwegian University of Science and Technology (NTNU-IGP). Since it is known that the reproducibility and repeatability of direct shear test results may vary (Converse, 1953; Bareither et al., 2008a) due to factors such as human imprecision (Thermann et al., 2006), a major focus in this study was that all the samples were prepared and tested as identically as practically possible with the same procedure. This was done to exclude variables and thereby increase the likelihood of obtaining an equal comparison basis, and, furthermore, so that the results could be linked to the geological parameters of the material. In the following, the processes for preparing and executing the material for shear testing, as well as testing the different geological parameters, are both described and illustrated by photographs.

3.3.1 Separating the samples

The process of separating the till samples was the first of several processes for preparing the material for laboratory testing. Due to the mentioned standard recommendations for the shear box apparatus (BS 1377-7, 1990), the material should not contain particle sizes above 20 mm, i.e., not larger than ‘medium gravel’ size (Table 3.3). Therefore, a 16-mm sieve (Endecotts) was chosen to separate the smaller fractions from the larger ones. The smaller 16-mm sieve was chosen instead of the 20-mm sieve due to the likely presence of some elongated particles in the samples (Fig. 3.4A, B). Apart from sample nos. 4, 8, and 33, which due to substantial moisture content had to be dried first, the samples were poured with a hand scoop and sieved in their original condition both manually and thereafter mechanically (CAPCO) for a minimum of five minutes (Fig. 3.4C), thereby discarding larger particles. In addition, any remaining organic material (roots, etc.) that was not removed during sampling in the field was with best effort manually removed during this process.

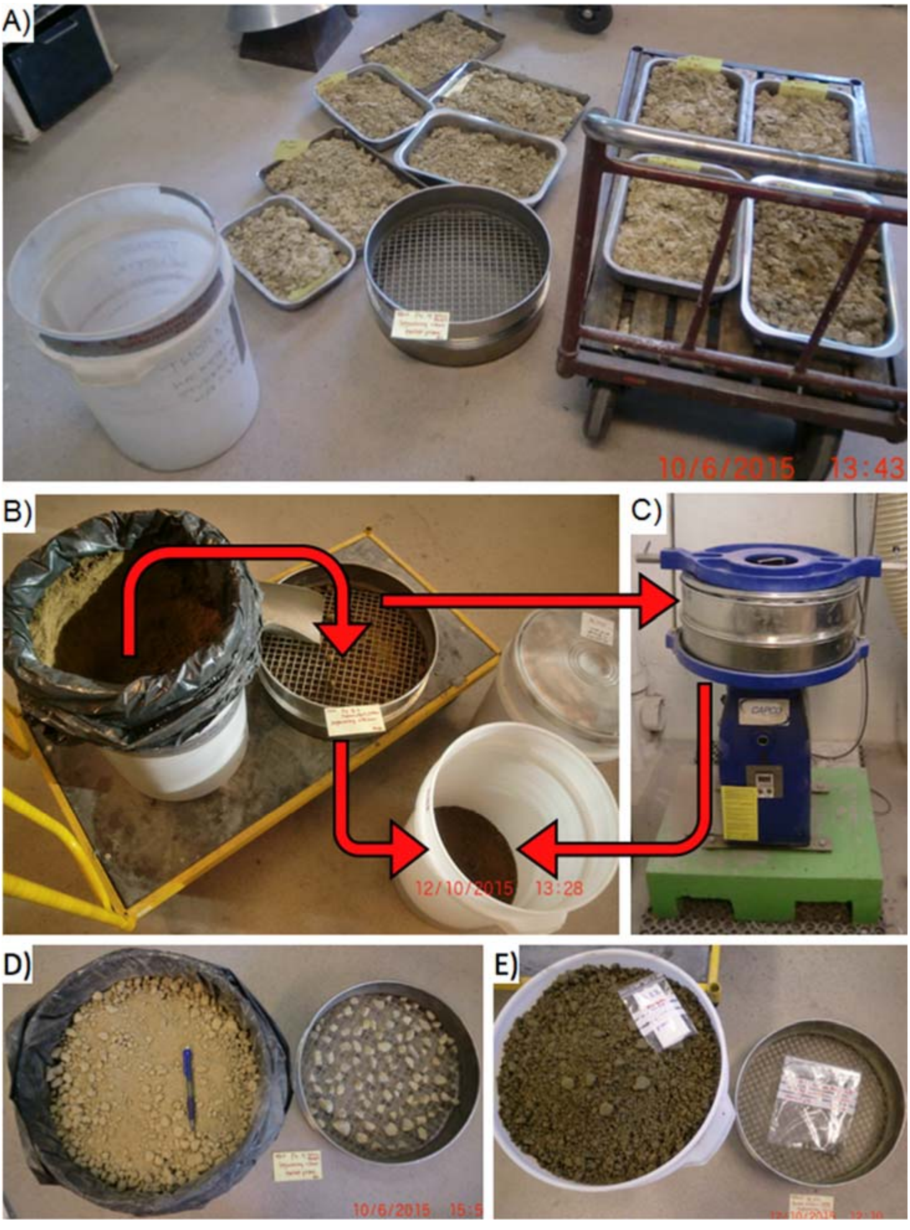

Figure 3.4 *The process of separating a till sample by using a hand scoop and one single 16-mm sieve to remove material ≥16 mm. (A) Example of all the original material in one sample (dried in this particular case) before separation. (B) With the use of a hand scoop, the material was sieved manually through the 16-mm sieve and the passing material was poured into another barrel. (C) The retained material was then mechanically sieved for a minimum of 5 minutes. (D) The sieved material <16 mm in the barrel (left) and the retained material ≥16 mm on the sieve (right). (E) Shows the bagged retained material (≥16 mm), and the 'personal package note' in the barrel for noting and keeping the logistics on all the work done on each sample.*

3.3.2 Splitting the samples

Following the process of separating the samples, and ahead of the shear testing, it was necessary to extract a randomised portion of till material (fractions <16 mm) from each sample. These portions were intended for the three other main laboratory tests of the study, i.e., particle size distribution, particle shape, and mineralogical composition. Based on NS–EN 932-2 (1999) and NS–EN 933-1 (2012) a relatively small portion of material of minimum 2.6 kg (due to the 'new' maximum particle size limit of 16 mm) from each sample was randomly selected by splitting with the use of a riffle box (Sample Splitter SP-1, Gilson Screen Co.) (Fig. 3.5A). Basically, the concept is that one splits the sample in two approximately equal halves, where one is discarded and the other is split again. This process continues until one has the necessary amount of material, which is then a randomly chosen portion of material. The splitting process was done on non-dried material, as recommended by ISO 17892-4 (2004) and NS–EN 933-1 (2012), to prevent eventual loss of the finest particles in the form of dust. However, for sample nos. 4, 8, and 33 the initial degree of moisture was considered too high for splitting in their original condition. To prevent clogging of the apertures of both the 16-mm sieve and the riffle box, these samples were dried beforehand in a drying oven at 30 °C for a minimum of 24 hours before the initial sieving and splitting processes were carried out. Apart from the shear test, note that these riffled portions of minimum 2.6 kg from each sample (Fig. 3.5B) were used as a sole basis for the three above-mentioned main tests of the study.

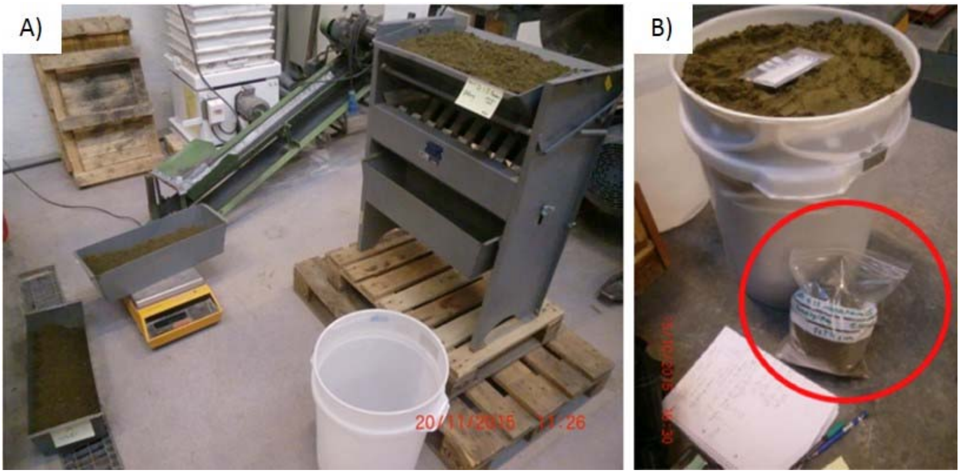

Figure 3.5 *(A) The process of splitting a till sample with the use of a riffle box, and (B) the final riffled portion of minimum 2.6 kg (circled in red) from the sample.*

3.3.3 Drying the samples

The third and final step of the sample preparation before the shear test was the process of drying. As described in Ch. 3.3.4.1, the initial plan was to perform shear tests on the till samples in both a dry and saturated conditions. However, to include water in the large-scale direct shear testing would result in a variable hard to control, as well as difficulties regarding the evaluation of its sole influence on the test results. Due to the high material variation of the till samples, it would also likely lead to, e.g., inhomogeneous saturation and removal of fines in the samples. Such loss of fines in suspension was actually confirmed in practice by doing a single shear test in a fully saturated condition (Ch. 3.3.4.1).

A main focus of this PhD project was the geological parameters of the tills and their influence on shear strength, not the influence of water. To be able to properly evaluate the influence of the geological parameters, it became clear that water had to be completely removed from the material. Thus, to exclude the variable of water, approximately 40 kg of material from each sample intended for shear testing was dried in shallow pans in an oven (Termaks) (Fig. 3.6A, B) at 110 °C ± 5 °C for a minimum of 16 hours, which according to ISO 17892-1 (2014) normally is enough to achieve a completely dry material. After this process, the oven-dried till material (Fig. 3.6C) was ready to be tested in the shear box apparatus.

Figure 3.6 *The process of drying till samples before shear testing. (A) Approx. 40 kg of material from each sample was dried in shallow pans in (B) a drying oven at 110 °C ± 5 °C for a minimum of 16 hours. (C) A dried sample ready for shear testing.*

3.3.4 Shear box apparatus

The large-scale direct shear box apparatus, the SB2010 from Testconsult Ltd. (Fig. 3.7), is a modern, fully automated machine, which incorporates a personal computer for operating the machine, for logging and displaying test data in real time and for reporting test results. During a shear test, it automatically registers the shear stress, τ (rounded to whole numbers of kPa), several times per millimeter displacement. It has a programmable shear rate up to 10 mm/min and can shear the sample up to a horizontal distance of 50 mm. The lateral and vertical load capacity range are 0 to 100 kN with a maximum vertical load capacity of 1000 kPa with the use of a precision stepper motor and hydraulics, whereas applied loads are measured directly using calibrated load cells (0.1% FS). The maximum inner dimensions of the stainless steel sample box are 305 mm x 305 mm x 200 mm, i.e., length and width (fixed), and height (adjustable sample height), respectively. The SB2010 is in fully accordance with BS 1377-7:1990 (Testconsult, 2012).

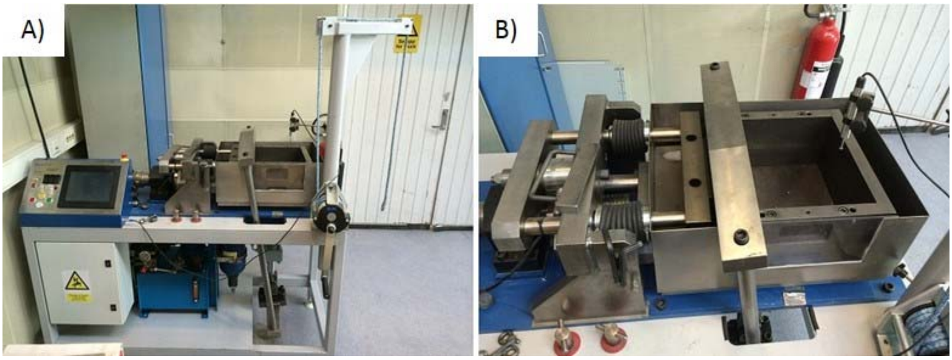

***Figure 3.7** An overview of (A) the SB2010 large-scale direct shear box apparatus located at NTNU-IGP, and (B) with the mounted, empty sample box (Opsal, 2017).*

3.3.4.1 Shear box test: saturated material

As water is a main trigger for Norwegian debris slides and flows (Kronholm et al., 2007; Bargel et al., 2011), the initial plan was to perform shear tests on the till samples in both a dry and saturated conditions. Such a testing regime was thought to be useful and of special interest for practical applications regarding slope stability assessment in Norwegian till-covered valleys. Therefore, a test portion of material from sample site no. 23 was wetted and left in its storage container overnight with an excess of water to complete the saturation. The fully saturated sample was put in the sample box and a shear test was started, although not completed. As can be seen in Fig. 3.8, the test was rather messy. The sample box could not be fully submerged in a water bath inside the shear box because water would then leak out of the apparatus through the areas of the reaction rods. In addition, saturated material (especially the fines) filled and clogged the threaded holes and other parts of the apparatus. Equipment such as screwdrivers had to be used for removal of material from the threaded holes (Fig. 3.8D), making it very hard and time-consuming to clean it properly, as well as increasing the risk for causing damage to the apparatus. As previously mentioned, the main disadvantage of using saturated samples was that it would likely introduce a significant uncertainty to the results regarding the actual influence of water as a variable. Another major disadvantage of using saturated samples was that one had to significantly reduce the shear rate to ≤0.5 mm/min (ISO 17892-10, 2004). This shear rate reduction was necessary to avoid the potential build-up of pore-water pressure in the sample, which, in turn, could also potentially damage the apparatus. Consequently, the shear rate reduction would significantly increase the time needed to perform a shear test and expand the laboratory work. In summary, based on the difficulty of controlling and identifying the sole influence of water, the alteration of the material (loss of fines), the reduction of shear rate and thereby the increased time needed for performing each test and thereafter cleaning the apparatus, as well as the increased risk of causing damage to the apparatus, it was decided to not proceed with shear tests on till material containing water. Thus, the remaining alternative was to shear test the samples in a dry condition.

Figure 3.8 *(A–C) show parts of the difficult and rather messy process of shear testing a till sample (from site no. 23, prov. E) in a fully saturated condition. (D–F) show the process of cleaning the apparatus after the shear test has been aborted. As can be seen, especially from the figures (D–F), significant amounts of material (particularly fines) are lost in suspension when shear testing and cleaning.*

3.3.4.2 Shear box test: dry material

Since shear testing of till material in saturated conditions was considered not practically possible in this project, it was decided to perform the shear testing only in a completely dry condition. Before testing the individual till samples in the SB2010, the sieved (fractions <16 mm) and dried material was firstly weighed in its storage container. The material was then carefully poured into the sample box with the use of a hand scoop (Fig. 3.9A). The pouring was done into the middle of the box, resulting in a randomised distribution within the box from the middle and outwards. Note that both the surfaces and contact area of the sample box halves were free of lubrication such as grease. A total sample height of approximately 180 mm was used, and as recommended in BS 1377–7 (1990) the sample was divided into three equally vertical-sized layers. These layers were manually divided and prepared with the use of two self-made wooden tools, ensuring that each layer in every sample was horizontally levelled at best possible equal vertical height, regardless of individual operator accuracy (Fig. 3.9B). Partly based on BS 1377–7 (1990), each layer was also compacted by doing five drops with a 4 kg weight (soft kettlebell) from a fixed height of approximately 20 cm on top of a steel plate covering the entire layer (Fig. 3.9C). According to recommendations in the newer ASTM D3080/D3080M (2011) the layer was, after compaction, ‘scarified’ before establishing a new layer. This scarification was performed with a garden hand fork on the first two layers, i.e., three times in two perpendicular directions over the entire layer area, to avoid distinct layer segregations (Fig. 3.9D). The last layer was compacted before performing a visual inspection of nine fixed points, i.e., the four corners, sides, and the middle, measuring with a ruler the distance in millimetres from top edge of the box down to the top compacted surface of the sample (Fig. 3.9E, F). This was done to calculate the volume of material contained in the sample box. Finally, the steel plate cover was put on top of the compacted material and the sample box was mounted in the shear box apparatus (Fig. 3.9G, H). Most of the excess spilled material was with best effort collected and put back into the storage container before it was weighed again, hereby giving the weight of the material contained in the sample box. With approximate information of both mass and volume, the ‘initial dry testing density’, ρ_d, of the sample was calculated once per sample on the first test.

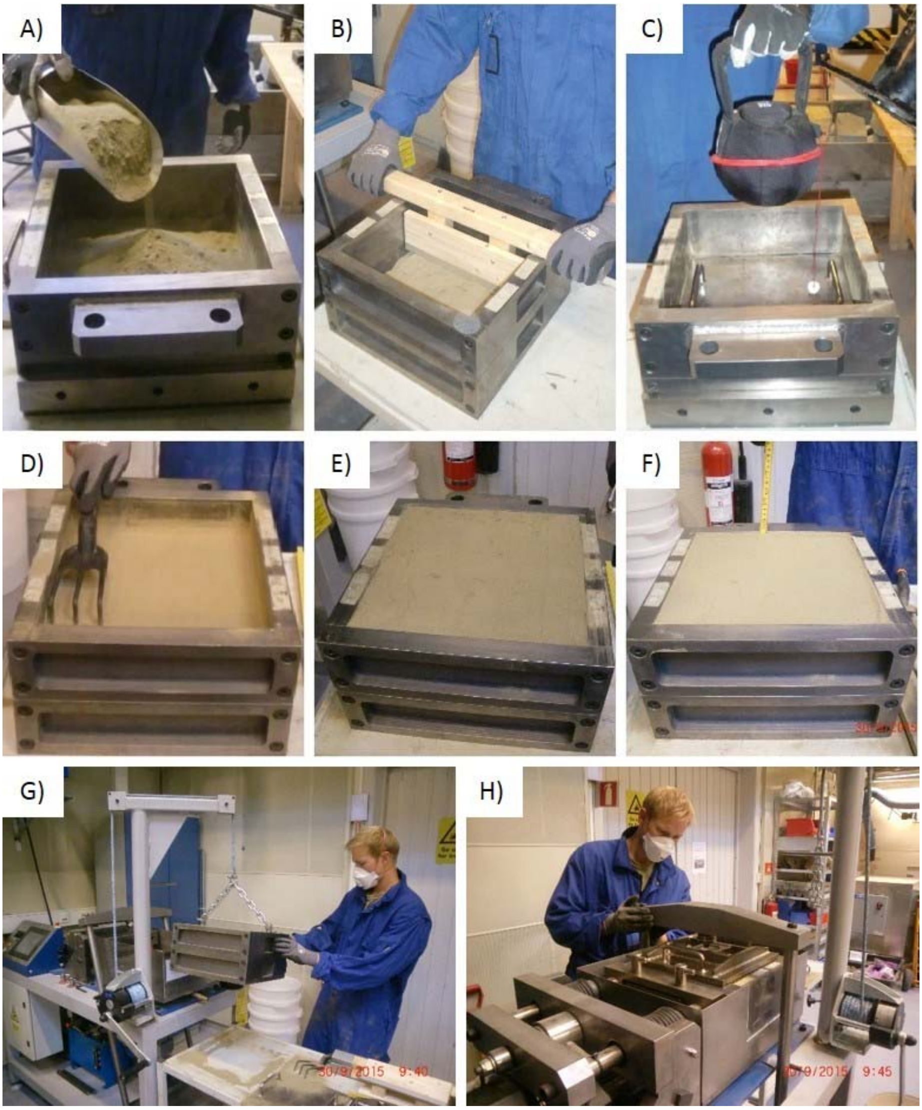

Figure 3.9 *The shear box testing procedure by preparing the till sample for shearing. (A) Pouring of sieved (<16 mm) and dried till material into the middle of the sample box. (B) Leveling of a total of three equally vertical sized layers (approx. 60 mm each) with self-made wooden tools. (C) Initial compaction of each layer by doing five drops from a fixed height of approx. 20 cm with a 4 kg kettlebell on top of a steel plate. (D) Scarifying the two first compacted layers three times in two perpendicular directions with a garden hand fork to avoid distinct layering. (E) Filled shear box before final compaction. (F) Visual measurement of the sample height from nine fixed points (corners, sides, and the middle) after compaction for calculation of sample volume and then the initial dry testing density. After the sample box was prepared, it had to be lifted into the shear box apparatus by a crane due to its total weight of roughly 100 kg (G) and then mounted (H). (A–F) are from Opsal (2017).*

Even though the SB2010 has a programmable shear rate up to 10 mm/min (Testconsult, 2012), it seems from other shear test studies that they, in general, have used considerably lower rates, e.g., 0.5 mm/min (Fannin et al., 2005), 0.01 mm/min (Gan et al., 1988) and 0.005 mm/min (Miller & Hamid, 2007). However, the purpose of shearing the sample slowly is, as previously described and according to ASTM D3080/D3080M (2011), to allow pore-water pressures to dissipate. The samples in this study were completely dry, thereby avoiding the potential build-up of pore-water pressure. Furthermore, since the water content may also have an influence on the shear strength due to the force of suction (Rahardjo et al., 1995; Fredlund et al., 1996; Lommler, 2012), drying the samples also excluded this variable. With no risk of a potential build-up of pore-water pressure in the material, the shear rate was increased to 2 mm/min, thereby significantly shortening the time needed to perform a shear test. Regarding shear distance, ASTM D3080/D3080M (2011) recommends that the sample should be sheared to at least 10% relative lateral displacement, i.e., minimum 30.5 mm for the SB2010. Although the SB2010 can shear the sample up to a distance of 50 mm (Testconsult, 2012), this may lead to spillage of material outside the sample box halves, as well as to a significantly decreased shearing area. Thus, it was decided to shear the samples for a horizontal distance of approximately 40.0 mm, which was similar to the shear distance in the study done by Bareither et al. (2008b).

As recommended by both BS 1377–7 (1990) and ASTM D3080/D3080M (2011), three shear tests with different normal stress, σ, were performed on all 33 samples. The three chosen levels of applied normal stress were 100, 200, and 300 kPa, as in the study by Skuodis & Tamošiūnas (2014). These levels of normal stress are relatively high when compared with other studies such as Fannin et al. (2005) and they do not reflect current field conditions. However, the main reason for selecting these levels of normal stress was former laboratory experience at NTNU-IGP showing that the SB2010 was somewhat inaccurate regarding constant loading during tests with a normal stress below 50 kPa (G. Vistnes, pers. comm., 2015). Before each shear test the samples were vertically preloaded at 350 kPa for a period of three minutes, thereby ensuring that all samples had an equal starting condition. After completion of each shear test, the sample box was emptied, cleaned and refilled as described. Note that the samples were reused, which is not recommended in both BS 1377–7 (1990) and ASTM D3080/D3080M (2011), probably due to the potential alteration or deterioration of the material when shearing, e.g., particle crushing. However, as Norwegian rocks are generally recognised as strong (e.g., Palmstrøm, 1997), the degree of potential particle crushing was considered to be low. Additionally, the sample box was not exposed to vibration, which would result in an increased particle rearrangement into a denser state. The samples were therefore still in a loose packed state when shear tested. As mentioned, it is known that an increase in the density increases the peak shearing resistance (Simoni & Houlsby, 2006;

Smith, 2014). Hence, shearing the samples in a loose packed state will minimise the risk of alteration or deterioration since there should be little or no dilatancy (Donald, 1956). Thus, the reuse of samples was regarded as having an insignificant influence on the geological parameters and the results. This reuse of the samples was also why lubrication of the sample box was avoided, as it would mix with the dry material thereby reducing the dryness. After completing the three shear tests, both the sample box and the shear box apparatus, as well as the other equipment, were thoroughly cleaned to avoid any mixing of material between different samples.

3.3.5 Particle size distribution

Particle size is fundamental for designating mineral soils, and by using particle fractions one may distinguish their mechanical behaviour (NS–EN ISO 14688-1, 2002). Sieving is the usual method for measuring particle size distribution (Hooke & Iverson, 1995; Rodriguez et al., 2013), and this was also conducted in this study. The method of sieving is a rather simple technique for separating particles of different sizes, which then can be categorised in different fractions (Fig. 3.10; Table 3.3). In summary, the particle size fractions are termed 'large boulder' (>630 mm), 'boulder' (>200 mm), 'cobble' (>63 mm), 'gravel' (>2 mm), 'sand' (>0.063 mm), 'silt' (>0.002 mm), and 'clay' (≤0.002 mm).

Table 3.3 *An overview of the particle size fractions (NS–EN ISO 14688-1, 2002).*

Soil fractions	Sub-fractions	Symbols	Particle sizes (mm)
Very coarse soil	Large boulder	LBo	>630
	Boulder	Bo	>200 to 630
	Cobble	Co	>63 to 200
Coarse soil	Gravel	Gr	>2.0 to 63
	Coarse gravel	CGr	>20 to 63
	Medium gravel	MGr	>6.3 to 20
	Fine gravel	FGr	>2.0 to 6.3
	Sand	Sa	>0.063 to 2.0
	Coarse sand	CSa	>0.63 to 2.0
	Medium sand	MSa	>0.2 to 0.63
	Fine sand	FSa	>0.063 to 0.2
Fine soil	Silt	Si	>0.002 to 0.063
	Coarse silt	CSi	>0.02 to 0.063
	Medium silt	MSi	>0.0063 to 0.02
	Fine silt	FSi	>0.002 to 0.0063
	Clay	Cl	≤0.002

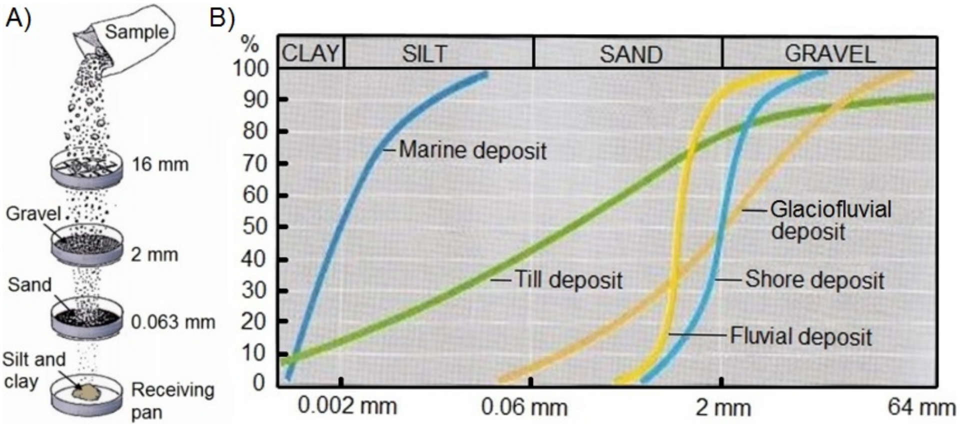

Figure 3.10 *(A) The basic principle of particle size distribution by performing sieving, modified from Jørgensen et al. (2013). (B) Typical particle size distributions for till and other deposits, modified from Neeb (1992).*

The sieving process in this project was performed in two stages, i.e., wet and dry sieving. However, it was decided to examine only the material larger than the fines (silt and clay). The riffled till samples (portions) were initially dried in an oven at 110 °C ± 5 °C for a minimum of 16 hours, as recommended in ISO 17892-1 (2014). The completely dry samples were after a period of cooling in room temperature for approximately 30 minutes weighed (Mettler PC 4400, DeltaRange) (Fig. 3.11A), and then placed in water-filled plastic barrels (Fig. 3.11B). The samples were left in these sealed barrels to saturate for a minimum of 24 hours to loosen up the potential clusters of fines stuck together or on larger, coarser particles. The samples were thereafter mechanically wet sieved (SWECO Separator LS18333, SWECO) to remove the fines by using sieves (SWECO) with apertures of 1.99 mm and 0.062 mm (Fig. 3.11C, D). Following the wet sieving, the samples were oven-dried (Fig. 3.11E) and weighed again, thereby giving the mass of removed fines in the samples.

For the dry sieving process (Fig. 3.11F, G), both principal sizes and supplementary sizes according to ISO 565 (1990) were used, since both the flakiness index test and shape index test use these sieves as a basis for the tests. Thus, each sample was sieved in two rounds, first with sieves (Endecotts) with apertures of 12.5, 10, 8, 6.3, 5, and 4 mm, and thereafter for the smaller particles, i.e., with apertures of 2, 1, 0.500, 0.250, 0.125, and 0.063 mm. The dry sieving process was performed mechanically (Rotap RX-29H&B, W.S. Tyler) for a minimum of 15 minutes (Fig. 11F) and thereafter manually for each individual fraction for a minimum of one minute (Norwegian Public Roads Administration, 2016). The sieving results are described by the share of fines content (weight %) and D50 (particle size in mm at 50% passing), as well as presented graphically. The finished sieved fractions for every sample were placed in 10 individual plastic bags of 12.5, 10, 8, 6.3, 5, 4, 2, 1, 0.500, and 0.250 mm and smaller, which then were ready to be used in the remaining tests, i.e., the tests of particle shape and the test of mineralogical composition.

Figure 3.11 *(A–E) The process of wet sieving for removing and calculating the amount of fines in a till sample. (F & G) The following dry sieving process, where (H) shows the finished sieved fractions for a sample placed in 10 individual plastic bags, i.e., 12.5, 10, 8, 6.3, 5, 4, 2, 1, 0.500, and 0.250 mm and smaller, which then were ready to be used in the remaining tests in the study.*

3.3.6 Particle shape

For coarse fractions, the shape of a particle may be expressed in terms of three independent properties, i.e., the form (overall shape), the roundness (large-scale smoothness), and the surface texture (small-scale smoothness) (Barret, 1980; NS–EN ISO 14688-1, 2002), see Figs. 3.12 and 3.13, and Table 3.4. The roundness of a particle depends on the sharpness of the edges and corners, and it is thus independent of the shape (Powers, 1953). For instance, sphericity may express the shape, while the roundness provides a summarised expression for certain detailed characteristics of the solid (Wadell, 1932). Elongated and cubical shaped particles are considered to have a low and high sphericity, respectively (McLean & Gribble, 1985).

Table 3.4 *Terms for the designation of particle shape (NS–EN ISO 14688-1, 2002).*

Parameter	Particle shape
Form	Cubic
	Flat
	Elongate
Roundness	Very angular
	Angular
	Subangular
	Subrounded
	Rounded
	Well-rounded
Surface texture	Rough
	Smooth

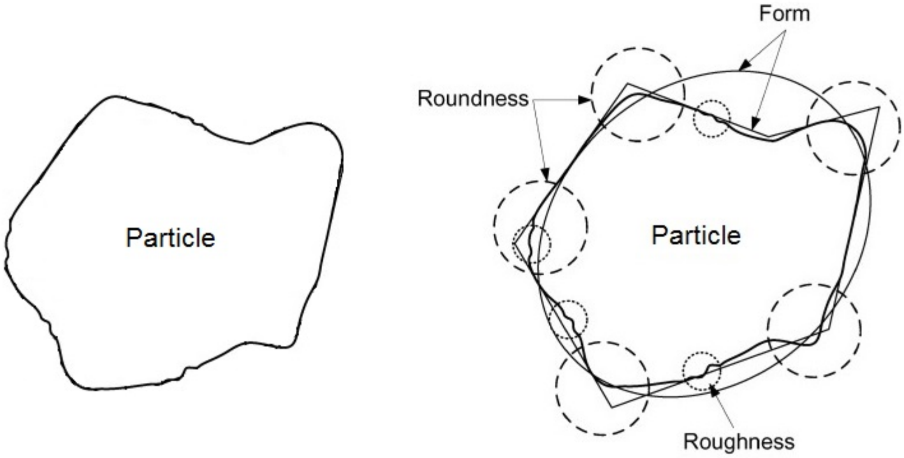

Figure 3.12 *The figure shows the three different terms of particle shape, i.e., form (overall shape), roundness/angularity (large-scale smoothness), and surface texture/roughness (small-scale smoothness), modified from Zhao & Wang (2016).*

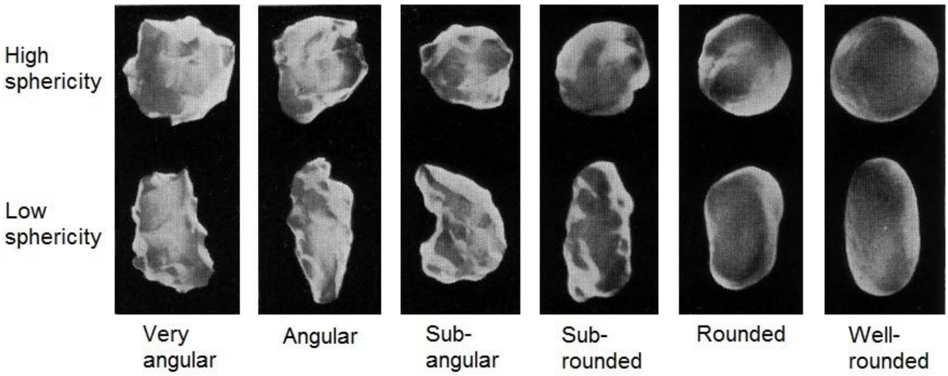

Figure 3.13 *An example of a particle roundness scale, ranging from 'very angular' to 'well-rounded', modified from Powers (1953).*

3.3.6.1 Flakiness index

In contrast to the particle size distribution test, several methods are possible regarding the evaluation of particle shape, such as digital image processing (e.g., Kwan et al., 1999). In order to describe the particle shape in detail, there are published a number of terms, quantities and definitions in the literature (Rodriguez et al., 2013). The flakiness index (FI) is a simple test commonly used in European countries that gives an indication of the amount of flaky particles in a sample as a percentage of the total mass of the sample (Uthus, 2007). Thus, a low flakiness index basically expresses that the majority of particles are closer to a cubic shape rather than a flaky shape. The descriptions provided in NS–EN 933-3 (2012) were used as a basis for this test. The six retrieved fractions from the sieves with apertures of 12.5/16, 10/12.5, 8/10, 6.3/8, 5/6.3, and 4/5 mm, i.e., material passing the highest and retained on the lowest value of sieve apertures (12.5, 10, 8, 6.3, 5, and 4 mm), were sieved with grid sieves (Endecotts) with a slot width of 8, 6.3, 5, 4, 3.15, and 2.5 mm, respectively (Fig. 3.14A). Each of these dry fractions was manually sieved for a minimum of two minutes (Fig. 3.14B), where both the initial and passing material were weighed to calculate the FI value for the sample (Fig. 3.14C, D), which was rounded to the nearest whole number.

Figure 3.14 *(A) The flakiness index test by using a total of six grid sieves. (B & C) Performing manual sieving. (D) Afterward, the material portions were weighed to calculate the FI value of the till sample. (C) is from Opsal & Langeland (2018).*

3.3.6.2 Shape index

The shape index (SI) is a test method for determining the elongation of particles. Like the flakiness index, the shape index is performed on particle sizes equal to or larger than 4 mm. Furthermore, the particle length is described as the maximum dimension of a particle, i.e., the greatest distance apart of two parallel planes tangential to the particle surface. Particle thickness is described as the minimum dimension of a particle, i.e., the least distance apart of two parallel planes tangential to the particle surface (Uthus, 2007). Each individual sample fraction retained on the 12.5, 10, 8, 6.3, 5, and 4 mm sieves was manually examined with the use of a customised particle slide gauge (Fig. 3.15A) according to the standard requirements (NS–EN 933-4, 2008). This was done to find the percentage share of particles with a length-to-thickness dimension ratio larger than 3 (Fig. 3.15B). Although image analyses are considered more sophisticated in their characterisation of the particle shape, a combination of FI and SI was chosen, as this combination, even without taking the roundness/angularity into account, was concluded useful by Uthus (2007). As for FI, the portions were weighed to calculate the SI value, rounded to the nearest whole number.

Figure 3.15 *(A) The shape index test by using a customised particle slide gauge to determine the length and thickness of particles. (B) After a completed shape index test, the elongated particles were placed in the blue plastic bags, while the cubical particles were placed in the smaller red bags. The portions of material were thereafter weighed to calculate the SI value of the till sample.*

3.3.6.3 Roundness and surface texture

In addition to the previous particle shape (form) tests, selected fractions of each sample were examined for the evaluation of particle roundness (angularity) and surface texture (roughness). The particles retained on the sieves of 16, 12.5, and 10 mm were both visually and manually examined by hand to evaluate the particle roundness and surface texture (Fig. 3.16; Appendix 3). In addition, the four smaller fractions (8, 6.3, 5, and 4 mm) were evaluated visually with the use of photographs. Since such particle characteristics may vary from one particle to another due to, e.g., the potential mix of different rock types in the tills, the presented results are therefore the considered most common particle roundness and surface texture of the samples. Although it is possible to provide numerical roundness values, this study describes the roundness qualitatively, as this method is more commonly used in geotechnical research (Altuhafi et al., 2016). For simplicity, the particles were thus classified according to four categories for roundness rather than the six categories given in NS–EN ISO 14688-1 (2002), i.e., ‘rounded’ (R), ‘subrounded’ (SR), ‘subangular’ (SA), and ‘angular’ (A) (Holtz & Kovacs, 1981; Mazzullo et al., 1988). For surface texture, two categories were used, i.e., ‘rough’ (Ro) and ‘smooth’ (Sm) (NS–EN ISO 14688-1, 2002).

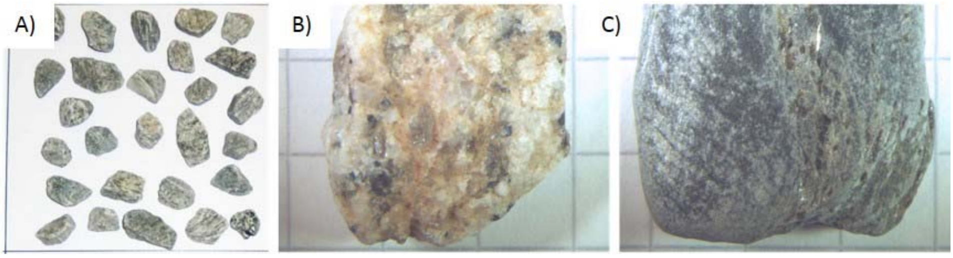

Figure 3.16 *(A) An example of a sieved fraction (material retained on the 10-mm sieve) of sample material (sample no. 11, prov. D) used together with other fractions for an evaluation of the most common particle roundness category of the till sample. (B & C) show examples of surface texture differences between particles (10-mm fraction) categorised as 'rough' (no. 9, prov. C) and 'smooth' (no. 21, prov. E), respectively (the paper squares behind the particles are 5 x 5 mm). From Opsal & Langeland (2018).*

3.3.7 Mineralogical composition

To investigate the relationship of bedrock geology and shear strength to mineralogy, till material from the 0.5-mm fraction, i.e., material passing the 1.0-mm sieve and retained on the 0.5-mm sieve, was chosen for XRD analysis. A test portion of approximately 20 g of material from each sample was chosen randomly by the process of splitting with a rotary sample divider (PT, Retsch) (Fig. 3.17A, B). The portions were thereafter crushed for one minute by a vibratory disc mill (SIEBTECHNIK) (Fig. 3.17C–E). The crushed material was then prepared in individual plastic discs (sample holders) before performing the test in the X-ray diffraction apparatus (D8 ADVANCE, Bruker Corp.) (Fig. 3.17F, G). The results were interpreted and then simplified, i.e., main mineral categories were used in the presentation of results. For example, biotite and muscovite were listed together as mica.

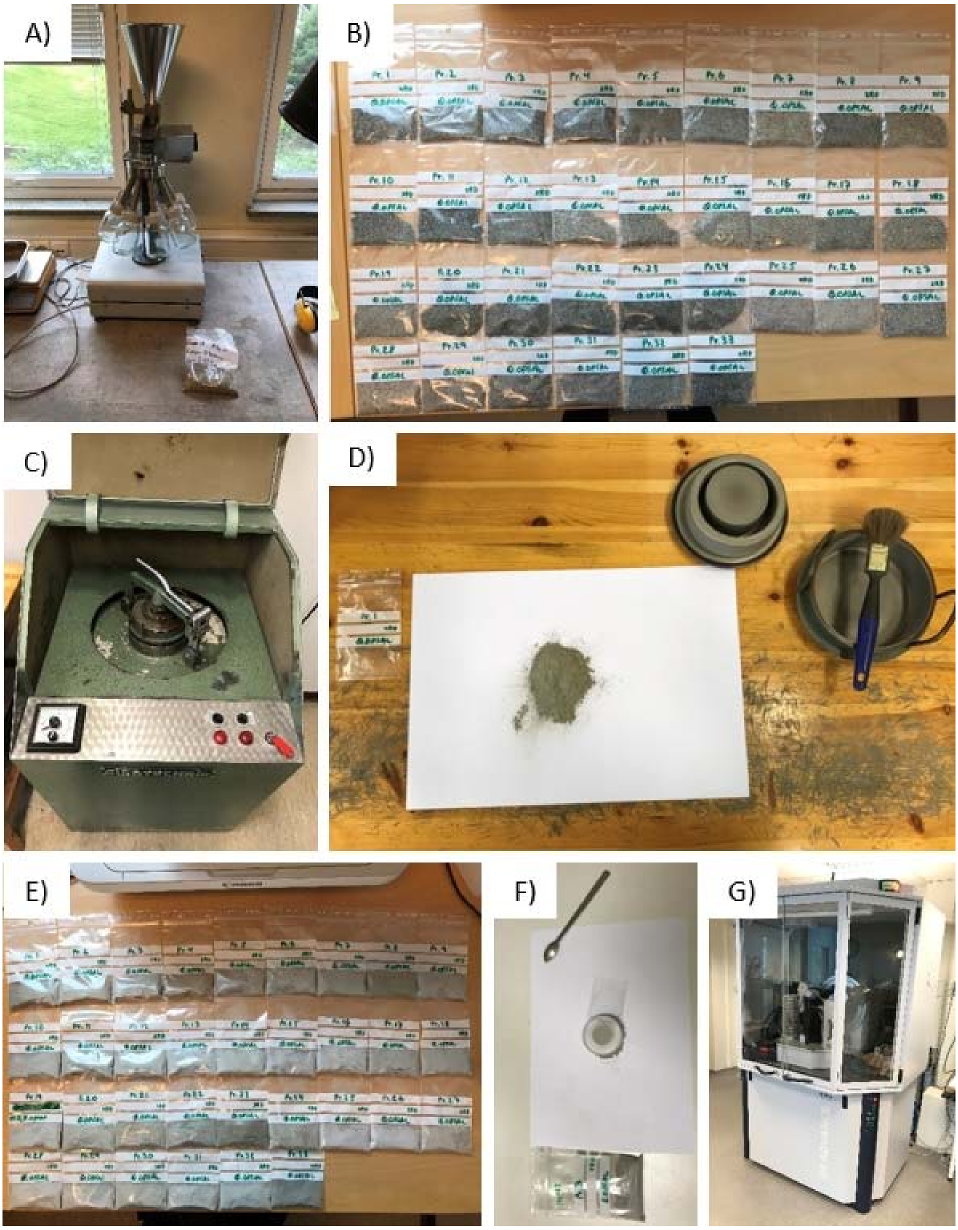

Figure 3.17 *(A) Splitting of sample material (0.5-mm fraction) to individual portions of approx. 20 g with a rotary sample divider. (B) Finished split portions from all 33 till samples. (C) Crushing the portions in a disc mill for 1 minute. (D) The collected crushed material from a sample. (E) Finished crushed portions from all 33 samples. (F) Preparation of crushed material in individual plastic discs (sample holders) for XRD analysis. (G) Testing in the XRD-apparatus, D8 ADVANCE.*

3.4 Supplementary work

3.4.1 Ice-flow directions, bedrock geology and till origin

From the sample locations (Table 3.2), a simplified bedrock geology map of the southern half of Norway was used as a basis to categorise the actual sample sites into regional, major rock provinces (Fig. 3.3; Table 3.1). For verification, the GPS-coordinates of the sample sites were compared to the bedrock geology map from NGU (2016b). In addition to transport distances of till, another key aspect in this context was the influence of the ice-flow directions, which during the different phases of the Weichselian glaciation altered due to the shifts of the ice divide (Vorren, 1977). Both regional and local studies by, e.g., Bergersen & Garnes (1971, 1972) and Reite (1994), have shown that the Weichselian ice-flow directions have altered quite significantly. Thus, for simplicity, only the major ice-flow directions on a national scale in the late Weichselian were considered when evaluating the possible rock material assumed to constitute the till samples.

After categorising the sample sites with respect to the major rock provinces A–H retrieved from the bedrock geology map, seven out of eight provinces were represented. Province H, which is also by far the smallest province, was not represented. It was therefore excluded, as it was considered too small, and that the amount of till deposits in this coastal area was relatively small. Similarly, province B was the second smallest in size, but it also overlapped with province A. Thus, due to the relatively small area of province B, as well as its overlapping with province A, there was a possibility of mixing of the rock types between these two provinces. However, due to the ice-flow directions in this southeastern part of Norway, it was considered more likely that province A was influenced by province B, rather than the opposite. For simplicity, provinces A and B were combined as one province, designated as A/B. Hence, between five to seven samples were collected from each of the remaining six provinces A/B–G (Fig. 3.3; Table 3.2).

When combining the late Weichselian ice-flow directions (Fig. 3.18A) and the bedrock geology map (NGU, 2016b) with the sample sites, a full (360º) or half (180º) circle with a radius of about five kilometres was drawn around the center of the sample sites and used as outer limits for sorting out the most likely rock type(s) constituting the till samples. A full circle was used for the samples considered to be in or near the area of the ice divide, as the ice-flow directions were unspecified in these areas (Fig. 3.18B). For samples considered to be outside the ice divide, a half circle was made from the sample site 'downstream' of the major ice-flow direction. Hence, for an ice-flow direction towards the west, rock type(s) east of the sample site were included, while rock type(s) further west of the sample site were excluded, as this would be ‘countercurrent’ and therefore considered unlikely (Fig. 3.18C). After excluding areas on the map where the bedrock is covered, i.e., fjords, lakes, and rivers, the up to three most dominant rock type(s) within the remaining radius zone were selected and listed for each sample site. Their assumed influence regarding till content was based on their individual area size within the full or half circle, which were approximately measured in the planar view and calculated. The first rock type listed represents the rock type in the area from which the sample itself was collected, independent of its area size, while the remaining rock types are listed with a chronological and decreasing respective percentage share.

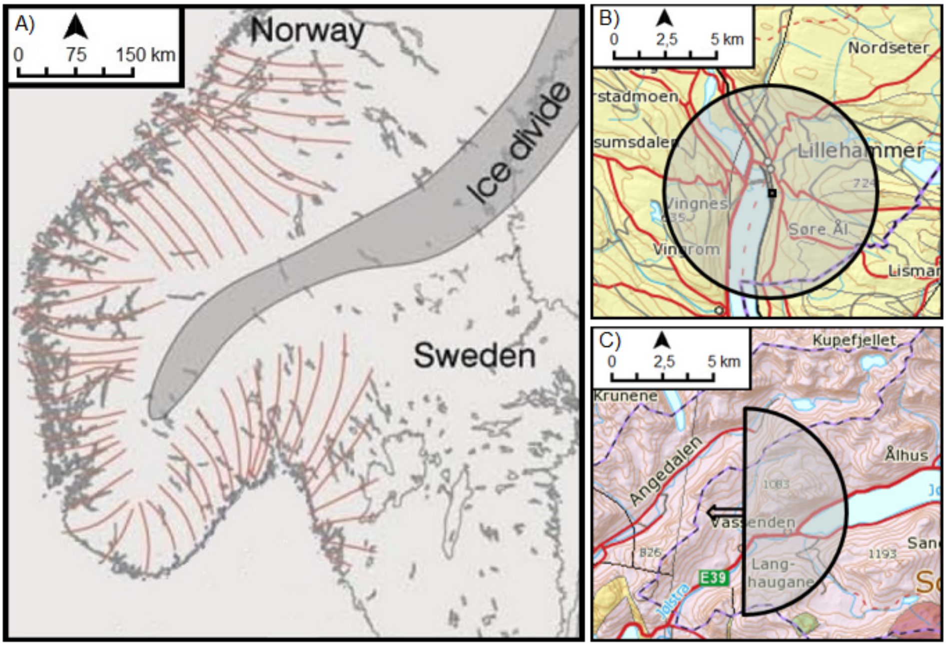

Figure 3.18 *(A) Reconstructed ice-sheet flow regime of the late Weichselian in the southern half of Norway, where red lines indicate ice-flow directions from the ice divide towards the coastline. Modified figure, originally from Ottesen et al. (2005), as cited by Opsal (2017). (B) Bedrock geology map showing the rock type(s) outside and within a full circle with a radius of five kilometres from sample no. 3, Lillehammer (prov. F), categorised as inside/near the ice divide. (C) Bedrock geology map showing the rock type(s) outside and within a half-circle with a radius of five kilometres from sample no. 16, Jølster (prov. G). This sample is categorised as outside the ice divide with westwards ice-flow direction illustrated by the black arrow. (B & C) are modified from NGU (2016b), as cited by Opsal (2017).*

3.4.2 Processing of shear test results

Regarding the shear test results, the maximum shear stress (rounded to whole numbers of kPa) registered by the SB2010 for the whole displacement length for each shear test were processed to estimate the angle of friction and cohesion by linear regression analysis, restraining the fit of the data to cohesion ≥ 0 kPa (Fig. 2.10). According to BS 1377–7 (1990), the reported angle of friction, ϕ, was rounded to the closest 0.5°, while the cohesion, c, was rounded to one decimal place of kPa. The obtained results were also processed for the purpose of graphical visualisation of shear stress versus horizontal displacement. This plotting was performed by choosing the registered shear stress value closest to each whole millimeter from the entire displacement length of each shear test. When processing all the till samples in each province, both the highest and lowest registered values (independent of sample no.), as well as the average for all samples, for each 'whole millimeter' were plotted. This method made it possible to visualise the average curve, and that all the individual curves for each province lie somewhere within the minimum and maximum curves.

3.4.3 Parameter relationships

As described in Ch. 2.2, till may consist of a variable assortment of fractions, ranging from small clay particles to large boulders, although one may also have extremes, e.g., tills with an excess of clay, or tills mainly consisting of sand and gravel. To display the natural variability of this type of sediment, all results were included in the analyses and presentations, i.e., no extremes (outliers) were excluded. To investigate the potential parameter relationships, two correlation tests, i.e., Pearson correlation and Spearman rho correlation, were performed on all samples. This was done on the geological parameters that were based on a quantitative evaluation, i.e., fines content, D50, FI, SI, and XRD. Particle roundness and surface texture were excluded from the correlation tests, as these were based on a qualitative evaluation. In addition, the relationships between the quantitative geological parameters and the parameters from the shear test were evaluated, i.e., the initial dry testing density, ρ_d, the maximum shear stresses (named here as τ_1-τ_3 for 100, 200, and 300 kPa normal stress, respectively), as well as the angle of friction, ϕ, and the cohesion, c. Regarding XRD, only the main minerals that were present in (almost) all samples were included in these correlation tests, i.e., quartz, plagioclase, alkali feldspar, mica, amphibole, pyroxene, and chlorite. Other minerals, such as epidote, calcite, and dolomite, were not included due to their rather irregular presence in the samples and/or their small quantities, which were typically less than 1% and therefore considered insufficient for this purpose. For both correlation tests, a P-value ≤ 0.05 was used regarding statistical significance. For interpretation of the correlation coefficient, r, the range is from -1 to +1, whereas zero indicates no correlation. The positive numbers are classified as positive correlation, while negative numbers are classified as negative correlation. Three categories were used for the strength of association for both tests, which, according to Cohen (1988) are:

- Positive correlation:
    - 'Small correlation' ($0.1 \leq r < 0.3$).
    - 'Medium correlation' ($0.3 \leq r < 0.5$).
    - 'Large correlation' ($r \geq 0.5$).
- Negative correlation:
    - 'Small correlation' ($-0.3 < r \leq -0.1$).
    - 'Medium correlation' ($-0.5 < r \leq -0.3$).
    - 'Large correlation' ($r \leq -0.5$).

4. Results

This chapter presents the results from all the studies performed on the till samples:

- Bedrock geology and till origin.
- Particle size distribution.
- Particle shape.
- Mineralogical composition.
- Shear strength.
- Parameter relationships.

4.1 Bedrock geology: till origin

The method regarding bedrock geology and assumed till origin is described in Ch. 3.4.1 and Fig. 3.18, while the results are presented in Tables 4.1–4.6. Categorised by the rock provinces, the five samples in province A/B ('Extrusive and plutonic rocks/Sedimentary rocks in the Oslo region') were, except for sample no. 6, dominated by syenites and granites. Apart from sample no. 8, the remaining five samples in province C ('Precambrian basement') were dominated by a variety of gneisses and granites. Province D ('Caledonian rocks, Overthrust sheets of Precambrian rocks') was in general dominated by mangerite, gabbro, amphibolite and gneiss, whereas sample no. 13 was solely represented by anorthosite. Province E ('Caledonian rocks, Metamorphic and igneous rocks') was the most variable concerning the number of represented rock types in the samples. Overall, mica gneiss, mica schist, greenstone, amphibolite, metasandstone, and phyllite were heavily represented in province E. Moreover, province F ('Caledonian rocks, Overthrust sheets of sandstone and schist') was relatively homogeneous regarding rock types, as the samples were dominated by sandstone. Province G ('Caledonian rocks, Precambrian basement, locally affected by the Caledonian orogeny') was also relatively homogeneous regarding rock types, as all of the five samples were dominated by various gneisses and migmatites.

Table 4.1 *Rock types within 5 km distance for the five sample sites from rock province A/B, Extrusive and plutonic rocks/Sedimentary rocks in the Oslo region (Opsal, 2017).*

Rock province	Sample no.	Rock types
A/B	5	Syenite, quartz syenite (~86%); Granite, granodiorite (~14%)
	6	Phyllite, mica schist (~28%); Rhomb-porphyry (~27%); Granite, granodiorite (~16%); Other (~29%)
	30	Syenite, quartz syenite (~68%); Granite, granodiorite (~32%)
	31	Syenite, quartz syenite (~83%); Unspecified volcanic rocks (~8%); Granite, granodiorite (~7%); Other (~2%)
	32	Granite, granodiorite (~67%); Monzonite, quartz monzonite (~24%); Rhomb-porphyry (~9%)

Table 4.2 *Rock types within 5 km distance for the six sample sites from rock province C, Precambrian basement (Opsal, 2017).*

Rock province	Sample no.	Rock types
C	4	Augen gneiss, granite, foliated granite (~18%); Amphibolite, hornblende gneiss, mica gneiss (locally migmatitic) (~62%); Sandstone, slate (~14%); Other (~6%)
	7	Augen gneiss, granite, foliated granite (~84%); Dioritic to granitic gneiss, migmatite (~8%); Amphibolite, hornblende gneiss, mica gneiss (locally migmatitic) (~4%); Other (~4%)
	8	Rhyolite, rhyodacite, dacite, keratophyre (~34%); Quartzite (~40%); Basalt (~26%)
	9	Granite, granodiorite (~88%); Amphibolite, hornblende gneiss, mica gneiss (locally migmatitic) (~7%); Augen gneiss, granite, foliated granite (~4%); Other (~1%)
	28	Gabbro, amphibolite (~24%); Dioritic to granitic gneiss, migmatite (~43%); Augen gneiss, granite, foliated granite (~33%)
	29	Augen gneiss, granite, foliated granite (~3%); Dioritic to granitic gneiss, migmatite (~81%); Gabbro, amphibolite (~16%)

Table 4.3 *Rock types within 5 km distance for the five sample sites from rock province D, Caledonian rocks, Overthrust sheets of Precambrian rocks (Opsal, 2017).*

Rock province	Sample no.	Rock types
D	10	Mangerite to gabbro, gneiss and amphibolite (~96%); Olivine rock, pyroxenite (~3%); Phyllite, mica schist (~1%)
	11	Mangerite to gabbro, gneiss and amphibolite (~100%)
	12	Mangerite to gabbro, gneiss and amphibolite (~74%); Gabbro, amphibolite (~16%); Dioritic to granitic gneiss (~10%)
	13	Anorthosite (~100%)
	14	Mangerite-syenite (~84%); Anorthosite (~12%); Dioritic to migmatitic gneiss (~3%); Other (~1%)

Table 4.4 *Rock types within 5 km distance for the seven sample sites from rock province E, Caledonian rocks, Metamorphic and igneous rocks (Opsal, 2017).*

Rock province	Sample no.	Rock types
E	1	Phyllite, mica schist (~47%); Metasandstone, mica schist (~31%); Amphibolite, hornblende gneiss, mica gneiss (locally migmatitic) (~18%); Other (~4%)
	20	Greenstone, amphibolite (~54%); Slate, sandstone, limestone (~38%); Conglomerate, sedimentary breccia (~7%); Other (~1%)
	21	Phyllite, mica schist (~77%); Quartzite (~17%); Greenstone, amphibolite (~6%)
	22	Greenstone, amphibolite (~29%); Slate, sandstone, limestone (~37%); Unspecified volcanic rocks (~21%); Other (~13%)
	23	Greenstone, amphibolite (~5%); Mica gneiss, mica schist, metasandstone, amphibolite (~65%); Quartzite (~30%)
	24	Mica gneiss, mica schist, metasandstone, amphibolite (~97%); Greenstone, amphibolite (~3%)
	33	Mica gneiss, mica schist, metasandstone, amphibolite (~92%); Quartzite (~6%); Greenstone, amphibolite (~2%)

Table 4.5 *Rock types within 5 km distance for the five sample sites from rock province F, Caledonian rocks, Overthrust sheets of sandstone and schist (Opsal, 2017).*

Rock province	Sample no.	Rock types
F	2	Sandstone (~65%); Metasandstone, mica schist (~22%); Quartzite (~6%); Other (~7%)
	3	Sandstone (~100%)
	25	Sandstone (~100%)
	26	Sandstone (~88%); Quartzite (~10%); Conglomerate, sedimentary breccia (~1%); Other (~1%)
	27	Sandstone (~93%); Conglomerate, sedimentary breccia (~6%); Limestone, dolomite (~1%)

Table 4.6 *Rock types within 5 km distance for the five sample sites from rock province G, Caledonian rocks, Precambrian basement, locally affected by the Caledonian orogeny (Opsal, 2017).*

Rock province	Sample no.	Rock types
G	15	Dioritic to granitic gneiss, migmatite (~97%); Augen gneiss, granite, foliated gneiss (~3%)
	16	Dioritic to granitic gneiss, migmatite (~100%)
	17	Dioritic to granitic gneiss, migmatite (~99%); Olivine rock, pyroxenite (~1%)
	18	Dioritic to granitic gneiss, migmatite (~100%)
	19	Dioritic to granitic gneiss, migmatite (~92%); Amphibolite and mica schist (~8%)

4.2 Particle size distribution

Regarding particle size distribution, the percentage share of fines was on average 25.8% (standard deviation (SD) = 13.2%; median = 26.5%), while the average D50 was 0.70 mm (SD = 1.03 mm; median = 0.23 mm), see Figs. 4.1–4.8 and Table 4.8. The percentage share of fines in the samples varied significantly, ranging from 1.2% to 50.4%. Correspondingly, the highest and lowest values for D50 were 4.81 mm and 0.06 mm, respectively. When categorised by the provinces, A/B, D, and G showed a considerably lower variation regarding the fines content than provinces C, E, and F. For D50, provinces C, F, and G showed the largest variations, while provinces D, E, and especially A/B, had a noticeably lower variation.

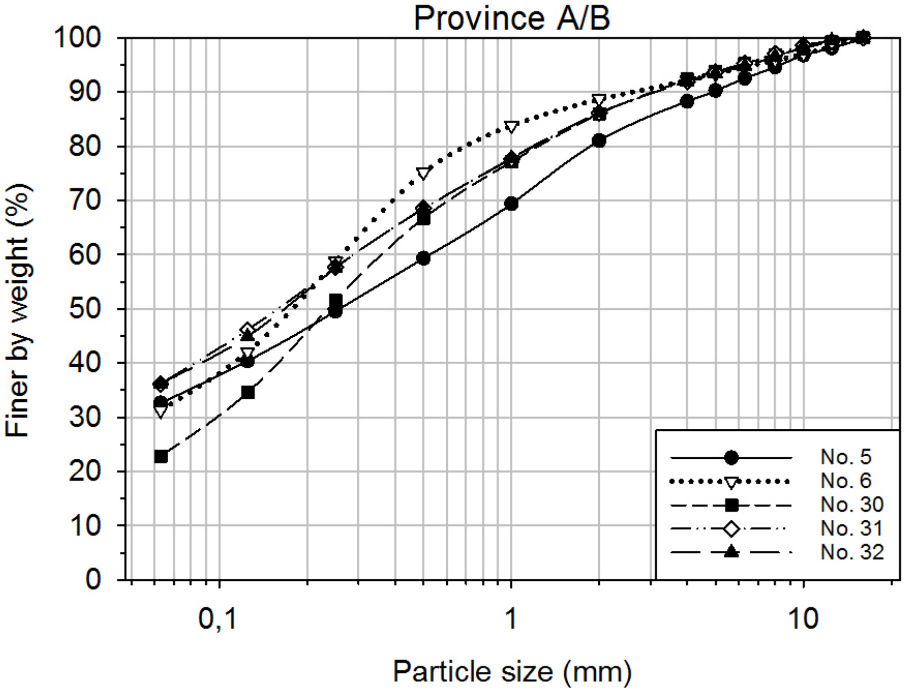

Figure 4.1 *Particle size distributions for province A/B (Opsal & Langeland, 2018).*

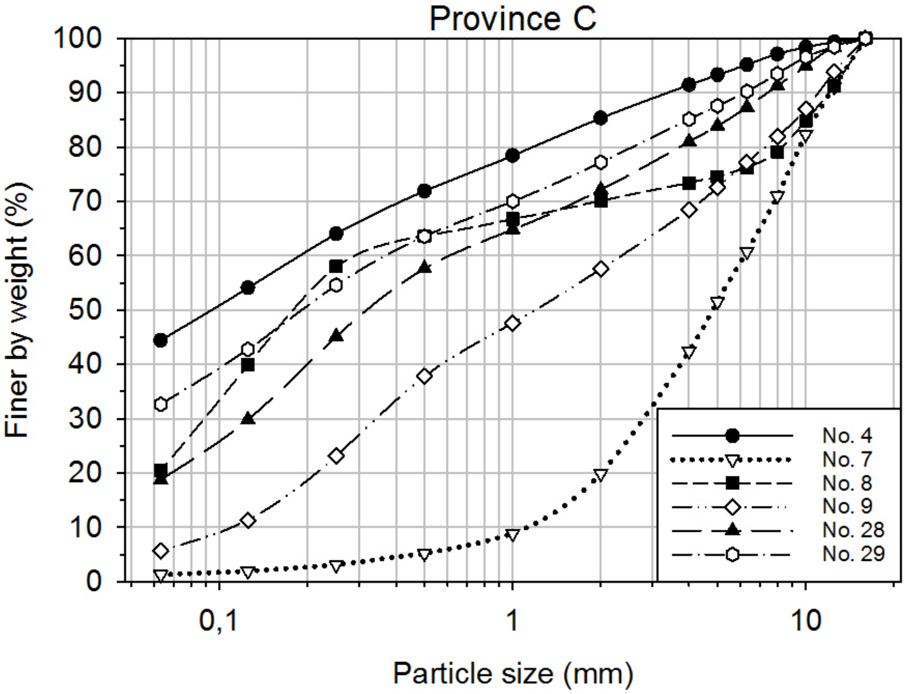

Figure 4.2 *Particle size distributions for province C (Opsal & Langeland, 2018).*

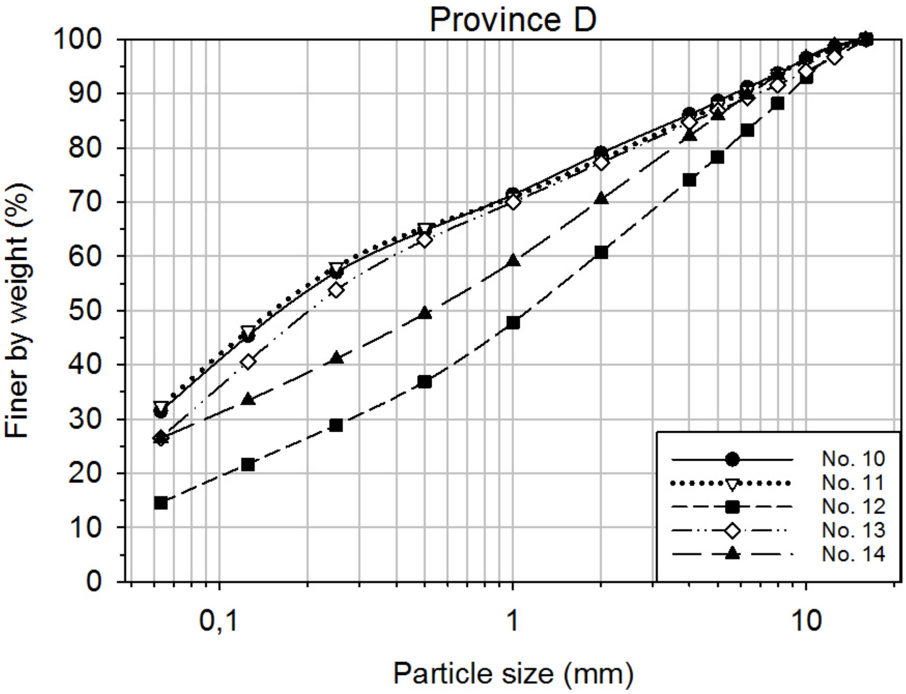

__Figure 4.3__ Particle size distributions for province D (Opsal & Langeland, 2018).

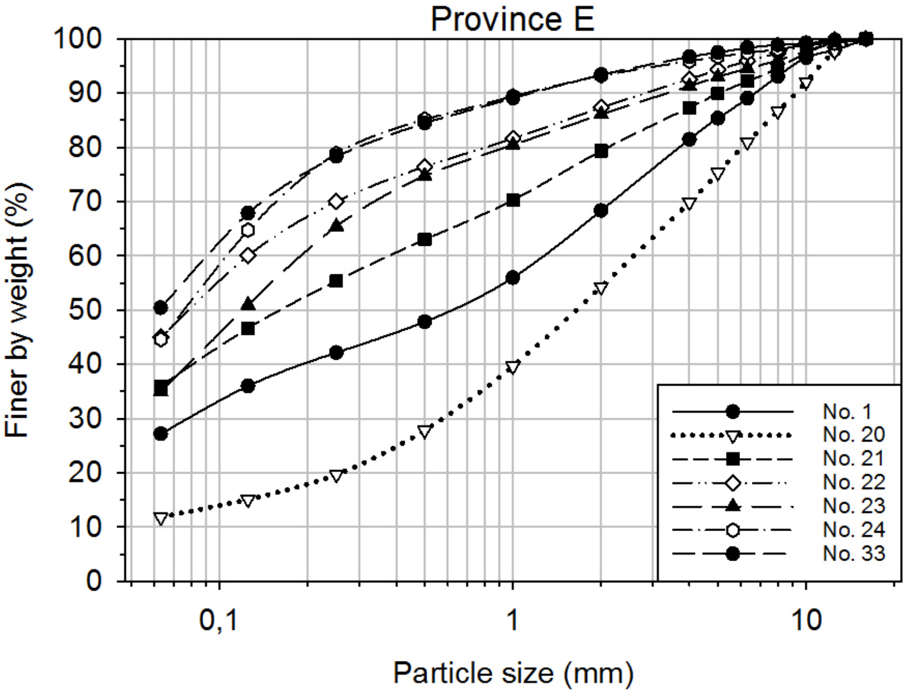

__Figure 4.4__ Particle size distributions for province E (Opsal & Langeland, 2018).

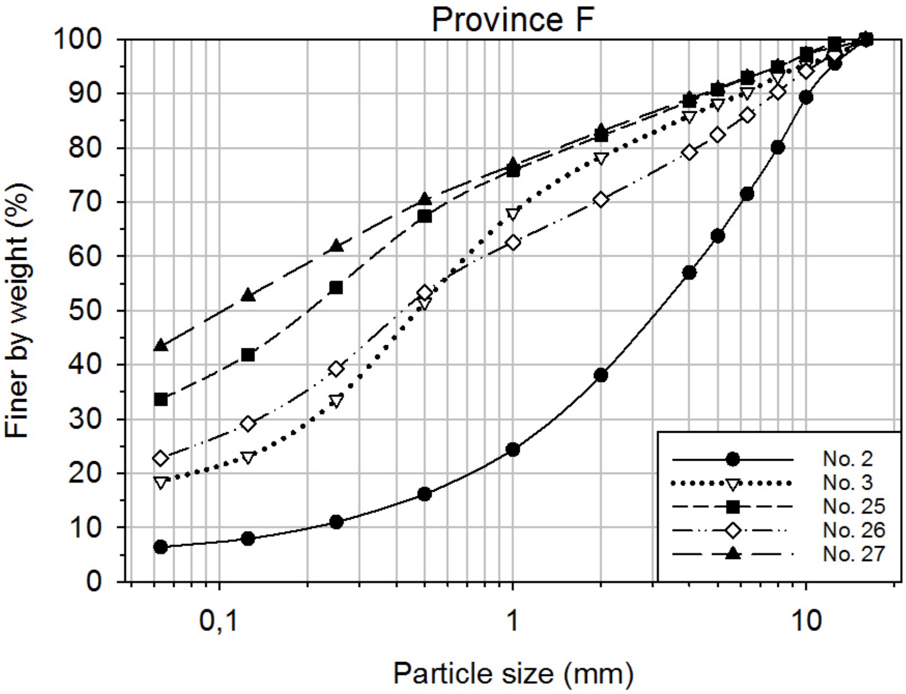

Figure 4.5 *Particle size distributions for province F (Opsal & Langeland, 2018).*

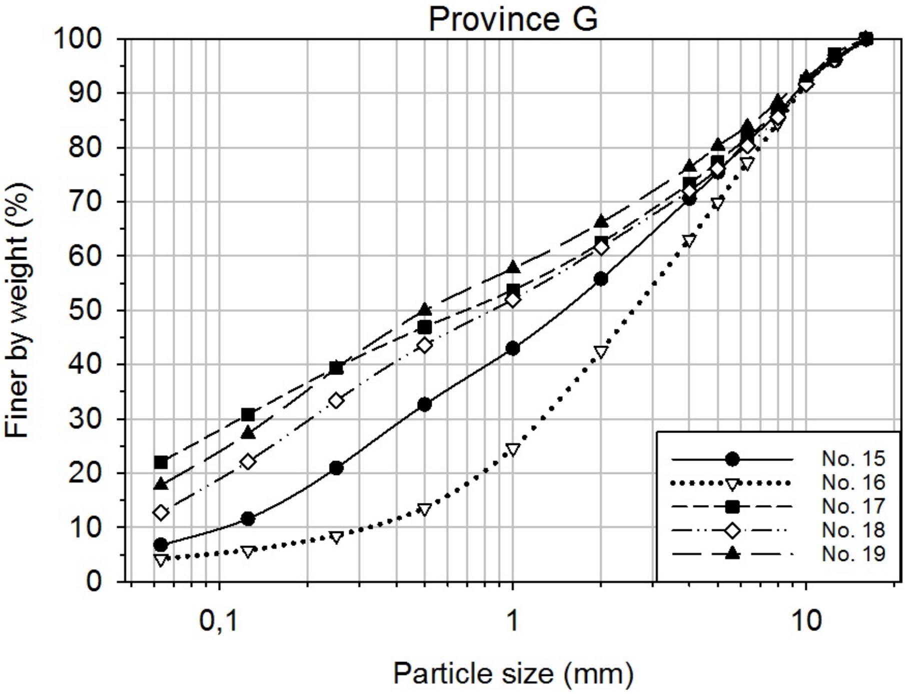

Figure 4.6 *Particle size distributions for province G (Opsal & Langeland, 2018).*

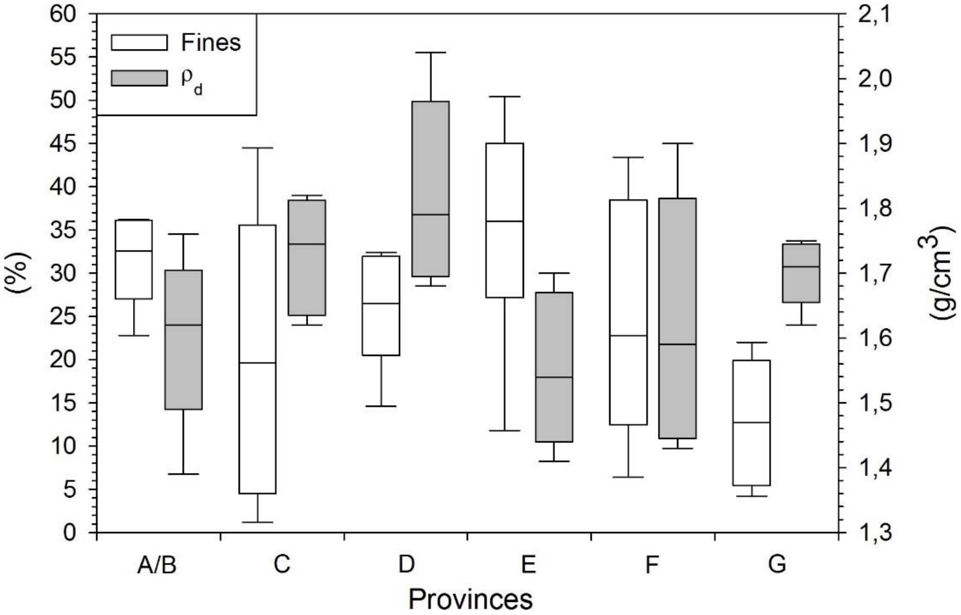

Figure 4.7 *Box plots for fines content, as well as initial dry testing density, ρ_d, from the shear test (Opsal, 2017; Opsal & Langeland, 2018). The results are categorised by the six rock provinces, where the boxes represent the 25th and 75th percentiles, and the solid line represents the median. The whiskers above and below the boxes show the maximum and minimum points, and the box plots are based on 5 to 7 samples per province (this also counts for the box plots in Figs. 4.8, 4.10, and 4.11).*

4.3 Particle shape

For the particle shape tests, the average of FI and SI were 7.9% (SD = 6.1%; median = 6.0%) and 11.4% (SD = 9.2%; median = 8.0%), respectively (Fig. 4.8; Table 4.8). The highest and lowest values for FI were 28% and 2%, respectively. Likewise, the highest value for SI was 39%, while the lowest value was 2%. Distributed by the provinces, provinces A/B, D, and G showed a quite similar, as well as a considerably lower variation of results compared to provinces C, E, and F regarding both FI and SI. When considering particle roundness, provinces A/B, C, and D ranged from angular to subangular, provinces E and G were classified solely as subangular, whereas province F ranged from subangular to subrounded. For particle surface texture, the most dominant category for 25 samples was rough, while the remaining eight samples were categorised as smooth. Apart from one sample in province C, the remaining samples classified as smooth were solely from provinces E and F.

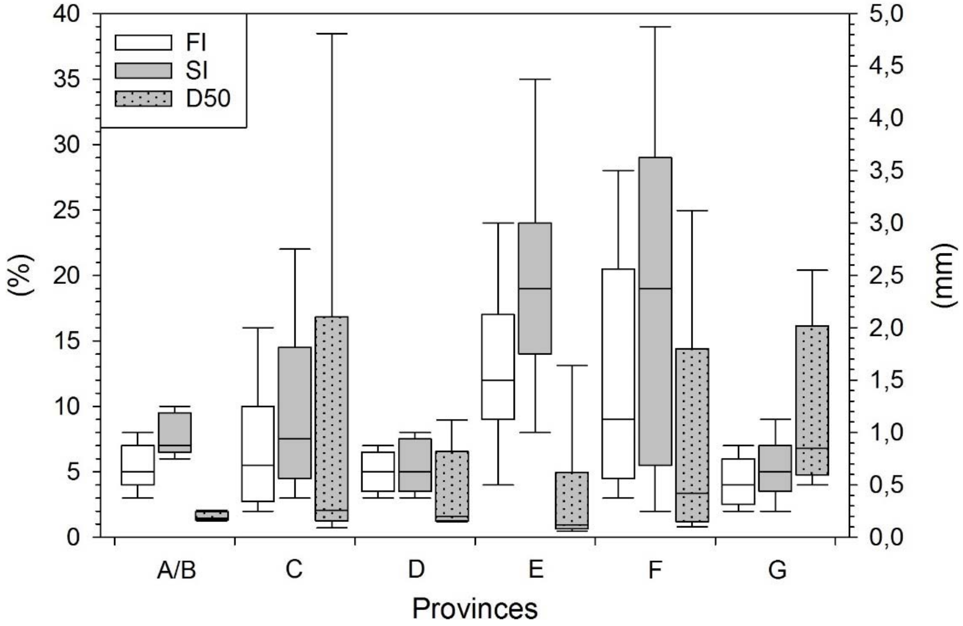

Figure 4.8 *Box plots for flakiness index (FI), shape index (SI), and D50, categorised by the six rock provinces (Opsal & Langeland, 2018).*

4.4 Mineralogical composition

Regarding the mineralogical composition based on the XRD analysis, the main minerals in all samples were quartz and plagioclase, i.e., these minerals had the largest percentage share in 18 and 15 samples, respectively (Fig. 4.9; Table 4.7). The individual maximum percentage share of quartz was 83%, while it was 61% for plagioclase. Other minerals, such as alkali feldspar, mica, amphibole and pyroxene, were also represented in most samples. In addition, minerals such as chlorite, dolomite and calcite were represented in many samples, although usually in less amounts. Distributed by the rock provinces, quartz was clearly dominating in provinces E and F, whereas provinces D and G were dominated by plagioclase. Provinces A/B and C were also dominated by quartz, even though the results varied more than for provinces E and F. The differences of plagioclase and quartz amongst the provinces were especially noticeable in provinces D and F.

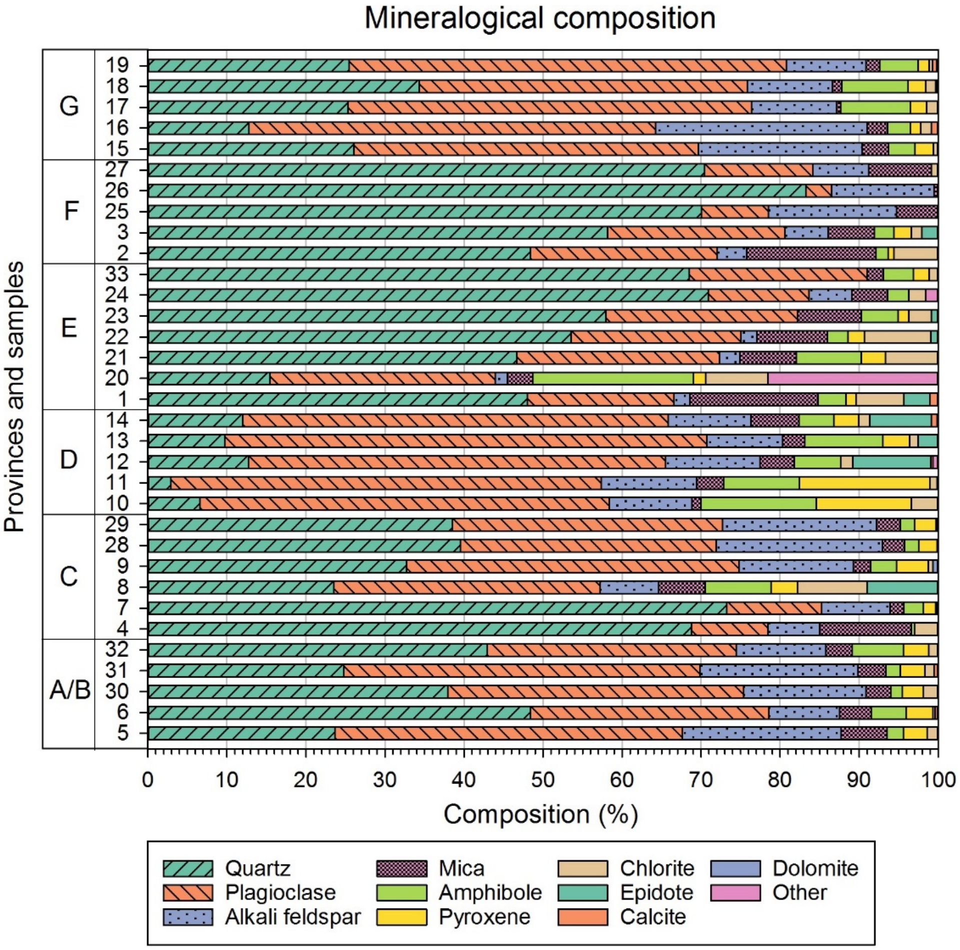

Figure 4.9 *A stacked horizontal bar diagram displaying the results from the XRD analysis, i.e., the mineralogical composition in each of the 33 till samples distributed by the respective rock provinces (Opsal & Langeland, 2018).*

Table 4.7 *The mineralogical composition in the 33 till samples based on the XRD analysis. 8 samples have other minerals in addition to the ones listed in the table*.*

Rock prov. & s. no.	**Mineralogical composition (%)**									
	Qtz	**Pl**	**Afs**	**Mca**	**Am**	**Px**	**Chl**	**Ep**	**Cal**	**Dol**
A/B–5	23.63	44.04	20.08	5.76	2.12	2.99	1.36	0.00	0.00	0.02
A/B–6	48.39	30.19	8.97	3.95	4.40	3.44	0.24	0.00	0.37	0.04
A/B–30	37.96	37.45	15.47	3.16	1.41	2.67	1.82	0.00	0.00	0.05
A/B–31	24.82	45.01	20.01	3.59	1.80	3.13	1.12	0.00	0.42	0.10
A/B–32	42.93	31.52	11.31	3.39	6.44	3.24	1.11	0.00	0.00	0.07
C–4	68.80	9.64	6.55	11.64	0.37	0.00	3.00	0.00	0.00	0.00
C–7	73.25	11.99	8.66	1.76	2.52	1.52	0.12	0.00	0.18	0.00
C–8*	23.52	33.73	7.36	5.87	8.36	3.36	8.83	8.93	0.00	0.00
C–9	32.74	42.01	14.52	2.21	3.28	3.97	0.58	0.00	0.00	0.69
C–28	39.54	32.40	20.99	2.79	1.79	2.36	0.08	0.00	0.00	0.04
C–29	38.55	34.13	19.48	3.00	1.81	2.74	0.23	0.00	0.00	0.05
D–10	6.57	51.82	10.47	1.16	14.59	12.01	3.37	0.00	0.00	0.00
D–11	2.88	54.49	12.06	3.44	9.59	16.44	0.99	0.00	0.00	0.12
D–12*	12.70	52.81	11.94	4.32	5.90	0.00	1.50	9.92	0.26	0.00
D–13	9.74	60.98	9.60	2.82	9.86	3.44	1.06	2.50	0.00	0.00
D–14*	11.98	53.86	10.44	6.13	4.39	3.15	1.38	7.85	0.71	0.00
E–1	48.00	18.59	1.99	16.20	3.52	1.28	6.08	3.29	1.04	0.00
E–20*	15.47	28.49	1.52	3.19	20.40	1.52	7.86	0.00	0.00	0.00
E–21*	46.69	25.63	2.58	7.16	8.20	3.08	6.57	0.00	0.00	0.00
E–22	53.59	21.46	1.97	8.94	2.61	2.06	8.43	0.94	0.00	0.00
E–23	57.98	24.18	0.00	8.08	4.71	1.33	2.83	0.90	0.00	0.00
E–24*	70.93	12.72	5.41	4.53	2.65	0.00	2.17	0.00	0.00	0.00
E–33	68.52	22.46	0.00	2.09	3.79	2.03	1.11	0.00	0.00	0.00
F–2	48.42	23.64	3.74	16.35	1.53	0.75	5.56	0.00	0.00	0.00
F–3*	58.14	22.47	5.43	5.91	2.47	2.16	1.36	1.98	0.00	0.00
F–25*	70.06	8.43	16.23	5.23	0.00	0.00	0.00	0.00	0.00	0.00
F–26	83.24	3.30	12.90	0.56	0.00	0.00	0.00	0.00	0.00	0.00
F–27	70.44	13.69	7.06	7.98	0.00	0.00	0.83	0.00	0.00	0.00
G–15	26.06	43.56	20.78	3.34	3.32	2.34	0.50	0.00	0.00	0.09
G–16	12.75	51.52	26.74	2.58	2.85	1.34	1.39	0.00	0.80	0.03
G–17	25.30	51.10	10.73	0.55	8.79	2.06	1.46	0.00	0.00	0.00
G–18	34.30	41.55	10.72	1.24	8.42	2.15	1.27	0.00	0.25	0.10
G–19	25.43	55.36	10.04	1.76	4.90	1.41	0.35	0.00	0.54	0.21
Average	39.80	33.16	10.48	4.87	4.75	2.67	2.26	1.10	0.14	0.05
Standard deviation	22.55	16.03	6.80	3.89	4.41	3.26	2.57	2.64	0.27	0.12
Median	38.55	32.4	10.44	3.44	3.32	2.15	1.36	0.00	0.00	0.00
Maximum	83.24	60.98	26.74	16.35	20.40	16.44	8.83	9.92	1.04	0.69
Minimum	2.88	3.30	0.00	0.55	0.00	0.00	0.00	0.00	0.00	0.00
Difference	80.36	57.68	26.74	15.80	20.40	16.44	8.83	9.92	1.04	0.69

Qtz*, Quartz;* Pl, *Plagioclase;* Afs, *Alkali feldspar;* Mca*, Mica;* Am*, Amphibole;* Px*, Pyroxene;* Chl*, Chlorite;* Ep*, Epidote;* Dol*, Dolomite;* Cal*, Calcite;* Py*, Pyrite;* Sps*, Spessartine;* Sd, *Siderite;* Czo, *Clinozoisite;* Hul*, Heulandite;* Po*, Pyrrhotite. Abbrevations after Siivola & Schmid (2007).*

** Other minerals: sample no. 3 (Sd, 0.07%), no. 8 (Py, 0.04%), no. 12 (Hul, 0.66%), no. 14 (Sps, 0.10%), no. 20 (Czo, 21.56%), no. 21 (Po, 0.10%), no. 24 (Sps, 1.60%), and no. 25 (Py, 0.06%).*

4.5 Summary of geological parameters

This section summarises the results regarding the tests of the different geological parameters.

Table 4.8 *The results from all 33 till samples regarding fines content, D50, flakiness index (FI), shape index (SI), roundness/angularity (R/A, angular (A), subangular (SA), subrounded (SR), and rounded (R)), surface texture (ST, rough (Ro) and smooth (Sm)), and the XRD analysis. From Opsal & Langeland (2018).*

Rock prov. & s. no.	**Fines (%)**	**D50 (mm)**	**FI (%)**	**SI (%)**	**R/A**	**ST**	**XRD - the three most dominating minerals (%)**
A/B–5	32.6	0.26	5.0	6.0	SA	Ro	Pl (44%); Qtz (24%); Afs (20%)
A/B–6	31.3	0.18	5.0	7.0	SA	Ro	Qtz (48%); Pl (30%); Afs (9%)
A/B–30	22.8	0.23	3.0	7.0	A	Ro	Qtz (38%); Pl (37%); Afs (15%)
A/B–31	36.1	0.16	6.0	9.0	SA	Ro	Pl (45%); Qtz (25%); Afs (20%)
A/B–32	36.2	0.17	8.0	10.0	SA	Ro	Qtz (43%); Pl (32%); Afs (11%)
C–4	44.5	0.09	16.0	22.0	SA	Ro	Qtz (69%); Mca (12%); Pl (10%)
C–7	1.2	4.81	4.0	5.0	SA	Ro	Qtz (73%); Pl (12%); Afs (9%)
C–8	20.5	0.18	7.0	12.0	SA	Sm	Pl (34%); Qtz (24%); Ep (9%)
C–9	5.6	1.20	2.0	3.0	SA	Ro	Pl (42%); Qtz (33%); Afs (15%)
C–28	18.7	0.32	3.0	5.0	A	Ro	Qtz (40%); Pl (32%); Afs (21%)
C–29	32.6	0.19	8.0	10.0	A	Ro	Qtz (39%); Pl (34%); Afs (19%)
D–10	31.5	0.16	3.0	4.0	SA	Ro	Pl (52%); Am (15%); Px (12%)
D–11	32.4	0.15	5.0	8.0	SA	Ro	Pl (54%); Px (16%); Afs (12%)
D–12	14.6	1.12	7.0	7.0	SA	Ro	Pl (53%); Qtz (13%); Afs (12%)
D–13	26.5	0.20	6.0	5.0	SA	Ro	Pl (61%); Am (10%); Qtz (10%)
D–14	26.4	0.52	4.0	3.0	A	Ro	Pl (54%); Qtz (12%); Afs (10%)
E–1	27.2	0.62	14.0	24.0	SA	Sm	Qtz (48%); Pl (19%); Mca (16%)
E–20	11.8	1.64	4.0	8.0	SA	Sm	Pl (28%); Czo (22%); Am (20%)
E–21	36.0	0.16	17.0	24.0	SA	Sm	Qtz (47%); Pl (26%); Am (8%)
E–22	45.0	0.08	24.0	35.0	SA	Sm	Qtz (54%); Pl (21%); Mca (9%)
E–23	34.9	0.12	9.0	14.0	SA	Ro	Qtz (58%); Pl (24%); Mca (8%)
E–24	44.6	0.08	12.0	19.0	SA	Ro	Qtz (71%); Pl (13%); Afs (5%)
E–33	50.4	0.06	9.0	16.0	SA	Ro	Qtz (69%); Pl (22%); Am (4%)
F–2	6.4	3.12	28.0	39.0	SA	Sm	Qtz (48%); Pl (24%); Mca (16%)
F–3	18.5	0.48	13.0	19.0	SR	Sm	Qtz (58%); Pl (22%); Mca (6%)
F–25	33.6	0.20	6.0	9.0	SA	Ro	Qtz (70%); Afs (16%); Pl (8%)
F–26	22.8	0.42	3.0	2.0	SA	Ro	Qtz (83%); Afs (13%); Pl (3%)
F–27	43.4	0.10	9.0	19.0	SA	Sm	Qtz (70%); Pl (14%); Mca (8%)
G–15	6.7	1.49	2.0	2.0	SA	Ro	Pl (44%); Qtz (26%); Afs (21%)
G–16	4.2	2.55	5.0	5.0	SA	Ro	Pl (52%); Afs (27%); Qtz (13%)
G–17	22.0	0.69	7.0	9.0	SA	Ro	Pl (51%); Qtz (25%); Afs (11%)
G–18	12.7	0.85	3.0	5.0	SA	Ro	Pl (42%); Qtz (34%); Afs (11%)
G–19	17.8	0.50	4.0	5.0	SA	Ro	Pl (55%); Qtz (25%); Afs (10%)
Average	25.8	0.70	7.9	11.4			
Median	26.5	0.23	6.0	8.0			
Standard deviation	13.2	1.03	6.1	9.2			
Maximum	50.4	4.81	28.0	39.0			
Minimum	1.2	0.06	2.0	2.0			
Difference	49.2	4.75	26.0	37.0			

4.6 Shear strength

The shear test results for the main test are given in Figs. 4.7 and 4.10–4.20, and Tables 4.9–4.15, while the six samples retested for the purpose of repeatability assessment are presented in Tables 4.16 and 4.17. When considering all the 33 till samples, the average angle of friction was 38.4° (SD = 1.3°; median = 38.5°), spanning from 36.0° as the lowest, and to 41.5° as the highest value, i.e., a difference of 5.5°. Regarding the registered maximum shear stresses, the results showed a difference up to approximately 16%. When the results of the angle of friction were categorised by the provinces, province G was on average found to be the 'strongest' province (39.2°), while province F was found to be the 'weakest' province (37.4°).

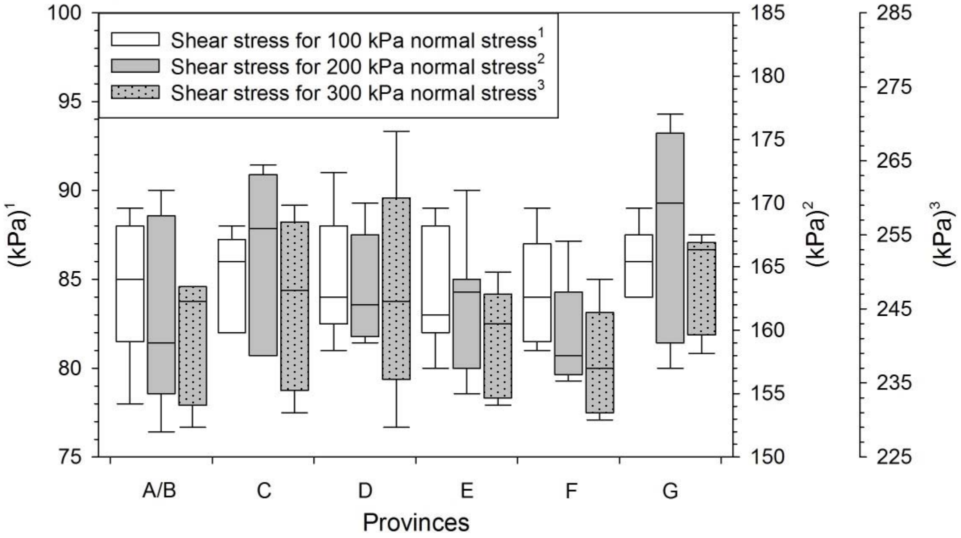

***Figure 4.10** Box plots for the main shear test results of the 33 till samples regarding the registered maximum shear stresses for 100, 200, and 300 kPa normal stress, categorised by the six rock provinces (Opsal & Langeland, 2018).*

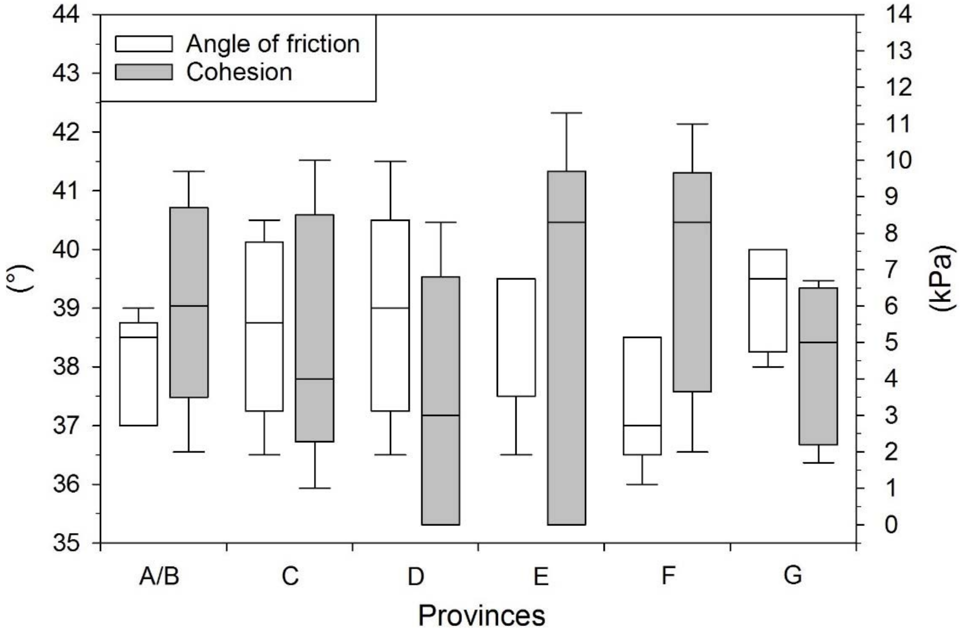

Figure 4.11 *Box plots for the main shear test results of the 33 till samples regarding the angle of friction and cohesion, categorised by the six rock provinces (Opsal & Langeland, 2018).*

Table 4.9 *The shear test results for the five till samples from rock province A/B (Opsal, 2017).*

Rock province	**Sample no.**	**Initial dry testing density, ρ_d (g/cm^3)**	**Max. shear stress, τ, with normal stress, σ (kPa)**			**Angle of friction, ϕ (°)**	**Cohesion, c (kPa)**
			σ = 100 (kPa)	**σ = 200 (kPa)**	**σ = 300 (kPa)**		
A/B	5	1.39	89.0	158.0	248.0	38.5	6.0
	6	1.65	85.0	159.0	235.0	37.0	9.7
	30	1.76	78.0	152.0	229.0	37.0	2.0
	31	1.59	85.0	171.0	248.0	39.0	5.0
	32	1.62	87.0	167.0	246.0	38.5	7.7
Average		1.60	84.8	161.4	241.2	38.0	6.1
Standard deviation		0.13	4.1	7.6	8.7	0.9	2.9
Median		1.62	85.0	159.0	246.0	38.5	6.0
Maximum		1.76	89.0	171.0	248.0	39.0	9.7
Minimum		1.39	78.0	152.0	229.0	37.0	2.0
Difference		0.37	11.0	19.0	19.0	2.0	7.7

Table 4.10 *The shear test results for the six till samples from rock province C (Opsal, 2017).*

Rock province	**Sample no.**	**Initial dry testing density, ρ_d (g/cm^3)**	**Max. shear stress, τ, with normal stress, σ (kPa)**			**Angle of friction, ϕ (°)**	**Cohesion, c (kPa)**
			σ = 100 (kPa)	**σ = 200 (kPa)**	**σ = 300 (kPa)**		
C	4	1.62	88.0	172.0	247.0	38.5	10.0
	7	1.64	87.0	172.0	256.0	40.0	2.7
	8	1.76	85.0	164.0	248.0	39.0	2.7
	9	1.73	87.0	173.0	259.0	40.5	1.0
	28	1.82	82.0	158.0	231.0	36.5	8.0
	29	1.81	82.0	158.0	235.0	37.5	5.3
Average		1.73	85.2	166.2	246.0	38.7	5.0
Standard deviation		0.08	2.6	7.1	11.1	1.5	3.5
Median		1.75	86.0	168.0	247.5	38.8	4.0
Maximum		1.82	88.0	173.0	259.0	40.5	10.0
Minimum		1.62	82.0	158.0	231.0	36.5	1.0
Difference		0.20	6.0	15.0	28.0	4.0	9.0

***Table 4.11** The shear test results for the five till samples from rock province D (Opsal, 2017).*

Rock province	**Sample no.**	**Initial dry testing density, ρ_d (g/cm^3)**	**Max. shear stress, τ, with normal stress, σ (kPa)**			**Angle of friction, ϕ (°)**	**Cohesion, c (kPa)**
			σ = 100 (kPa)	**σ = 200 (kPa)**	**σ = 300 (kPa)**		
D	10	1.89	85.0	160.0	242.0	38.0	5.3
	11	2.04	81.0	159.0	229.0	36.5	8.3
	12	1.79	91.0	170.0	269.0	41.5	0.0
	13	1.68	84.0	165.0	246.0	39.0	3.0
	14	1.71	84.0	162.0	251.0	39.5	0.0
Average		1.82	85.0	163.2	247.4	38.9	3.3
Standard deviation		0.15	3.7	4.4	14.6	1.9	3.6
Median		1.79	84.0	162.0	246.0	39.0	3.0
Maximum		2.04	91.0	170.0	269.0	41.5	8.3
Minimum		1.68	81.0	159.0	229.0	36.5	0.0
Difference		0.36	10.0	11.0	40.0	5.0	8.3

***Table 4.12** The shear test results for the seven till samples from rock province E (Opsal, 2017).*

Rock province	**Sample no.**	**Initial dry testing density, ρ_d (g/cm^3)**	**Max. shear stress, τ, with normal stress, σ (kPa)**			**Angle of friction, ϕ (°)**	**Cohesion, c (kPa)**
			σ = 100 (kPa)	**σ = 200 (kPa)**	**σ = 300 (kPa)**		
E	1	1.70	88.0	171.0	247.0	38.5	9.7
	20	1.67	82.0	163.0	250.0	39.5	0.0
	21	1.41	82.0	163.0	246.0	39.5	0.0
	22	1.54	89.0	164.0	243.0	37.5	11.3
	23	1.55	83.0	157.0	232.0	36.5	8.3
	24	1.44	87.0	158.0	240.0	37.5	8.7
	33	1.53	80.0	155.0	233.0	37.5	3.0
Average		1.55	84.4	161.6	241.6	38.1	5.9
Standard deviation		0.11	3.5	5.4	6.9	1.1	4.7
Median		1.54	83.0	163.0	243.0	37.5	8.3
Maximum		1.70	89.0	171.0	250.0	39.5	11.3
Minimum		1.41	80.0	155.0	232.0	36.5	0.0
Difference		0.29	9.0	16.0	18.0	3.0	11.3

Table 4.13 *The shear test results for the five till samples from rock province F (Opsal, 2017).*

Rock province	**Sample no.**	**Initial dry testing density, ρ_d (g/cm^3)**	**Max. shear stress, τ, with normal stress, σ (kPa)**			**Angle of friction, ϕ (°)**	**Cohesion, c (kPa)**
			σ = 100 (kPa)	**σ = 200 (kPa)**	**σ = 300 (kPa)**		
F	2	1.59	89.0	167.0	249.0	38.5	8.3
	3	1.43	81.0	156.0	232.0	37.0	5.3
	25	1.73	85.0	159.0	237.0	37.0	8.3
	26	1.90	84.0	157.0	230.0	36.0	11.0
	27	1.46	82.0	158.0	240.0	38.5	2.0
Average		1.62	84.2	159.4	237.6	37.4	7.0
Standard deviation		0.20	3.1	4.4	7.5	1.1	3.4
Median		1.59	84.0	158.0	237.0	37.0	8.3
Maximum		1.90	89.0	167.0	249.0	38.5	11.0
Minimum		1.43	81.0	156.0	230.0	36.0	2.0
Difference		0.47	8.0	11.0	19.0	2.5	9.0

Table 4.14 *The shear test results for the five till samples from rock province G (Opsal, 2017).*

Rock province	**Sample no.**	**Initial dry testing density, ρ_d (g/cm^3)**	**Max. shear stress, τ, with normal stress, σ (kPa)**			**Angle of friction, ϕ (°)**	**Cohesion, c (kPa)**
			σ = 100 (kPa)	**σ = 200 (kPa)**	**σ = 300 (kPa)**		
G	15	1.74	89.0	174.0	255.0	39.5	6.7
	16	1.62	86.0	177.0	253.0	40.0	5.0
	17	1.69	86.0	170.0	253.0	40.0	2.7
	18	1.71	84.0	161.0	239.0	38.0	6.3
	19	1.75	84.0	157.0	244.0	38.5	1.7
Average		1.70	85.8	167.8	248.8	39.2	4.5
Standard deviation		0.05	2.0	8.5	6.9	0.9	2.2
Median		1.71	86.0	170.0	253.0	39.5	5.0
Maximum		1.75	89.0	177.0	255.0	40.0	6.7
Minimum		1.62	84.0	157.0	239.0	38.0	1.7
Difference		0.13	5.0	20.0	16.0	2.0	5.0

Table 4.15 *A summary of the shear test results, i.e., the average values based on all 33 till samples regarding initial dry testing density (ρ_d) shear stress (named here as τ_1–τ_3 for normal stress 100, 200, and 300 kPa, respectively), angle of friction (ϕ) and cohesion (c) sorted on the distinct rock provinces A/B–G with their corresponding values in parenthesis. From Opsal (2017).*

Average ρ_d, high to low (g/cm^3)	**Average τ_1, high to low (kPa)**	**Average τ_2, high to low (kPa)**	**Average τ_3, high to low (kPa)**	**Average ϕ, high to low (°)**	**Average c, high to low (kPa)**
D (1.82)	G (85.8)	G (167.8)	G (248.8)	G (39.2)	F (7.0)
C (1.73)	C (85.2)	C (166.2)	D (247.4)	D (38.9)	A/B (6.1)
G (1.70)	D (85.0)	D (163.2)	C (246.0)	C (38.7)	E (5.9)
F (1.62)	A/B (84.8)	E (161.6)	E (241.6)	E (38.1)	C (5.0)
A/B (1.60)	E (84.4)	A/B (161.4)	A/B (241.2)	A/B (38.0)	G (4.5)
E (1.55)	F (84.2)	F (159.4)	F (237.6)	F (37.4)	D (3.3)

Table 4.16 *The results from the second shear test for six of the till samples, from Opsal (2017).*

	Test 2: Max. shear stress, τ, with normal stress, σ (kPa)				
Sample no.	**σ = 100 (kPa)**	**σ = 200 (kPa)**	**σ = 300 (kPa)**	**Angle of friction, ϕ (°)**	**Cohesion, c (kPa)**
12	94.0	176.0	256.0	39.0	13.3
15	97.0	178.0	251.0	37.5	21.3
24	81.0	158.0	243.0	39.0	0.0
25	80.0	155.0	235.0	38.0	1.7
28	85.0	160.0	242.0	38.0	5.3
32	90.0	170.0	249.0	38.5	10.7

Table 4.17 *The results from the third shear test for six of the till samples, from Opsal (2017).*

	Test 3: Max. shear stress, τ, with normal stress, σ (kPa)				
Sample no.	**σ = 100 (kPa)**	**σ = 200 (kPa)**	**σ = 300 (kPa)**	**Angle of friction, ϕ (°)**	**Cohesion, c (kPa)**
12	97.0	177.0	271.0	41.0	7.7
15	92.0	176.0	255.0	39.0	11.3
24	81.0	155.0	233.0	37.0	4.3
25	80.0	156.0	225.0	36.0	8.7
28	86.0	167.0	241.0	38.0	9.7
32	88.0	170.0	251.0	39.0	6.7

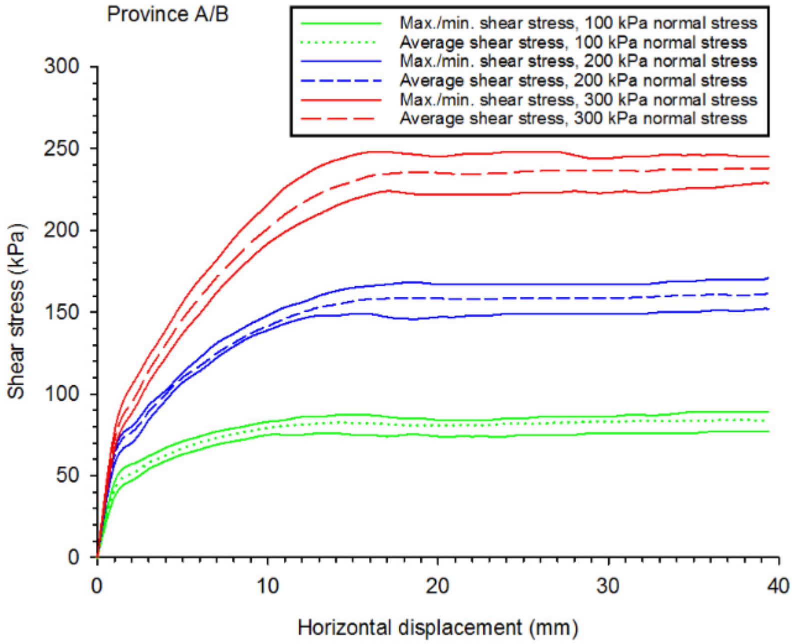

Figure 4.12 *Shear test results for the five samples of rock province A/B for 100 kPa (green), 200 kPa (blue) and 300 kPa (red) normal stress. Dot/dash is average, while solid lines are maximum and minimum, independent of sample no. (Opsal, 2017).*

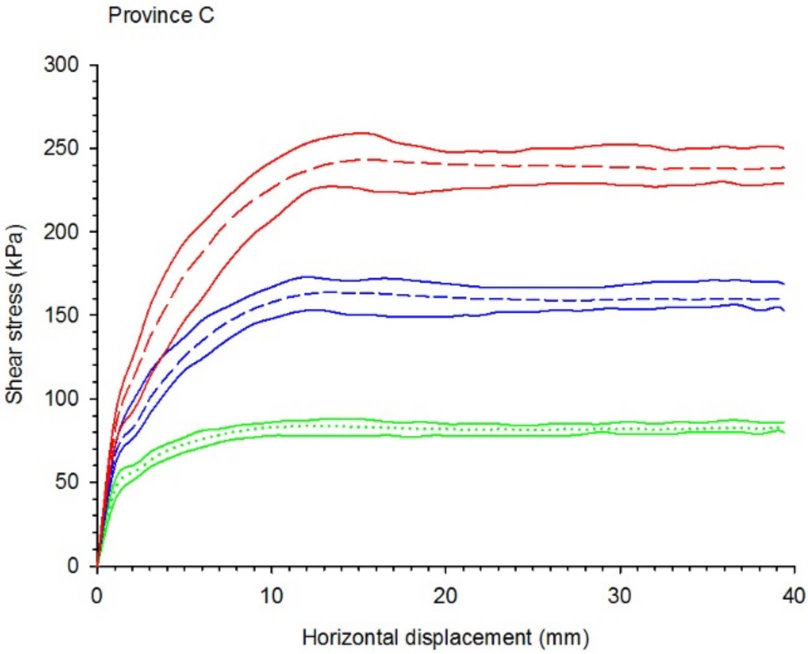

Figure 4.13 *Shear test results for the six till samples of rock province C (Opsal, 2017).*

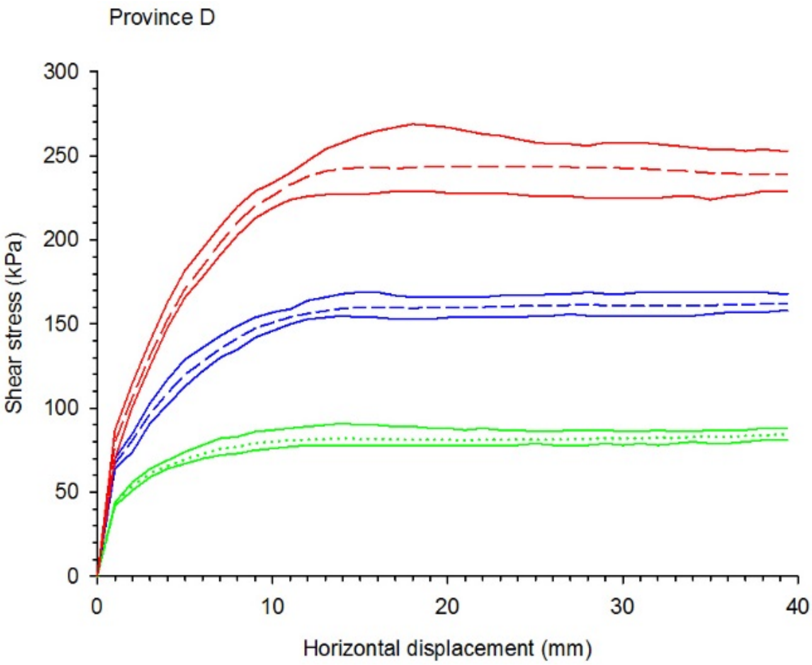

Figure 4.14 *Shear test results for the five till samples of rock province D (Opsal, 2017).*

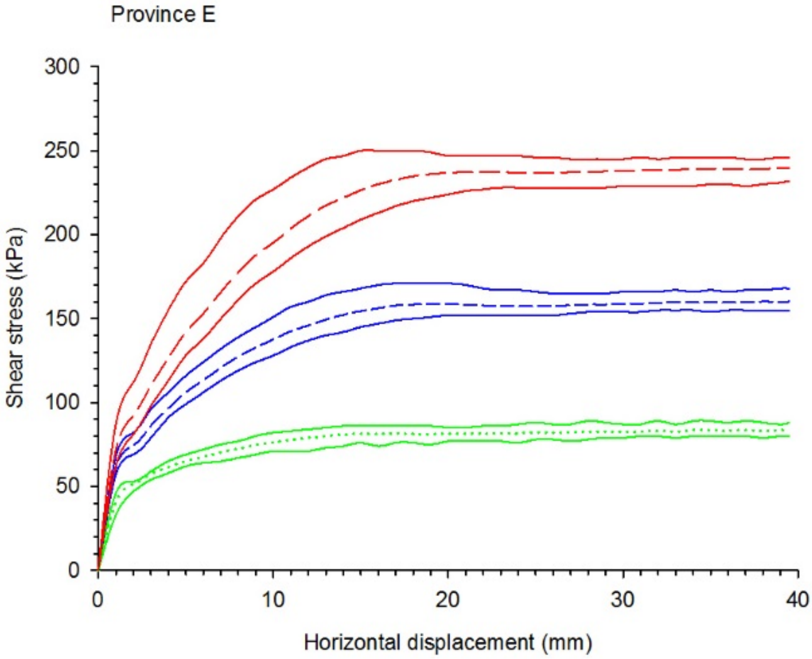

Figure 4.15 *Shear test results for the seven till samples of rock province E (Opsal, 2017).*

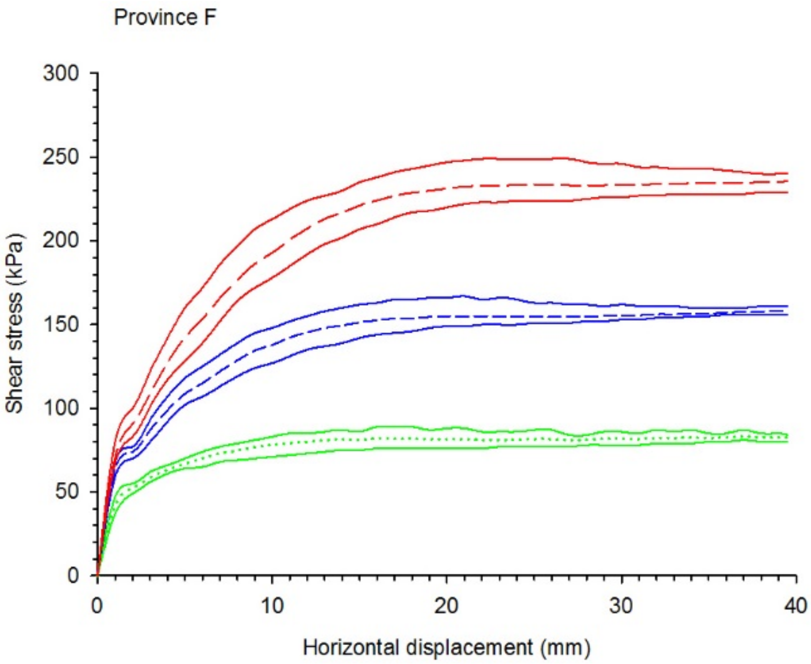

Figure 4.16 *Shear test results for the five till samples of rock province F (Opsal, 2017).*

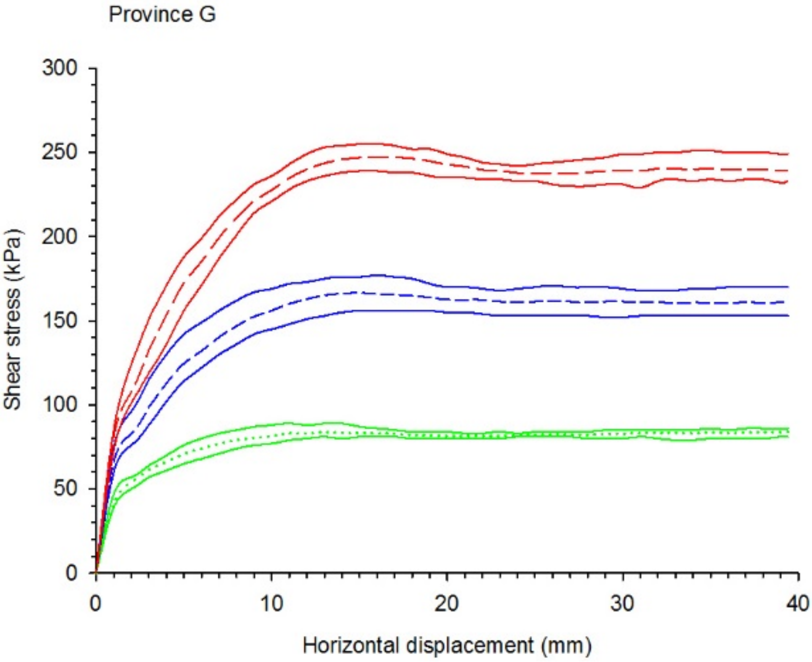

Figure 4.17 *Shear test results for the five till samples of rock province G (Opsal, 2017).*

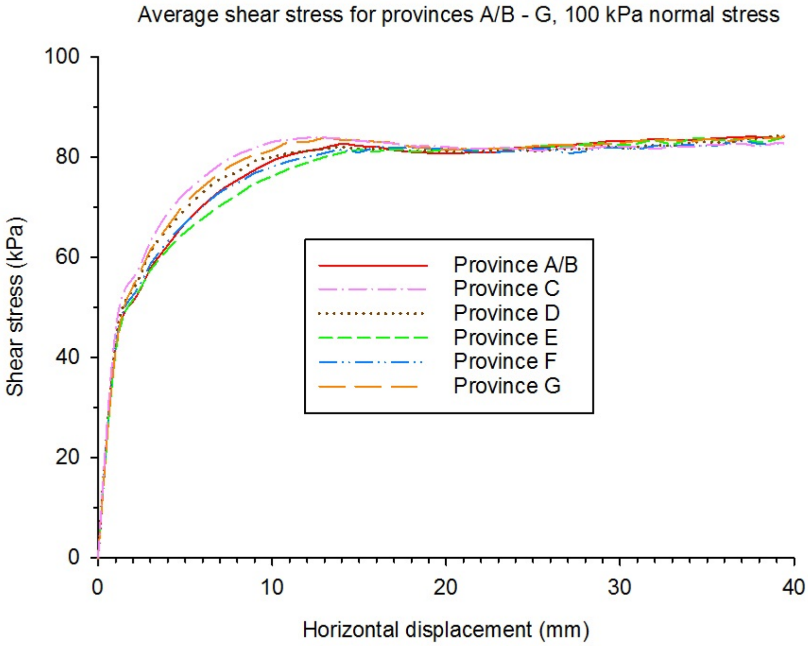

Figure 4.18 *The average shear stress vs. horizontal displacement for all till samples in each of the six rock provinces A/B–G for 100 kPa normal stress (Opsal, 2017).*

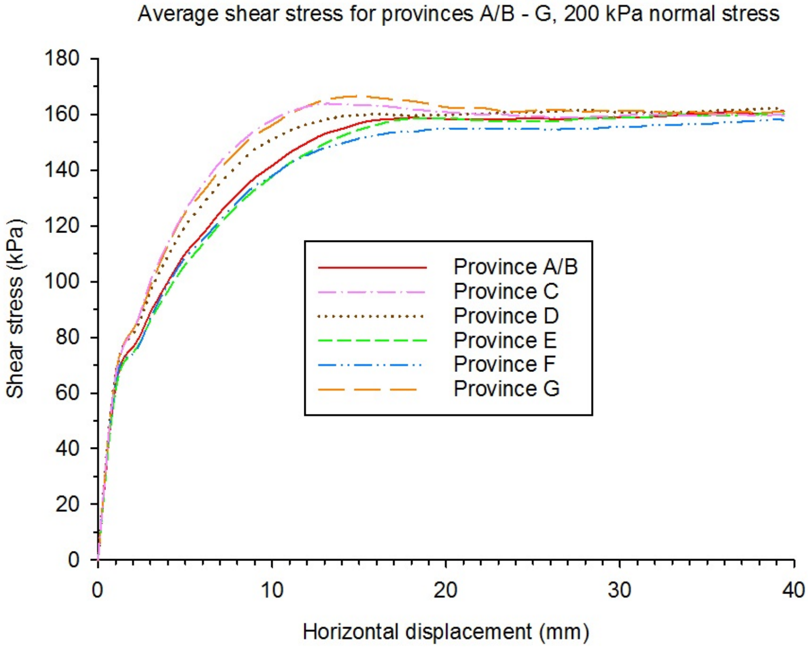

Figure 4.19 *The average shear stress vs. horizontal displacement for all till samples in each of the six rock provinces A/B–G for 200 kPa normal stress (Opsal, 2017).*

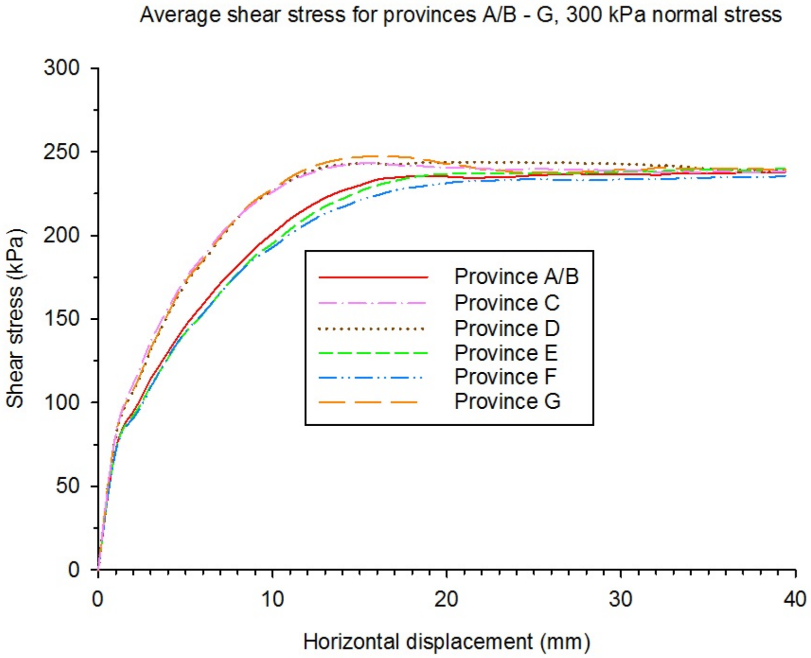

Figure 4.20 *The average shear stress vs. horizontal displacement for all till samples in each of the six rock provinces A/B–G for 300 kPa normal stress (Opsal, 2017).*

4.7 Parameter relationships

Based on the correlation tests (Pearson and Spearman rho), this section presents the results regarding parameter relationships, i.e., between the geological parameters, as well as the obtained parameters from the main shear test (Fig. 4.21; Table 4.18). When considering all 33 till samples, the results showed that for the angle of friction, D50 had a medium positive correlation, fines had a medium negative correlation, while both FI and SI showed no statistically significant correlation. Regarding the mineralogical composition to the angle of friction, quartz had a medium negative correlation, while plagioclase had a medium positive correlation. For the maximum shear stresses, τ_2 and τ_3, there were medium to large positive correlations to D50. Fines had medium negative correlations to τ_2 and τ_3. Furthermore, D50 had a medium negative correlation to FI and SI, while fines showed a medium to large positive correlation to FI and SI. Moreover, chlorite, mica, and quartz had a medium to large positive correlation to FI and SI, and mica also had a medium positive correlation to fines. In contrast, alkali feldspar and plagioclase had a medium to large negative correlation to FI and SI, and alkali feldspar also had a medium negative correlation to fines.

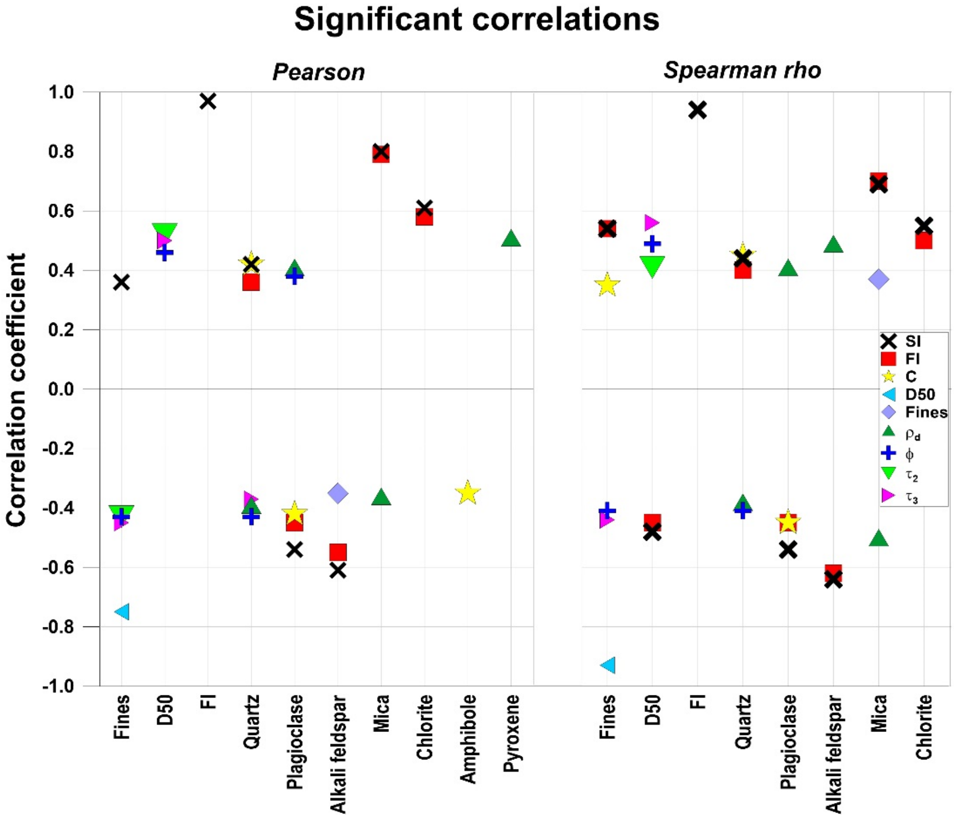

Figure 4.21 *The statistically significant test results from Pearson correlation and Spearman rho correlation regarding the relationships between the geological parameters, as well as their relation to the shear test results of the till samples, also listed in Table 4.18 (Opsal & Langeland, 2018).*

Table 4.18 *The parameter relationships based on all 33 till samples that resulted in statistically significant correlations, divided into Pearson correlation and Spearman rho correlation, visualised in Fig. 4.21. The letters, i.e., MP and LP, are short for 'medium positive' correlation (*$0.3 \leq r < 0.5$*) and 'large positive' correlation (*$r \geq 0.5$*), respectively. Likewise, MN and LN are short for 'medium negative' correlation (*$-0.5 < r \leq -0.3$*) and 'large negative' correlation (*$r \leq -0.5$*), respectively.*

Parameters		**Pearson correlation**		**Spearman rho correlation**	
D50	ϕ	0.46	MP	0.49	MP
D50	τ_2	0.52	LP	0.41	MP
D50	τ_3	0.50	LP	0.56	LP
D50	FI			-0.45	MN
D50	SI			-0.48	MN
Fines	ϕ	-0.43	MN	-0.41	MN
Fines	τ_2	-0.43	MN		
Fines	τ_3	-0.45	MN	-0.44	MN
Fines	c			0.35	MP
Fines	D50	-0.75	LN	-0.93	LN
Fines	FI			0.54	LP
Fines	SI	0.36	MP	0.54	LP
FI	SI	0.97	LP	0.94	LP
Quartz	ρ_d	-0.40	MN	-0.39	MN
Quartz	τ_3	-0.37	MN		
Quartz	ϕ	-0.43	MN	-0.41	MN
Quartz	c	0.42	MP	0.45	MP
Quartz	FI	0.36	MP	0.40	MP
Quartz	SI	0.42	MP	0.44	MP
Plagioclase	ρ_d	0.40	MP	0.40	MP
Plagioclase	ϕ	0.38	MP		
Plagioclase	c	-0.42	MN	-0.45	MN
Plagioclase	FI	-0.45	MN	-0.45	MN
Plagioclase	SI	-0.54	LN	-0.54	LN
Alkali feldspar	ρ_d			0.48	MP
Alkali feldspar	Fines	-0.35	MN		
Alkali feldspar	FI	-0.55	LN	-0.62	LN
Alkali feldspar	SI	-0.61	LN	-0.64	LN
Mica	ρ_d	-0.37	MN	-0.51	LN
Mica	Fines			0.37	MP
Mica	FI	0.79	LP	0.70	LP
Mica	SI	0.80	LP	0.69	LP
Amphibole	c	-0.35	MN		
Pyroxene	ρ_d	0.50	LP		
Chlorite	FI	0.58	LP	0.50	LP
Chlorite	SI	0.61	LP	0.55	LP

5. Discussion

Since the 33 till samples were collected from a diversity of both geographical and geological provinces, the presented results expectedly show a large range of values. However, there are also similarities among the samples, which are noticeable when categorising the sample results by the six individual rock provinces. Regarding particle size distribution, there are both similarities and differences. Such a variety of results was expected, as the particle sizes of tills are dependent on, among others, the bedrock geology (e.g., Rueslåtten, 1995). Tills may as previously described vary significantly, so the substantial difference of particle size distribution between, e.g., sample no. 7 and 33, may be explained by such natural variations in this kind of sediment. Jørgensen (1977) concluded that there was a clear influence of bedrock upon the mechanical composition of tills in Norway, and found that tills from Cambro-Silurian rocks (metamorphic) in the Caledonides had a larger content of fines (silt and clay) than tills from Precambrian rocks, i.e., generally above 35% and 15–25%, respectively. Those results correspond well to the results in this study, showing that the fines content on average for province E was approximately 36%, and approximately 21% for province C. The reason for this may be that rock types rich in soft minerals, such as chlorite and mica, which are common minerals in schist and phyllite, produce fines at a higher rate than rocks composed of harder minerals (Watters et al., 1987). These rock types are heavily represented in the samples of province E. Although the relationship between till particle size and bedrock type is complex due to glacial processes, hard rocks such as gneisses and granites generally result in granular (clast dominated) till textures with only minor amounts of rock flour matrix (Derbyshire et al., 1979). Coarse-grained tills are therefore characteristic of the greater part of Norway where coarse-grained and/or hard bedrock types dominate (Haldorsen, 1981). When comparing the province results for D50, the various gneisses of province G have on average the highest value.

For particle form, i.e., FI and SI, provinces A/B, D, and G have less variety of results and they are also quite similar to one another regarding a low average and median, compared to provinces C, and especially E and F, which have a larger variety, in addition to higher average and median. The results suggest that tills in provinces E and F are constituted of more elongated and flaky particles, while the particles in tills from the other provinces are considerably more cubical. When considering roundness, all six provinces are dominated by subangular particles, which is a rather normal characteristic for tills (e.g., Thoresen, 2000) and therefore as one could expect. Apart from five samples, i.e., one sample in province A/B, two in province C, and one in province D, which are categorised as angular, in addition to one sample in province F categorised as subrounded, the diversities among the samples and provinces are therefore low for this parameter. It can be added that the degree of roundness of particles is related to the amount of abrasion suffered during transport, i.e., the distance travelled from their source before deposition. It is also dependent on, e.g., particle size, hardness, and the violence of impact between particles (McLean & Gribble, 1985). While roundness, as well as sphericity, increase by abrasion, this increase is not proportional (Cho et al., 2006). Fracturing and chipping of a particle may increase the sphericity, but it also decreases the roundness (Wadell, 1932). Since high-strength rocks are usually more abrasion-resistant (Langer, 2006; Hudec, 2011), this also corresponds to the presented results of roundness, i.e., the samples of angular particles were solely from provinces generally constituted of stronger rocks (compressive strength) compared to the provinces E and F. Furthermore, for surface texture there is also a clear difference between the provinces, as four of seven samples in province E, as well as three of five samples in province F, were categorised as smooth. In comparison, only one sample in province C was categorised as smooth, while the remaining 25 samples were categorised as rough. These 25 samples categorised as rough were mainly from areas represented by, e.g., gabbro, and various gneisses and granites, which are typically medium to coarse-grained rocks. In contrast, the seven samples from provinces E and F categorised as smooth were from areas represented by, e.g., mica schist, sandstone, amphibolite, phyllite, and slate, which are typically medium to fine-grained rocks (NS–EN ISO 14689-1, 2004). In addition, rock types such as gneisses and granites are generally considered stronger than rock types such as mica schist and phyllite (e.g., Nilsen & Palmstrøm, 2000).

Regarding the relationship between mineralogy and particle form, high contents of flaky minerals are known to favour a high material flakiness (Brattli, 1992). Mica and chlorite are flaky minerals, and the content of these minerals corresponds well to the presented results for FI and SI. These minerals are also considered major minerals in rocks such as phyllite, slate, and mica schist (e.g., Prestvik, 1995), which are represented in province E. As previously mentioned, province E stands out as having a high FI and SI. On the other hand, the lowest values of FI and SI are found in provinces D and G, dominated by feldspars (plagioclase and alkali feldspar), which, in contrast to the plate structure of mica, produces blocky fragments (Christiansen & Hamblin, 2014). It can also be noted that samples categorised as smooth generally have a relatively large share of chlorite and mica, i.e., soft minerals commonly present in metamorphic rocks such as slate, phyllite, and schist, which, in turn, are often associated with smooth particle surfaces (Watters et al., 1987).

Furthermore, on the mineralogical composition, the provinces are dominated by different rock types, which seem to correspond quite well to the mineralogical composition of the till samples. For instance, province D is represented by rocks such as gabbro, amphibolite, and anorthosite, i.e., rocks mainly constituted by plagioclase, which is a mineral highly represented in this province. The relatively high amount of quartz in the samples of province F is also corresponding to the fact that common sandstones, which dominate in this province, normally consist of a high amount of this mineral (e.g., Prestvik, 1995). Thus, the differences regarding rock provinces and the rock types assumedly composing the till samples in the respective provinces are considered likely to explain the presented differences and similarities for the geological parameters, i.e., particle size distribution, shape, and mineralogical composition. However, in this context it must be noted that glacial processes are not accounted for.

Concerning the performed shear tests, it must be emphasised that the samples were not tested in their in-situ state. However, the decision of testing disturbed material was considered acceptable, as it is regarded as nearly impossible to collect undisturbed samples of till (e.g., Hencher, 2012). From the descriptions in Ch. 3.3.1–3.3.3, the disturbed samples were also prepared in the laboratory with sieving, splitting and drying before the shear testing was performed. It must be noted though, that if a proper assessment of the shear strength parameters is to be achieved, the laboratory preparation of samples must closely represent the physical conditions and the stress state conditions likely to occur in the field (Vanapalli et al., 1996). As an example, it is regarded as practically impossible to obtain a soil with zero saturation (Budhu, 2015). The oven-dried samples in this study are thus not representative for normal Norwegian field conditions. As previously mentioned, water is a main trigger for Norwegian debris slides and flows (e.g., Bargel et al., 2011). Hence, shear testing the samples in saturated conditions instead of in a completely dry condition would clearly be more appropriate for practical applications regarding slope stability assessment. However, as described in Ch. 3.3.4.1, the process of including water in the large-scale direct shear testing would introduce a variable very hard to control, as well as to evaluate its actual influence on the results. Moreover, the relatively high levels of applied normal stress (due to apparatus imprecision on low stress levels) do not reflect current field conditions either. Consequently, the shear test results are not likely to replicate the factual in-situ/field conditions at the sample sites regarding till shear strength.

Nevertheless, the samples in this study were not tested with the purpose of replicating their field conditions, but with the same procedure for achieving a best possible, equal comparison basis. Hence, the aim of the shear test was to show if shear strength differences in relation to bedrock geology and the respective rock provinces do exist, regardless of individual field variables such as stress state, density, and water content. To exclude these, although highly important, variables was considered necessary to be able to establish equal conditions of testing with a minimum of laboratory variables.

When comparing bedrock geology with the shear test results, both similarities and differences among the samples are shown within each rock province and when comparing the provinces to one another. It is well known that the compressive strength of different rock types varies (Afrouz, 1992; Waltham, 2009). According to the compressive strength description listed in NS–EN ISO 14689-1 (2004), the terms are ‘extremely weak’ (<1 MPa), ‘very weak’ (1–5 MPa), ‘weak’ (5–25 MPa), ‘medium strong’ (25–50 MPa), ‘strong’ (50–100 MPa), ‘very strong’ (100–250 MPa), and ‘extremely strong’ (>250 MPa). Due to the differences of rock provinces, the tills are constituted of rock types of varying compressive strengths. In summary, province A/B is mainly dominated by syenite and quartz syenite, as well as granite and granodiorite, which are typically classified as ‘very strong’ rocks. Province C is dominated by various gneisses and granites, also typically ‘very strong’ rocks. Province D is mainly dominated by mangerite and gabbro, in addition to gneiss and amphibolite, which are classified as ‘very strong’ to ‘extremely strong’ rocks. In contrast, province E varies more regarding rock strength and rock types, e.g., mica schist, greenstone, phyllite, amphibolite, quartzite, slate, and limestone are heavily represented. These rocks are normally weaker than the previously mentioned rock types, usually ranging from ‘strong’ to ‘very strong’ rocks. Province F is mainly dominated by sandstone, generally ranging from ‘strong’ to ‘very strong’ (Palmstrøm, 1997; Nilsen & Palmstrøm, 2000), but may also be ‘medium strong’ (Waltham, 2009). For the last province, province G, various gneisses are dominant, which typically are classified as ‘strong’ to ‘very strong’ (Palmstrøm, 1997; Nilsen & Palmstrøm, 2000).

As initially mentioned, this difference in bedrock geology and associated geological parameters including rock (particle) strength, should to some extent influence the till shear strength as well (e.g., Duncan et al., 2014). However, when comparing individual samples to one another, it is rather difficult to establish clear and direct relations between the sample strength and their rock type(s), rock strength and associated geological parameters. An important uncertainty on this matter though, is that the compressive strengths from the literature often include a significant range, e.g., 80–200 MPa for gneiss (Palmstrøm, 1997). According to the literature, rock strength cannot be the only parameter influencing till shear strength. This implies the influence of other geological parameters, such as particle size distribution and particle shape, which are also known to have an effect on soil shear strength (e.g., Yagiz, 2001). Although rock strength may be considered likely to have influenced the till samples regarding, e.g., particle roundness and fines content, its direct influence in the shear test of this study is considered rather negligible compared to the other geological parameters. However, if the study rather focused on shear testing the samples in a densely packed state, which most likely would introduce dilatancy and the potential of particle crushing, rock strength would possibly be more directly influential. In turn, this suggests that the other geological parameters, i.e., particle size distribution, particle shape, and mineralogy, are the parameters influencing the results when shear testing the till samples in such loose packed state. Thus, it is considered a strength of the study that it has investigated all these parameters for each sample, as one thereby has obtained a more ‘complete picture’ of the material characteristics.

Furthermore, the exclusion of variables such as water is also considered a strength of the study, as this makes it more likely to link the shear test results solely to the geological parameters of the material. Therefore, the shear strength differences between the rock provinces are assumed to be related to the differences of bedrock geology and associated geological parameters. When evaluating the geological parameters of the ‘weakest’ province F and the ‘strongest’ province G, there are some noticeable differences that could potentially explain the registered differences of the shear test results. Province G has on average a lower value regarding the fines content than province F, as well as a higher value of D50. These parameters were found to have a medium negative and positive correlation to the angle of friction, respectively. This is also in accordance to, e.g., Li (2013), which stated that the angle of shearing resistance is generally increasing with increasing median particle diameter. In addition, samples in province G are constituted of particles with a rough surface texture, which is also known to increase the shear strength. This stands in contrast to province F, as well as province E, where the majority of the samples are categorised as having a smooth surface texture. Furthermore, quartz is clearly the main mineral in all samples of province F, while plagioclase is the main mineral in all samples of province G. For this case, quartz and plagioclase were found to have a medium negative and positive correlation to the angle of friction, respectively. These results correspond to the findings in other studies. For instance, Koerner (1970) prepared quartz and feldspar soil samples for shear testing, and found that feldspar showed a greater strength than quartz. Bolton (1986) also presented results showing that quartz sands had a lower angle of friction than feldspathic sands. Moreover, Terzaghi et al. (1996) listed the interparticle angle of friction for some common minerals, where quartz was significantly lower than feldspar. Thus, the registered differences of mineralogical composition, i.e., the distributions of quartz and feldspars between provinces F and G, also support the higher shear strength of province G.

The results show that the overall dominant type regarding particle roundness was subangular, which is typical for tills. From the literature, the angle of internal friction should increase with increasing particle angularity (e.g., Shinohara et al., 2000), but for this study such a relationship has not been demonstrated. Then again, if the samples were more clearly diverse regarding roundness, it would possibly be easier to evaluate the real influence of this parameter to the angle of friction. According to Cho et al. (2006), the critical state angle of friction is strongly affected by particle shape. However, there were also no significant correlations between the values of FI and SI to the angle of friction amongst the 33 samples. When comparing the provinces though, the 'strongest' province G is generally constituted of subangular particles having low values of FI and SI, i.e., predominantly cubical particles, as well as a rough surface texture. This stands in contrast to the samples in provinces E and F, which mainly are constituted of subrounded to subangular particles having higher values of FI and SI, i.e., a relatively large share of flaky and elongated particles, in addition to a generally smooth surface texture.

Although there were no significant correlations regarding the particle shape (FI and SI) to the angle of friction in this study, it is considered likely that particle shape may still have an influence on the obtained results. When comparing the graphs of average shear stress versus horizontal displacement of the provinces (Figs. 4.18–4.20), 'strong' provinces such as G initially exerted more shear resistance than provinces E and F. In general, it may seem that provinces with low values of FI and SI, in combination with more angular and rough particle surfaces, promote a higher initial shear resistance than provinces with higher values of FI and SI, in combination with less angular particles and smooth surfaces, see also Fig. 5.1.

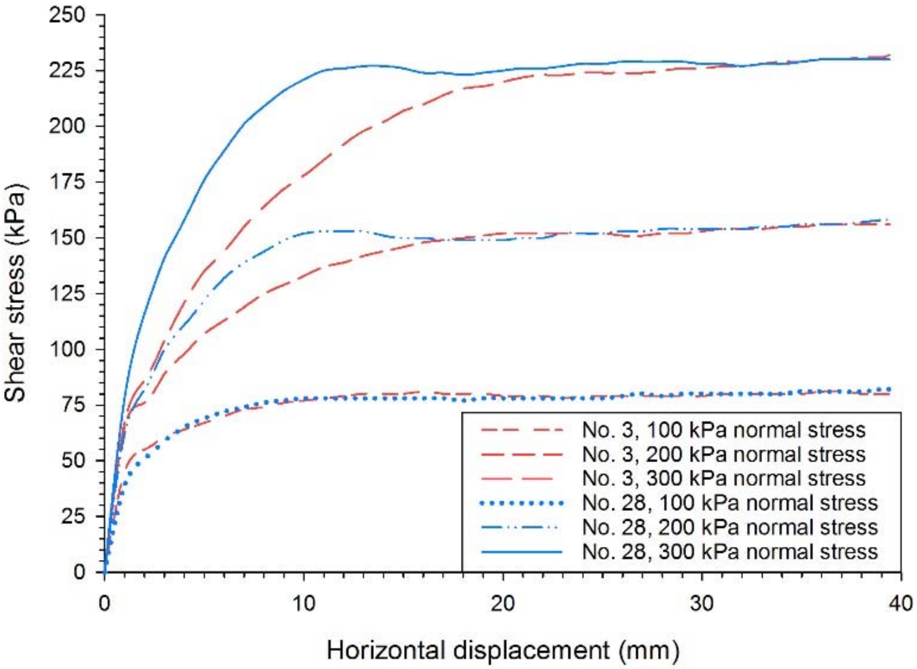

Figure 5.1 *A shear test comparison between two till samples, i.e., no. 3 (prov. F) and no. 28 (prov. C), that are very similar with regard to fines, D50, max. shear stresses and angles of friction, but very different with regard to the particle shape, i.e., FI, SI, roundness, and surface texture. No. 3 has an FI of 13.0, an SI of 19.0, and is subrounded with smooth surface texture. In contrast, no. 28 has an FI of 3.0, an SI of 5.0, and is angular with rough surface texture. Such noticeable variations of initial shear resistance may therefore be due to differences of particle shape.*

From Figs. 4.18–4.20 and 5.1, one can see that the shear stress levels eventually become quite similar, thus indicating that the differences of geological parameters eventually become less influential. However, in the context of landslides, the presented results suggest that the particle shape may be of special importance for till deposits regarding the potential initiation of debris slides and flows due to its indicated influence on the initial shear resistance. Consequently, till-covered valley slopes with a large share of flaky/elongated, smooth and less angular particles may potentially be more prone to initiation of such landslides. For this case, provinces E and F may be more prone to debris slides and flows than the other provinces.

From Fig. 2.12, however, one can see that it is the area of the ‘strongest’ province G that has a large number of registered debris slides, not the area of the ‘weakest’ province F. Although this may seem somewhat contradictory to the results of this study, where province G is found to be the ‘strongest’ province, it must be emphasised that what makes an area prone to such landslides also depends on many other parameters, e.g., characteristics of the terrain, vegetation, relief, precipitation and hydrological conditions, etc. (e.g., Chatwin et al., 1994). For example, water (rainfall and/or snowmelt) is recognised as the main trigger of debris slides and flows in Norway (e.g., Bargel et al., 2011). It is the western part of the southern half of Norway that is most exposed to extreme precipitation events (e.g., Førland et al., 2007), in addition to having high relief. When compared to province F, this corresponds well to the higher number of past registered debris slides in this region. According to, e.g., Roald & Asvall (2007), such extreme precipitation events are also expected to generally increase in the future climate scenarios, particularly in the western and middle parts of the southern half of the country (Fig. 2.15). In that case, provinces E and F may be especially prone to debris slides and flows, and according to Fig. 2.16 an increase in the frequency of debris slides in these areas is also assumed. In addition, it can be pointed out that the bedrock geology of Norway is in some areas similar to that of other countries, such as Sweden with regard to the Caledonides (e.g., Lahtinen, 2012). As the tills in Scandinavia are known to closely reflect the composition of the local bedrock, the presented results may thus potentially be quite similar for the countries in such comparable areas.

However, it is also necessary to address the uncertainties of the study. Firstly, throughout the fieldwork there were some challenges regarding field interpretation for choosing the ideal sample sites. Thus, for practical reasons the tills were chosen independently of genesis. Genesis is known to influence the geotechnical properties of tills through its control on important characteristics such as particle size distribution and stress history. In addition, postdepositional processes, such as freezing and thawing, wetting and drying, and downward percolation of fines, may further change the till characteristics (Boulton & Paul, 1976). Another important aspect is that the changed direction of ice motion and/or climatic fluctuations may have resulted in many tills that are a mixture of glacially eroded rock material and redeposited older sediments (Gillberg, 1977). Furthermore, in the context of bedrock geology and till origin, it must be emphasised that the given percentage shares of rock types originating the till samples are only assumed on a theoretical basis. Accordingly, the percentage share of the area of rock type(s) surrounding each sample site is based on an approximate measurement and calculation of the bedrock geology map, which is a planar projection not accounting for topography. Even though different studies (e.g., Perttunen, 1977) have shown that the Scandinavian tills closely reflect the composition of the local bedrock, the bedrock geology can change over short distances, thus introducing significant uncertainty to this theoretical approach. Additionally, the ice-flow directions and the chosen maximum transport distance of five kilometres are also simplifications likely to induce some uncertainty in the results.

Moreover, to distinguish a till deposit from an old, revegetated debris slide/flow deposit of till material was also rather challenging as the outcrops often were limited. As described by Cammeraat & Rappol (1987), there is a possibility that such till-like resedimentation products may be incorporated in the sampling, as this can be difficult to differentiate from 'true' tills, especially in cases where the exposure in the field is poor. It can also be mentioned that the degree of detailed mapping available from the Quaternary geology map (NGU, 2016c), particularly in the transition zone from one deposit type to another, is in some areas poor. Although the fieldwork focused on locations marked on the map as till, one cannot exclude the possibility that some of the samples are from, e.g., debris slide/flow deposits of till material. However, this latter potential source of uncertainty was regarded as having no significant influence, as the sampling itself disturbed the material.

In addition, it must be emphasised that the number of till samples, especially when distributed by the provinces, is relatively small and they are geographically scattered. Since they are individual samples, i.e., only one from each location, they do not necessarily represent the whole area from which they are collected, nor the rock province. It must also be added that the genetically independent samples are collected from the upper part (surface) layer of the till deposits, and, e.g., the particle size distribution may thus not be fully representative for the deposits. This may be due to previously mentioned post-depositional processes, such as downward percolation of fines, which, in turn, may change the particle size distribution. In fact, the process of percolation of fines may partly explain the low amount of fines in some of the samples, e.g., no. 7. Even if the till material was made solely from erosion of unweathered bedrock material, there is also an unknown variable regarding glacial comminution ('terminal grades') of mineral grains, e.g., between grains from unmetamorphic clastic sedimentary rocks and grains from crystalline rocks. For this example, the latter are to a large extent unstable when subjected to glacial and other mechanical crushing processes (Haldorsen, 1978). Also, due to the relatively passive transport of supraglacial tills, the associated occurrence of comminution is known to be minor (Boulton, 1978). Consequently, variables such as transport are likely to have influenced both the particle size and particle shape (Clark, 1987), in addition to the actual percentage share of different rock type fragments and thereby the mineralogical composition in the tills. Furthermore, regarding particle size distribution, only particle sizes retained on the 12.5-mm sieve and below were analysed, thereby excluding the distribution of larger particles occurring at the sample sites. It is important to note that the discarded larger particles may actually have somewhat different characteristics than the smaller particles. Hence, by excluding these larger fractions one thereby introduces a significant uncertainty regarding how the obtained laboratory results reflect the actual characteristics of the till deposits in the field. Moreover, the fines content was not separated into individual amounts of clay and silt. Although the clay fraction (≤0.002 mm) generally constitutes a rather small part of Norwegian tills (Garnes & Bergersen, 1977; Jørgensen, 1977), it would be useful to know the exact amount of this fraction, as the clay content may significantly influence the initiation of a debris flow (Chen et al., 2010). The silt content would also be useful to quantify, as it is considered as one of the most important size fractions of till (Dreimanis & Vagners, 1971), e.g., for the build-up of pore-water pressure in slopes, which, in turn, decreases the frictional resistance (Karaca & Goodman, 1993). For this particular study, however, pore-water pressure was not an issue, as water was not present in the dried samples.

Another key aspect to address on uncertainties regarding the geological parameters is that the roundness and surface texture tests were qualitatively evaluated visually and manually, in contrast to the other tests, which were based on quantitative measurements. Particle shape may vary due to the potential mix of different rock types in the till samples. Thus, the roundness and surface texture results are merely considerations of the general (most common) characteristics of the samples. These considerations are therefore also associated with some uncertainty. One more source of uncertainty that needs to be addressed is with regard to the XRD analysis, where only the 0.5-mm fraction was tested. For this case, one cannot exclude the possibility that performing XRD analysis on both smaller and larger fractions could give somewhat different results regarding the mineralogical composition of the samples. It can also be noted that the given box plots are based on five to seven samples per province, and that five values in a dataset are considered as a minimum to make such plots (Midtgård et al., 2007).

Independent of limitations and uncertainties in the procedures of sampling and testing, one should also evaluate the main apparatus that was used in the study, i.e., the large-scale direct shear box apparatus. Concerning the use of a shear box apparatus, Das (2010) pointed out that the direct shear test method has some inherent shortcomings. For instance, the reliability of shear box results may in general be questioned because the soil is forced to fail along the contact plane of the two halves of the box, rather than along a potentially weaker plane in the sample. Yet, the disturbed, heterogeneous material tested in this study should be relatively homogeneous when prepared in the sample box, thus having no significantly weaker planes than the plane of split. The relatively high normal stress levels needed for the apparatus (the SB2010) to function properly is also a limitation that affected the study regarding its possible reflection of current field conditions, as the samples were collected from the upper (surface) layer of the till deposits. This is also the case regarding the described difficulty of using saturated samples in the SB2010. Although the SB2010 was the only alternative in this PhD project, the shear strength can also be found by using other laboratory tests, such as the triaxial test. However, the direct shear test is considered to be the simplest and most economical for a dry sandy soil (Das, 2010). According to Lommler (2012), the direct shear test is actually the commercial laboratory test of choice for granular soils.

Furthermore, it is known that the reproducibility and repeatability of the results from shear tests may vary (e.g., Bareither et al., 2008a). Therefore, six of the samples were retested to observe the potential change of results (Tables 4.16 & 4.17). Bareither et al. (2008a) studied the repeatability and reproducibility of direct shear tests on granular backfill material (sand). In that context, 'repeatability' meant testing identical items in the same laboratory by the same operator using both the same equipment and method (intra-laboratory). 'Reproducibility' meant testing the identical items with the same method, but in 10 other laboratories by both different operators and equipment (inter-laboratory). In summary, the reproducibility varied significantly more than the repeatability. Concerning repeatability, the intra-laboratory tests on the angle of friction lead to a SD of 0.1°. On the other hand, the inter-laboratory tests reported an average reproducibility of 8.8°, with a range of variability up to 18.8°. Compared to this project, where the SD of the angle of friction ranged from 0.3°–1.3°, the results were considerably better than the reproducibility results reported by Bareither et al. (2008a), although the repeatability was not as good. However, the reason for this diversity of results may be due to factors such as the difference of material used (relatively homogeneous sand versus heterogeneous till material), as well as the number of tests performed (five versus three). Even though there were some clear differences in some of the additional tests, it is difficult to isolate the exact reason(s), as these may be due to uncertainties in the shear box apparatus, geological parameters, procedure, operator, or a combination of these. However, as the till samples consist of a mixture of gravel, sand and fines, emptying and refilling the sample box gives significantly more combinations of particle arrangements and interactions and, consequently, the repeatability should thus vary more than retesting a homogeneous sand. The results were therefore considered satisfactory regarding the assessment of repeatability.

Moreover, as mentioned in Ch. 2.3, it seems that relatively few shear test studies have been performed on heterogeneous soils consisting of multiple fractions such as till. Internationally, from shear tests on tills from eastern England, Bell (2002) presented angles of friction mainly ranging from approximately 20°–30°, although the fraction of fines constituted up to 60–80% of these tills. Iverson et al. (1994) reported an angle of friction of 31° in a till from Sweden, whereas a study by Rathbun et al. (2008) on two tills from Alaska and Ohio, USA, resulted in 31.4° and 29.4°, respectively. Others give that the angle of friction for till ranges from 35° to 45° (Koloski et al., 1989). Clearly, the angles of friction for tills may vary significantly, which may be due to the significant natural differences of this kind of material, as well as laboratory differences regarding operators, methods and equipment. However, when considering the initially mentioned shear test studies of Norwegian tills in Ch. 2.3, Lund (2013), Langåker (2014), and Langeland (2016) investigated one locality each, i.e., Nesbyen in Nes municipality, Buskerud county, Seim in Granvin municipality, Hordaland county, and Soknedal in Midtre Gauldal municipality, Sør-Trøndelag county, respectively. The angles of friction in the study by Langåker ranged between 38.9°–42.7°, while the studies by Lund and Langeland resulted in 39.5° and 37.4°, respectively. Although the localities in those studies do not overlap with any samples in this study, as well as not being tested with exactly the same procedure, the results are still quite comparable and substantiate the presented results. Particularly the angle of friction from Langeland is near identical to the results from the three closest samples presented here, i.e., nos. 22, 23, and 33.

6. Conclusions

This PhD project has tested 33 genetically independent till samples collected from six regional rock provinces in the southern half of Norway to investigate the potential relationships between bedrock geology, dry till shear strength and associated geological parameters. The geological parameters of the tills were studied by performing six laboratory tests, i.e., particle size distribution, flakiness index, shape index, roundness, surface texture, and XRD analysis. In addition, the till shear strength was tested by the use of a large-scale direct shear box apparatus. In general, the results were as expected regarding the relation of geological parameters to bedrock geology amongst the different provinces, although some samples may be considered as extremes. For instance, province E, which is dominated by rocks such as mica schist and phyllite, had on average a significantly higher fines content and a higher share of flaky/elongated particles than province G, which is dominated by various gneisses. In addition, province F, which is mainly sandstones, was dominated by quartz, whereas province G was dominated by feldspars.

Prior to the main shear test, the disturbed till samples were prepared in the laboratory with sieving (fractions <16 mm), splitting and drying before performing three shear tests per sample on the loose packed material with 100, 200, and 300 kPa applied normal stress. Overall, the test results show that the angle of friction varies by 5.5°, ranging from 36.0° to 41.5°, with an average of 38.4°. Although various studies have shown that the angle of friction for tills may vary significantly, the results in this project correspond well to previous shear tests on Norwegian tills, and also with international literature, such as Koloski et al. (1989) who reported a range between 35° and 45°. When observing the average province angles of friction, as well as average shear stresses, a clear relation to bedrock geology does appear. This is especially noticeable in the first half of the horizontal displacement length, where the differences of shear stress are the greatest. On a province level, the rock provinces C, D, and G are higher regarding shear stress and angle of friction than A/B, E, and F, which are consistently lower. In general, provinces of assumedly ‘strong rocks’ have a higher registered shear stress level and angle of friction than provinces of ‘weaker rocks’. For this study, regarding the average angle of friction, province G is the ‘strongest’ province (39.2°), while province F is the ‘weakest’ province (37.4°). However, when comparing individual samples to one another, it is rather difficult to establish clear and direct relations between the sample strength and their rock type(s), rock strength and associated geological parameters. For example, when focusing solely on rock strength, it is suggested that rock (particle) strength is not directly the governing parameter of till shear strength. Rock strength would possibly be more influential on the results if the study rather focused on shear testing the till samples in a densely packed state, which most likely would introduce dilatancy and potential particle crushing. It is considered more likely that rock strength rather indirectly influences till shear strength due to its effect on, e.g., particle size distribution and shape, and, furthermore, that these geological parameters are more directly influential when shear testing the samples in such loose packed state.

According to the literature, all the investigated geological parameters should have an influence on the till shear strength. For this study, particle size distribution and mineralogical composition seem to relate to the angle of friction. For instance, it seems that low fines content and high D50, as well as low quartz content promote a higher angle of friction. However, no such relationship was demonstrated for particle shape. In the second half of horizontal displacement, all six provinces show a relatively similar level of average shear stress. Even though the general trend regarding the provinces of high shear stress and low shear stress seems to continue towards the end, it seems that the geological parameters influencing the till shear stress of the respective rock type(s) eventually become less influential. Although no statistically significant correlation between the angle of friction and particle shape was demonstrated, an interesting observation is that provinces with generally low FI and SI, more angular and rough particles may seem to promote a higher initial shear resistance than provinces with generally high FI and SI, less angular and smooth particles. This difference of particle shape may be of special importance, as it may influence the initiation of debris slides and flows. For this case, provinces E and F could be more prone to debris slides and flows than the other provinces.

In summary, the study indicates several relationships between bedrock geology, dry till shear strength and associated geological parameters, and that the till shear strength is not specifically governed by one geological parameter, but rather by an interaction of all the parameters combined. Furthermore, the study suggests that some rock provinces may, solely on the basis of their associated geological parameters, be more prone to debris slides and flows than others, although it must be emphasised that what makes an area prone to debris slides and flows depends on many other parameters as well, such as terrain characteristics, vegetation, precipitation, etc. The presented relationships may potentially also apply to tills in other (Scandinavian) countries with similar bedrock geology. However, it must also be emphasised that the number of till samples tested is relatively few and they are geographically scattered. Moreover, the sampling and testing procedures, and thereby the results, do not replicate individual field/in-situ conditions at the sample sites, as the samples were disturbed when collected and prepared for the purpose of achieving a comparison basis with a minimum of laboratory variables. Hence, the presented results should be regarded as preliminary, and additional till samples should be tested if one is to improve the statistical base of the presented relationships.

7. Further work

On the basis of this study, the following points are suggested as future work:

- Perform additional sampling and testing of both geological parameters and shear strength of more till samples in the different rock provinces to improve the statistical base of the results and relationships for the southern half of Norway.
- As for the former, but on till samples from the rock provinces of the northern half of Norway.
- Perform tests of geological parameters on till material collected from actual failure zones of registered debris slides, as well as material from nearby similar areas that have not failed, even though the areas have been exposed to the same amount of rainfall, etc. This could be done to investigate if there are noticeable differences regarding the geological parameters in the failure zone compared to the nearby area.
- Perform shear strength tests on till material from actual failure zones of debris slides.
- Perform shear strength tests on till material in other apparatuses, e.g., a triaxial apparatus.
- Perform shear strength tests on till material with various water content, density and stress state conditions likely to occur in the field (in an apparatus suitable for such tests).
- Explore the potential for shear testing undisturbed tills, which represent the material in the field.
- Explore the potential to apply the presented results in general debris-slide risk mapping of till-covered valley slopes.
- Explore the potential to apply the presented results as input parameters in computer modelling of debris slides and flows.
- Explore the potential to apply the presented results in the national online debris-slide warning system (Jordskredvarsling).

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Appendix 1 Sample sites: GPS-coordinates

This appendix presents the locations with GPS-coordinates (World Geodetic System (WGS) 1984, Universal Transverse Mercator (UTM) 32N) of each of the 33 till sampling sites.

***Table A1.1** The GPS-coordinates (WGS 84, UTM 32N) for the till sampling sites.*

Sample no. & rock province	Municipality	Location	North	East	Altitude (m)
1–E	Nord-Fron	Kvam	6838673	0536204	463
2–F	Sør-Fron	Fosse	6822392	0552057	315
3–F	Lillehammer	Sustad	6775115	0579117	186
4–C	Vestre Toten	Raufoss	6732442	0585905	527
5–A/B	Lunner	Harestua	6676011	0595775	319
6–A/B	Lier	Røyne	6645430	0571376	260
7–C	Kongsberg	Jondalen	6618595	0526322	286
8–C	Kviteseid	Brunkeberg	6588972	0471290	375
9–C	Valle	Valle	6565310	0417381	415
10–D	Lom	Heranostangen	6839585	0491838	1278
11–D	Lom	Leirvassbu	6825663	0458654	1330
12–D	Årdal	Murane	6808142	0431813	1083
13–D	Sogndal	Kaupanger	6783700	0401777	439
14–D	Voss	Jordalen	6752326	0376152	573
15–G	Gulen	Indre Oppedal	6772723	0314910	82
16–G	Jølster	Vassenden	6821464	0343612	314
17–G	Volda	Tunga	6892989	0353709	355
18–G	Rauma	Voll	6930963	0414825	374
19–G	Nesset	Meisalstranda	6961851	0459387	345
20–E	Stjørdal	Skatval	7044816	0594391	325
21–E	Selbu	Tømra	7019450	0602725	297
22–E	Melhus	Korsvegen	7004135	0553175	231
23–E	Midtre Gauldal	Budalen	6975746	0574656	466
24–E	Tynset	Yset	6939292	0569231	755
25–F	Rendalen	Åkerådalen	6871460	0629626	877
26–F	Stor-Elvdal	Steinbekkbua	6840809	0597048	464
27–F	Stor-Elvdal	Opphus	6802767	0622280	447
28–C	Åsnes	Flisa	6721673	0673094	281
29–C	Kongsvinger	Sørli	6672767	0678643	308
30–A/B	Nannestad	Sandsnessætra	6691014	0609641	314
31–A/B	Nittedal	Hakadal	6664318	0599313	374
32–A/B	Kongsberg	Passebekk	6595774	0546149	375
33–E	Midtre Gauldal	Enodden	6973468	0575100	461

Appendix 2 Sample sites: photographs

This appendix presents photographs of each of the 33 till sampling sites (pits), distributed by the six rock provinces, A/B–G. Note that the carpenter's ruler is 1 m.

Sample no. 5	Sample no. 6
	
Sample no. 30	Sample no. 31
	
Sample no. 32	
	

***Figure A2.1** The five till sampling sites from rock province A/B.*

Sample no. 4	Sample no. 7
	
Sample no. 8	Sample no. 9
	
Sample no. 28	Sample no. 29
	

Figure A2.2 *The six till sampling sites from rock province C.*

Sample no. 10	Sample no. 11
	
Sample no. 12	Sample no. 13
	
Sample no. 14	
	

***Figure A2.3** The five till sampling sites from rock province D.*

Sample no. 1	Sample no. 20
	
Sample no. 21	Sample no. 22
	
Sample no. 23	Sample no. 24
	
Sample no. 33	
	

Figure A2.4 *The seven till sampling sites from rock province E.*

Sample no. 2	Sample no. 3
	
Sample no. 25	Sample no. 26
	
Sample no. 27	
	

Figure A2.5 *The five till sampling sites from rock province F.*

Sample no. 15	Sample no. 16
	
Sample no. 17	Sample no. 18
	
Sample no. 19	
	

Figure A2.6 *The five till sampling sites from rock province G.*

Appendix 3 Particle shape: photographs

This appendix presents photographs of the sieved till material in the 10-mm fraction, i.e., particles passing the 12.5-mm sieve and retained on the 10-mm sieve, for all samples in each of the six rock provinces, A/B–G. The photographs were used as a part of the evaluation of particle shape. Note that the photographs do not have a scale.

Sample no. 5	Sample no. 6
	
Sample no. 30	Sample no. 31
	
Sample no. 32	
	

Figure A3.1 *Particles (10-mm fraction) from the five till samples of rock province A/B.*

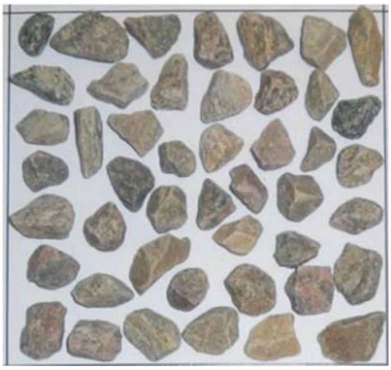
Sample no. 4	Sample no. 7
	
Sample no. 8	Sample no. 9
	
Sample no. 28	Sample no. 29
	

Figure A3.2 *Particles (10-mm fraction) from the six till samples of rock province C.*

Sample no. 10	Sample no. 11
	
Sample no. 12	Sample no. 13
	
Sample no. 14	
	

Figure A3.3 *Particles (10-mm fraction) from the five till samples of rock province D.*

Sample no. 1	Sample no. 20
	
Sample no. 21	Sample no. 22
	
Sample no. 23	Sample no. 24
	
Sample no. 33	
	

Figure A3.4 *Particles (10-mm fraction) from the seven samples of rock province E.*

Sample no. 2	Sample no. 3
	
Sample no. 25	Sample no. 26
	
Sample no. 27	
	

Figure A3.5 *Particles (10-mm fraction) from the five till samples of rock province F.*

Sample no. 15	Sample no. 16
	
Sample no. 17	Sample no. 18
	
Sample no. 19	
	

Figure A3.6 *Particles (10-mm fraction) from the five till samples of rock province G.*

Article 1

Shear strength of dry tills from the southern half of Norway in relation to bedrock geology

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Shear strength of dry tills from the southern half of Norway in relation to bedrock geology

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Till is the dominant Quaternary sediment in Norway, where the till deposits mostly originate from local rocks with a transport distance less than five kilometres. Debris slides and flows are among the main geohazards on till-covered valley slopes, and in this context the shear strength of Norwegian tills is poorly studied. Therefore, a set of 33 near-surface, genetically independent till samples were collected from various locations in the southern half of Norway to investigate the shear strength and its relation to bedrock geology. The disturbed samples were sieved (<16 mm) and dried before they were tested in a large-scale direct shear box apparatus at normal stresses of 100, 200 and 300 kPa, and with a shear rate of 2.0 mm/min for approximately 40.0 mm horizontal displacement. Overall, the result regarding the average 'initial dry testing density' was 1.67 g/cm^3, while the maximum shear stresses for the given normal stresses on average were 84.9 kPa, 163.2 kPa and 243.7 kPa, respectively. The average angle of friction and cohesion were 38.4° and 5.3 kPa. Furthermore, the samples were categorised into six regional rock provinces. The mapped rock type assumed to represent the origin of the till samples were based on their area of extent around the sample sites, and adjusted for by the late-Weichselian ice-flow directions. On average, the 'Precambrian basement' province locally affected by the Caledonian orogeny (mainly gneisses) had the highest angle of friction. In comparison, the 'Caledonian' province of overthrust sheets of sandstone and schist (mainly sandstones) had the lowest angle of friction. Although not conclusive, this study provides indications of a relationship between till shear strength and bedrock geology, suggesting that some provinces may, solely on the basis of their associated geological parameters, be more prone to debris slides and flows than others.

Keywords: till, shear box, shear strength, bedrock geology, landslide

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Introduction

The Norwegian bedrock geology is highly variable, both in terms of formation (igneous, metamorphic and sedimentary) as well as age, ranging from Precambrian to Permian (Johnsen, 1995). In addition to the Precambrian 'Basement', Caledonian rocks comprising overthrust sheets of both Precambrian rocks and sandstone and schist, metamorphic and igneous rocks, as well as Precambrian basement locally affected by the Caledonian orogeny, constitute the main part of the Norwegian bedrock (Geological Survey of Norway [NGU], 2016a). Regarding the formation of till, Boulton (1974) stated that the processes of crushing, plucking and abrasion of rock masses depend largely on rock strength and hardness. The variation of the rocks also affects the composition of till, as it is normally composed of local rock material (Låg, 1948; Dreimanis et al., 1957). Due to the several ice ages (Vorren & Mangerud, 2006), till is regarded as the dominant Quaternary sediment in Norway (Bergersen & Garnes, 1972; Garnes, 1973; Haldorsen et al., 1983). For onshore areas, almost all Quaternary deposits are younger than 300 ka, and probably more than 90% of the present, remaining glacial deposits derive from the Weichselian glaciation, i.e., younger than 115 ka (Olsen et al., 2013).

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While the till cover in higher relief areas is mostly discontinuous and its thickness only locally exceeds two metres (Haldorsen & Krüger, 1990), a consistent layer of till is covering about 25% of the Norwegian mainland area (Thoresen, 2000; Olsen et al., 2013). Even though the transport distances of till may be several tens of kilometres (Clark, 1987), or even hundreds of kilometres (Dreimanis & Vagners, 1971), most of the Norwegian till material has been transported a relatively short distance, i.e., less than five kilometres (Reite, 1990; Thoresen, 2000). Studies done in the neighbouring Scandinavian countries, Sweden and Finland, have found similar results, concluding that the majority of tills are transported only a few kilometres (Perttunen, 1977).

In geotechnical aspects, till is generally regarded as a 'good' foundation soil (Milligan, 1976), although the shearing resistance is essential in the analysis of soil stability problems such as slope stability (Fredlund & Rahardjo, 1993; Allred, 2000; Das, 2010). When excluding floods, it is primarily slope stability issues, such as avalanches and landslides, which count for the main geohazards in Norway. Historically, landslides and avalanches in snow, rock and clay are the main causes of fatalities (Jaedicke et al., 2008), but even though debris slides and flows seldom result in human fatalities, they often cause damage to buildings and infrastructure. Valley slopes that are mostly covered in till are, consequently, most prone to such landslides (Bargel et al., 2011). Furthermore, due to the predicted future climate change, the frequency of debris slides and flows in Norway is expected to increase (Kronholm et al., 2007; Norem & Sandersen, 2014; Sandersen, 2014).

The Norwegian Water Resources and Energy Directorate (NVE) holds the overall responsibility for governmental management tasks regarding the prevention of accidents due to landslides (NVE, 2016). Additionally, the NVE, in cooperation with the Norwegian Public Roads Administration, the Norwegian Meteorological Institute, and the Norwegian National Rail Administration, regularly publish online national forecasts of debris-slide warnings (NVE, 2013). This warning system is based on the correlation between past landslide incidents and both meteorological and hydrological variables (Boje et al., 2014), thus not directly including parameters such as shear strength. Concerning the present and future potential of debris slides and flows in Norwegian valleys, as well as the geological limitations of the national warning system, it is of special interest for NVE to investigate the shear strength in a variety of tills, thereby resulting in the motivation for this project.

Regarding slope stability, the soil mass shear strength can be defined as *'the internal resistance per unit area that the soil mass can offer to resist failure and sliding along any plane inside it'* (Das, 2010, p. 365). Controlled shear tests have been a method to measure the shear strength of soils since the 1930s (Bishop & Eldin, 1950). However, as also indicated by Thermann et al. (2006), it seems that homogeneous soils consisting of one or a few closely related fractions such as clay, as well as non-cohesive soils, such as sand, have been the most commonly used material for shear strength tests (e.g., Donald, 1956; Bjerrum & Landva, 1966; Palmeira, 1987; Yagiz, 2001; Miller & Hamid, 2007; Schnellmann et al., 2013). In comparison, it seems that fewer studies have been done on heterogeneous soils consisting of multiple fractions such as till or colluvium (e.g., Gan et al., 1988; Iverson et al., 1994; Vanapalli et al., 1996; Fannin et al., 2005; Thermann et al., 2006). Apart from limited and local studies such as construction project reports and master theses (e.g., Lund, 2013; Langåker, 2014; Langeland, 2016), the shear strength of Norwegian tills is rather poorly documented.

For cohesionless materials, the shear strength is usually expressed in terms of the so-called angle of internal friction. On this matter, the shear stress-deformation relations are largely influenced by the initial soil density. For densely packed soils, this is visualised by a significant peak in the shear stress-deformation curve due to dilatancy, before levelling out horizontally in an 'ultimate steady state condition'. In contrast, loose to medium-packed soils show either no peak or only a minor peak in the curve before reaching the ultimate, horizontal level (Kaniraj, 1988; Ishibashi & Hazarika, 2015). According to Simoni & Houlsby (2006), this critical (ultimate) shear strength represents the minimum shear strength that the soil can display in a shear test. Furthermore, geological parameters, such as particle size distribution and particle shape (Cornforth, 1973; Yagiz, 2001), as well as particle roughness and strength (Duncan et al., 2014), are known to have an effect on soil shear strength. Mineralogy is also known to influence soil shear strength (Fannin et al., 2005), and the critical state angle of shearing resistance is, according to Bolton (1986), principally a function of mineralogy. Therefore, since till largely originates from local rocks, differences in bedrock geology should to some extent also influence till shear strength, and, consequently, there should be some noticeable differences among different rock types and provinces.

Typically, the upper parts and surfaces of Norwegian till deposits are more porous than the underlying, consolidated till due to processes such as weathering and biological activity (Norem & Sandersen, 2014; Sandersen, 2014), which, in turn, may reduce the relative soil density (Dearman, 1991). Debris slides and flows are usually triggered in this upper and weathered part of the deposits (Sandersen, 2014). Rather than finding the maximum peak shear strength, which is more likely occurring in the underlying, relatively non-weathered and densely packed till, this study focuses on the critical shear strength of the upper, loose to medium-packed surface till.

Hence, this study presents results of the critical shear strength for 33 tills from various locations in the southern half of Norway, i.e., south of and including Nord-Trøndelag county (Fig. 1; Table 1 & 2). The study examines the test results with regard to the mapped bedrock geology, i.e., the samples are geographically divided into regional, major rock provinces and then further into rock types. This categorisation of samples into rock provinces is done for the purpose of displaying both internal differences and similarities, as well as to evaluate the relation between till shear strength and regional bedrock geology and the various associated rock types. Additionally, to distinguish between samples and provinces of presumably 'strong rocks' and 'weak rocks', brief descriptions of the typical compressive strengths of the dominating rock types of each province are included for an evaluation of this potential relation to the shear test results. In summary, the aim of the study is to investigate the potential relation of till shear strength to bedrock geology, and evaluate if some provinces in the southern half of Norway may be more prone to debris slides and flows than others on the basis of bedrock geology and associated geological parameters. However, it must be emphasised that the aim of the study is not to replicate current individual field conditions regarding e.g., stress conditions, density and saturation for the sake of retrieving the actual, in situ shear strength, but to test different tills under equal test settings to show the differences and for the purpose of a comparative analysis. Due to the limited documentation of previous, comparable, Norwegian studies on till shear strength, the sampling and testing procedure are tailored for this study, and are therefore described in detail. Note that this is the first introductory article of the study, whereas a subsequent article will further investigate the samples and results with regard to geological parameters such as particle size distribution and particle shape.

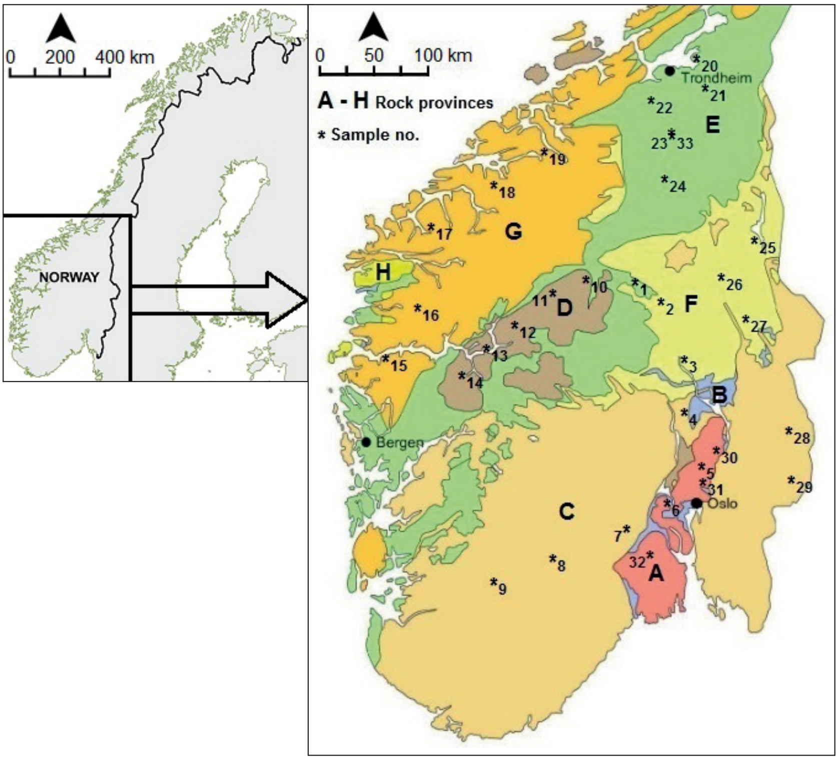

Figure 1. Simplified bedrock geology map of the southern half of Norway illustrating the major rock provinces (named here as A–H) listed in Table 1, and the approximate locations of the 33 till samples listed in Table 2, modified from Norsk Betongforening [NB] (1988, as cited by Haugen & Lindgård, 2012, p. 3, fig. 22).

Table 1. A brief description of the major rock provinces (named here as A–H) in Norway, as illustrated on the map in Fig. 1, modified from NB (1988, as cited by Haugen & Lindgård, 2012) and NGU (2016a, b).

Rock province	*Description*
A	Extrusive and plutonic rocks in the Oslo region; mainly syenite, granite, monzonite and rhomb-porphyry
B	Sedimentary rocks in the Oslo region; mainly slate, limestone and sandstone
C	Precambrian basement; mainly gneiss, granite, metamorphosed volcanic and sedimentary rocks
	Caledonian rocks
D	Overthrust sheets of Precambrian rocks; mainly metamorphosed plutonic rocks, particularly gabbro
E	Metamorphic and igneous rocks; mainly phyllite, mica schist, metamorphosed sandstone, gneiss and greenstone
F	Overthrust sheets of sandstone and schist; mainly sandstone, conglomerate and slate
G	Precambrian basement, locally affected by the Caledonian orogeny; mainly gneiss
H	Sedimentary rocks; mainly sandstone and conglomerate

Methods

Preliminary work and fieldwork

Due to the greater variety of bedrock geology in the southern half of Norway (NGU, 2016a), the northern half of Norway was not included in the study. When concentrating on the southern half, the study focused on collecting till samples from a variety of locations. Accordingly, the locations were based on a bedrock geology map from NGU (2016b), as well as a Quaternary geology map (NGU, 2016c) to ensure that the samples were collected from a variety of both geographical and geological provinces. Areas above the marine limit containing till deposits were identified and chosen for further investigation in the field. However, it is often considered difficult to distinguish between different types of till in the field without performing detailed investigations (Dreimanis, 1976; Haldorsen, 1982; Haldorsen & Krüger, 1990). Thus, for simplicity, the tills sampled in this study were independent of their genesis, i.e., no distinction was made between subglacial till and supraglacial till.

When in the field, the sampling of the tills was done manually with the use of a shovel and bucket. For practical reasons, the sample locations were chosen in natural or man-made slope cuts with minimal vegetation cover, preferably along side slopes to forest roads (Fig. 2A–C). The samples were collected from till deposits within roughly 1.5 m beneath the base of the organic top soil. This was done intentionally so that all samples were approximately from the same depth and therefore relatively similar concerning their possible exposure to processes such as weathering, regardless of the total till cover thickness. Furthermore, about 15 cm of the uppermost till cover was removed before sampling was done further into the deposit, thus preventing the mixing of other potentially non-local material such as sand from winter road maintenance. Note that the samples collected are disturbed and do not represent the original in situ/field conditions. This was acceptable, as it is considered almost impossible to obtain undisturbed samples in this type of material (Andresen, 1979; Hencher, 2012). Likewise, due to the well-known range in size of solids forming a till, from clay size particles to boulders (Clarke, 1987; Bell, 2002), it was not practically possible to sample or examine the larger fractions such as cobbles and boulders in the laboratory. According to recommendations in BS 1377–7 (1990) one should not include particles larger than 20 mm in the shear box apparatus. Consequently, and by visual inspection, particles with a diameter clearly larger than 20 mm were manually sorted out on site and not included in the sampling. Organic material such as roots and insects were also as far as possible removed manually during the sampling. From NS–EN 932–1 (1996), the samples were weighed on site with a spring scale to follow the given standard mass recommendations for a sample with a maximum particle size of 20 mm, i.e., minimum 53 kg per sample. The collected samples were put in individual plastic barrels and sealed to prevent any mixing of the material during transport. For the same reason, both the shovel and the bucket were cleaned after each sampling.

Laboratory work

The laboratory work was performed at the Department of Geoscience and Petroleum at the Norwegian University of Science and Technology (NTNU–IGP). As it is known that the reproducibility and repeatability of direct shear test results may vary (Converse, 1953; Bareither et al., 2008a) due to factors such as human imprecision (Thermann et al., 2006), a major focus in this study was that all the samples were prepared and tested as identically as practically possible with the same procedure. This was done to exclude variables and

Table 2. *Overview of the locations of 33 collected till samples from 29 municipalities in 11 counties in the southern half of Norway, also categorised by the rock provinces as shown in Fig. 1.*

Sample no.	*Location*	*Municipality*	*County*	*Rock province*
1	Kvam	Nord-Fron	Oppland	E
2	Fosse	Sør-Fron	Oppland	F
3	Sustad	Lillehammer	Oppland	F
4	Raufoss	Vestre Toten	Oppland	C
5	Harestua	Lunner	Oppland	A/B
6	Røyne	Lier	Buskerud	A/B
7	Jondalen	Kongsberg	Buskerud	C
8	Brunkeberg	Kviteseid	Telemark	C
9	Valle	Valle	Aust-Agder	C
10	Heranostangen	Lom	Oppland	D
11	Leirvassbu	Lom	Oppland	D
12	Murane	Årdal	Sogn og Fjordane	D
13	Kaupanger	Sogndal	Sogn og Fjordane	D
14	Jordalen	Voss	Hordaland	D
15	Indre Oppedal	Gulen	Sogn og Fjordane	G
16	Vassenden	Jølster	Sogn og Fjordane	G
17	Tunga	Volda	Møre og Romsdal	G
18	Voll	Rauma	Møre og Romsdal	G
19	Meisalstranda	Nesset	Møre og Romsdal	G
20	Skatval	Stjørdal	Nord-Trøndelag	E
21	Tømra	Selbu	Sør-Trøndelag	E
22	Korsvegen	Melhus	Sør-Trøndelag	E
23	Budalen	Midtre Gauldal	Sør-Trøndelag	E
24	Yset	Tynset	Hedmark	E
25	Åkerådalen	Rendalen	Hedmark	F
26	Steinbekkbua	Stor-Elvdal	Hedmark	F
27	Opphus	Stor-Elvdal	Hedmark	F
28	Flisa	Åsnes	Hedmark	C
29	Sørli	Kongsvinger	Hedmark	C
30	Sandsnessætra	Nannestad	Akershus	A/B
31	Hakadal	Nittedal	Akershus	A/B
32	Passebekk	Kongsberg	Buskerud	A/B
33	Enodden	Midtre Gauldal	Sør-Trøndelag	E

thereby increase the likelihood of obtaining an equal comparison basis, and, furthermore, so that the results could be linked to the geological parameters of the material. In addition to the main test, six samples were therefore retested for two complete tests to investigate the repeatability of the results.

Initially, the samples were sieved both mechanically and manually for a minimum of five minutes on one single 16 mm sieve in their original condition, thereby discarding larger particles. As previously described, BS 1377–7 (1990) recommends not including particles larger than 20 mm, so the 16 mm sieve was chosen due to the likely presence of some larger, elongated particles in the samples. Based on NS–EN 932–2 (1999) and NS–EN 933–1 (2012), a small portion of material of minimum 2.6 kg from each sample was thereafter randomly selected by splitting with the use of a riffle box, this for the purpose of performing future studies such as particle size distribution. Then, about 40 kg of each sieved sample (<16 mm) were put in shallow pans and dried in an oven at 110°C ± 5°C for a minimum of 16 hours, which according to ISO 17892–1 (2014) is normally enough time to achieve a completely dry material. The main reason for drying was to exclude the possibility that the moisture content could be a variable in the testing.

Figure 2. An example of a typical till sampling location, here from sample no. 14, Jordalen in Voss municipality, Hordaland county: (A) A non-vegetated slope cut reachable by car, (B) Overview of the sample site (pit marked by shovel and carpenter's ruler), (C) Excavation of sample pit (the carpenter's ruler is 1 m).

After this preparation procedure, the samples were ready to be tested in the SB2010 located at NTNU–IGP, which is a large-scale direct shear box apparatus from Testconsult Ltd. (Fig. 3A, B). The SB2010 is a modern, fully automated machine which incorporates a personal computer for operating the machine, for logging and displaying test data in real time and for reporting test results. During a shear test, the SB2010 automatically registers the shear stress, τ (rounded to whole numbers of kPa), several times per millimetre displacement. The lateral and vertical load capacity range are 0 to 100 kN with a maximum vertical load capacity of 1000 kPa with the use of a precision stepper motor and hydraulics, whereas applied loads are measured directly using calibrated load cells (0.1% FS). The maximum inner dimensions of the stainless steel sample box are 305 mm x 305 mm x 200 mm, i.e., length and width (fixed), and height (adjustable sample height), respectively. The SB2010 machine is in full accordance with BS 1377–7:1990 (Testconsult, 2012).

Before testing the individual samples in the SB2010, the sieved and dried material was firstly weighed in its storage container. The material was then carefully poured into the sample box with the use of a hand scoop (Fig. 4A). The pouring was done into the middle of the box, resulting in a randomised distribution within the box from the middle and outwards. Note that both the surfaces and contact area of the sample box halves were free of lubrication such as grease. A total sample height of approximately 180 mm was used, and as recommended in BS 1377–7 (1990) the sample was divided into three equally vertical-sized layers. These layers were manually divided and prepared with the use of two self-made wooden tools, ensuring that each layer in every sample was horizontally levelled at best possible equal vertical height, regardless of individual operator accuracy (Fig. 4B). Partly based on BS 1377–7 (1990), each layer was also compacted by doing five drops with a 4 kg weight (kettlebell) from a fixed height of approximately 20 cm on top of a steel plate covering the entire layer (Fig. 4C). According to recommendations in the newer ASTM D3080/D3080M (2011) the layer was, after compaction, 'scarified' before establishing a new layer. This scarification was performed with a garden hand fork on the first two layers, i.e., three times in two perpendicular directions over the entire layer area, to avoid distinct layer segregations (Fig. 4D). The last layer was compacted before performing a visual inspection of nine fixed points, i.e., the four corners, sides and the middle, measuring with a ruler the distance in millimetres from top edge of the box down to the top compacted surface of the sample (Fig. 4E, F). This was done to calculate the volume of material contained in

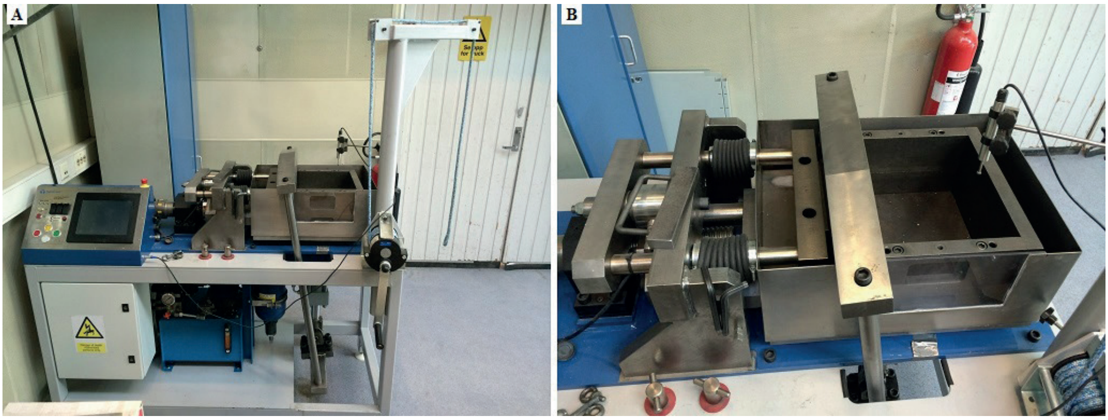

Figure 3. *An overview of (A) the SB2010 large-scale direct shear box apparatus located at NTNU–IGP, and (B) with the installed, empty sample box.*

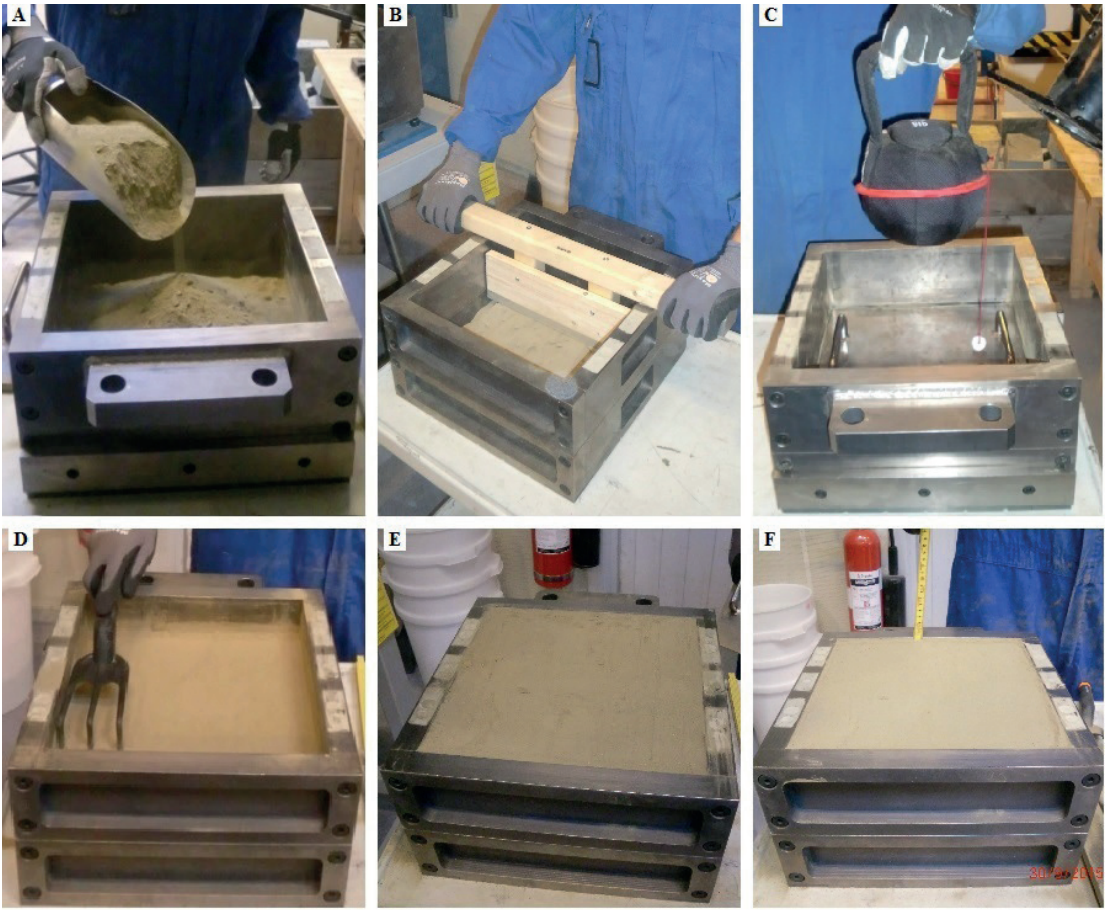

Figure 4. *The figures show the shear box testing procedure by preparing the sample for shearing: (A) Pouring of sieved (<16 mm) and dried till material into the middle of the sample box, (B) Levelling of a total of three equally vertical sized layers (approximately 60 mm each) with self-made wooden tools, (C) Initial compaction of each layer by doing five drops from a fixed height of approximately 20 cm with a 4 kg kettlebell on top of a steel plate, (D) Scarifying the two first compacted layers three times in two perpendicular directions with a garden hand fork to avoid distinct layering, (E) Filled shear box before final compaction, (F) Visual measurement of the sample height from nine fixed points (corners, sides and the middle) after compaction for calculation of sample volume and thereafter the initial dry testing density.*

the sample box. Finally, the steel plate cover was put on top of the compacted material and the sample box was installed in the shear box apparatus. Most of the excess spilled material was with best effort collected and put back into the storage container before it was weighed again, hereby giving the weight of the material contained in the sample box. With approximate information of both mass and volume, the 'initial dry testing density', ρ_d, of the sample was calculated once per sample on the first test.

Even though the SB2010 has a programmable shear rate up to 10 mm/min (Testconsult, 2012), it seems from other shear test studies that they, in general, have used considerably lower rates, e.g., 0.5 mm/min (Fannin et al., 2005), 0.01 mm/min (Gan et al., 1988) and 0.005 mm/min (Miller & Hamid, 2007). In addition, ISO 17892–10 (2004) recommends a rate not higher than 0.5 mm/min. However, the purpose of shearing the sample slowly is, according to ASTM D3080/D3080M (2011), to allow pore-water pressures to dissipate. The samples in this study were, as described, completely dry, thereby avoiding the potential build-up of pore-water pressure. Furthermore, since the water content may also have an influence on the shear strength due to the force of suction (Rahardjo et al., 1995; Fredlund et al., 1996; Lommler, 2012), drying the samples excluded this variable as well. Therefore, the samples were tested with a higher shear rate of 2.0 mm/min.

Regarding shear distance, ASTM D3080/D3080M (2011) recommends that the sample should be sheared to at least 10% relative lateral displacement, i.e., minimum 30.5 mm for the SB2010. Although the SB2010 can shear the sample up to a distance of 50 mm (Testconsult, 2012), this may lead to spillage of material outside the sample box halves, as well as to a significantly decreased shearing area. Thus, it was decided to shear the samples for a horizontal distance of approximately 40.0 mm, which was also similar to the shear distance in the study done by Bareither et al. (2008b).

As recommended by both BS 1377–7 (1990) and ASTM D3080/D3080M (2011), three shear tests with different normal stress, σ, were performed on all 33 samples. The three chosen levels of applied normal stress were 100, 200 and 300 kPa, as in the study by Skuodis & Tamošiūnas (2014). These levels of normal stress are relatively high when compared with other studies such as Fannin et al. (2005) and they do not reflect current field conditions. However, the main reason for selecting these levels of normal stress was former laboratory experience at NTNU–IGP showing that the SB2010 was somewhat inaccurate regarding constant loading during tests with a normal stress below 50 kPa (G. Vistnes, pers. comm., 2015). Before each shear test the samples were vertically preloaded at 350 kPa for a period of three minutes, thereby ensuring that all samples had an equal starting condition.

After completion of each shear test, the sample box was emptied, cleaned and refilled as described. On this matter, it must be noted that the samples were reused, which is not recommended in both BS 1377–7 (1990) and ASTM D3080/D3080M (2011), probably due to the potential alteration or deterioration of the material when shearing, e.g., particle crushing. However, as Norwegian rocks are generally recognised as strong (Palmstrøm, 1997; Grimstad et al., 2007), the degree of potential particle crushing was considered to be low. Additionally, the sample box was not exposed to vibration, which would result in an increased particle rearrangement into a denser state. The samples were therefore still in a loose packed state when shear tested. As mentioned, it is known that an increase in the density increases the peak shearing resistance (Simoni & Houlsby, 2006; Smith, 2014). Hence, shearing the samples in a loose packed state will minimise the risk of alteration or deterioration since there should be little or no dilatancy (Donald, 1956). Thus, the reuse of samples was regarded as having an insignificant influence on the geological parameters and the results. This reuse of the samples was also why lubrication of the sample box was avoided, as it would mix with the dry material thereby reducing the dryness. After completing the three shear tests, both the sample box and the shear box apparatus, as well as the other equipment, were thoroughly cleaned to avoid any mixing of material between different samples.

Supplementary work

From the locations (Table 2), a simplified bedrock geology map of the southern half of Norway was used as a basis for categorising the sample sites into regional, major rock provinces (Fig. 1; Table 1). For verification, the sample locations by GPS-coordinates were compared to the bedrock geology map from NGU (2016b). In addition to the transport distance of till, another key aspect in this context was the influence of the ice-flow directions which, during the different phases of the Weichselian glaciation, changed due to the shifts of the ice divide (Vorren, 1977). Both regional and local studies by e.g., Bergersen & Garnes (1971, 1972) and Reite (1994) have shown that the Weichselian ice-flow directions have altered quite significantly. Thus, for simplicity, only the major ice-flow directions on a national scale in the late-Weichselian were considered when evaluating the character of the possible rock material assumed to constitute the till samples.

After categorising the sample sites with respect to the major rock provinces A–H retrieved from the bedrock geology map, seven out of eight provinces were represented. Province H, which by far was also the smallest province, was not represented. Similarly, province B was the second smallest in size, but it also overlapped with province A. Due to the relatively small area of province B, as well as its overlap with province A, there was a possibility of mixing of the rock types between these two provinces. However, due to the main ice-flow directions in this southeastern part of Norway

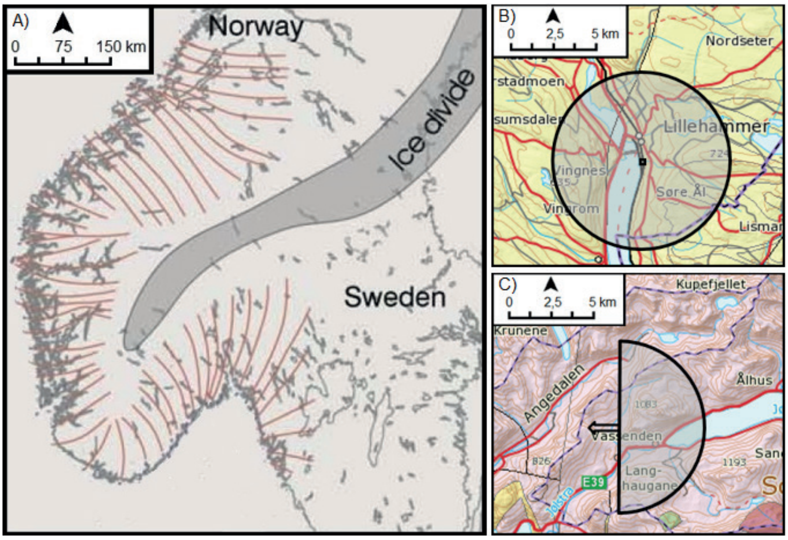

Figure 5. *(A) Reconstructed ice-sheet flow regime of the late-Weichselian in the southern half of Norway, where red lines indicate ice-flow directions from the ice divide towards the coastline, modified from Ottesen et al. (2005, p. 1048, fig. 13). (B) Bedrock geology map showing the rock type(s) outside and within a full circle with a radius of five kilometres from sample no. 3, Lillehammer (prov. F), categorised as inside/near the ice divide, (C) Bedrock geology map showing the rock type(s) outside and within a half-circle with a radius of five kilometres from sample no. 16, Jølster (prov. G). This sample is categorised as outside the ice divide with a westward ice-flow direction illustrated by the black arrow. (B) and (C) are modified from NGU (2016b).*

(Fig. 5A), it was considered more likely that province A was influenced by province B, rather than the opposite. For simplicity, provinces A and B were therefore combined as one province, noted as A/B. Hence, between five to seven samples were collected from each of the remaining six provinces A/B–G (Table 2).

When combining the bedrock geology map (NGU, 2016b) with the sample sites and the late-Weichselian ice-flow directions (Fig. 5A), a full (360°) or half (180°) circle with a radius of about five kilometres was drawn around the center of the sample sites and used as outer limits for sorting out the most likely rock type or types constituting the till samples. A full circle was used for the samples considered to be in or near the area of the ice divide, since the ice-flow directions were unspecified in these areas (Fig. 5B). For samples considered to be outside the ice divide, a half circle was made from the sample site 'downstream' of the major ice-flow direction. Thus, for an ice-flow direction towards the west, rock types east of the sample site were included, while rock types farther west of the sample site were excluded, as this would be 'countercurrent' and therefore considered unlikely (Fig. 5C). After excluding areas on the map where the bedrock is covered, i.e., rivers, lakes and fjords, the up to three most dominant rock types within the remaining radius zone were selected and listed for each sample site. Their assumed influence regarding till content was based on their individual area size within the half or full circle, which were approximately measured in the planar view and calculated. The first rock type listed represents the rock type in the area from which the sample itself was collected, independent of its area size, whereas the remaining rock types are listed with a chronological and decreasing respective percentage share.

The maximum shear stress registered by the SB2010 for the whole displacement length for each shear test was further processed to estimate the angle of friction and cohesion by linear regression analysis, restraining the fit of the data to cohesion ≥0 kPa. According to BS 1377–7 (1990), the reported angle of friction, ϕ, was rounded to the nearest 0.5°, while the cohesion, c, was rounded to one decimal place of kPa. The samples and associated results were then summarised in tables for each of the six major rock provinces, including e.g., the average and the standard deviation (SD). In addition, the obtained results were processed for the purpose of graphical visualisation of shear stress vs. horizontal displacement. This simplified plotting was done by choosing the registered shear stress value closest to each whole millimetre from the entire displacement length of each shear test. When processing all the samples in each province, both the highest and lowest registered values (independent of sample number), as well as the average for all samples, for each 'whole millimetre' were plotted. This made it possible to visualise the average curve, and that all the individual curves for each province thus lie somewhere within the minimum and maximum curves.

Results

When considering all the 33 samples, the average initial dry testing density, ρ_d, was 1.67 g/cm^3 (SD = 0.15 g/cm^3; median = 1.68 g/cm^3). The lowest and highest registered values of ρ_d were 1.39 g/cm^3 (sample no. 5, prov. A/B) and 2.04 g/cm^3 (no. 11, prov. D), respectively, i.e., a difference of 0.65 g/cm^3. For the main shear test with 100 kPa applied normal stress, the average shear stress value, τ, based on the maximum value for each sample, was 84.9 kPa (SD = 3.0 kPa; median = 85.0 kPa), with 78.0 kPa (no. 30, prov. A/B) as the lowest value and 91.0 kPa (no. 12, prov. D) as the highest value. With the increase of the normal stress to 200 kPa, the average shear stress was 163.2 kPa (SD = 6.5 kPa; median = 162.0 kPa), with 152.0 kPa (no. 30, prov. A/B) and 177.0 kPa (no. 16, prov. G) as the lowest and highest values, respectively. For 300 kPa normal stress, the average shear stress was 243.7 kPa (SD = 9.6 kPa; median = 246.0 kPa), with 229.0 kPa (no. 11, prov. D, and no. 30, prov. A/B) as the lowest value and 269.0 kPa (no. 12, prov. D) as the highest registered value. Thus, the differences in the shear stress results were up to 13.0 kPa, 25.0 kPa and 40.0 kPa for 100, 200 and 300 kPa applied normal stress, respectively. Furthermore, the diversities in shear stress resulted in a similar variety of estimated angles of friction, ϕ, and cohesion, c. The average angle of friction was 38.4° (SD = 1.3°; median = 38.5°), spanning from 36.0° (no. 26, prov. F) as the lowest, to 41.5° (no. 12, prov. D) as the highest registered value, i.e., a difference of 5.5°. Cohesion ranged from 0.0 kPa (nos. 12 and 14, prov. D, and nos. 20 and 21, prov. E) to 11.3 kPa (no. 22, prov. E), with an average of 5.3 kPa (SD = 3.5 kPa; median 5.3 kPa).

Regarding the mapped bedrock geology, the five samples in province A/B ('Extrusive and plutonic rocks/ Sedimentary rocks in the Oslo region'), except for sample no. 6, were dominated by syenites and granites. Apart from sample no. 8, the other five samples in province C ('Precambrian basement') were dominated by a variety of gneisses and granites. Province D ('Caledonian rocks, Overthrust sheets of Precambrian rocks') was generally dominated by various mangerite, gabbro, amphibolite and gneiss, whereas sample no. 13 was solely represented by anorthosite. Province E ('Caledonian rocks, Metamorphic and igneous rocks') was the most variable regarding the number of represented rock types in the samples. Overall, mica schist, mica gneiss, amphibolite, greenstone, metasandstone and phyllite were heavily represented in province E. Furthermore, province F ('Caledonian rocks, Overthrust sheets of sandstone and schist') was relatively homogeneous regarding rock types, as the samples were dominated by sandstone. Lastly, province G ('Caledonian rocks, Precambrian basement, locally affected by the Caledonian orogeny') was also relatively homogeneous regarding rock types, as all of the five samples were dominated by various gneisses and migmatites. The results regarding both bedrock geology and shear test are further elaborated by the individual rock provinces (Figs. 6 & 7; Tables 3–14) and then summarised in Table 15.

Considering the six samples retested for the purpose of repeatability assessment (Table 16), the results were variably equal to, higher and lower than the ones obtained from the main test. Analysing all six samples for the three test series performed, i.e., a total of nine shear tests per sample, the SD for the shear stress results for 100, 200 and 300 kPa normal stress ranged between 1.5–4.0 kPa, 1.7–4.7 kPa, and 2.3–8.1 kPa, respectively. For the angle of friction, the SD varied between 0.3° and 1.3°, while the SD for the cohesion ranged between 2.1 and 7.5 kPa.

Table 3. *Rock types within 5 km distance for the five sample sites from rock province A/B, extrusive and plutonic rocks / sedimentary rocks in the Oslo region, from NGU (2016b).*

Rock province	*Sample no.*	*Rock types*
A/B	5	Syenite, quartz syenite (~86%); Granite, granodiorite (~14%)
	6	Phyllite, mica schist (~28%); Rhomb-porphyry (~27%); Granite, granodiorite (~16%); Other (~29%)
	30	Syenite, quartz syenite (~68%); Granite, granodiorite (~32%)
	31	Syenite, quartz syenite (~83%); Unspecified volcanic rocks (~8%); Granite, granodiorite (~7%); Other (~2%)
	32	Granite, granodiorite (~67%); Monzonite, quartz monzonite (~24%); Rhomb-porphyry (~9%)

Table 4. *The shear test results for the five till samples from rock province A/B.*

Rock province	*Sample no.*	*Initial dry testing density, ρ_d (g/cm^3)*	*Max. shear stress, τ, with normal stress, σ (kPa)*			*Angle of friction, ϕ (°)*	*Cohesion, c (kPa)*
			σ = 100 (kPa)	*σ = 200 (kPa)*	*σ = 300 (kPa)*		
A/B	5	1.39	89.0	158.0	248.0	38.5	6.0
	6	1.65	85.0	159.0	235.0	37.0	9.7
	30	1.76	78.0	152.0	229.0	37.0	2.0
	31	1.59	85.0	171.0	248.0	39.0	5.0
	32	1.62	87.0	167.0	246.0	38.5	7.7
Average		1.60	84.8	161.4	241.2	38.0	6.1
Standard deviation		0.13	4.1	7.6	8.7	0.9	2.9
Median		1.62	85.0	159.0	246.0	38.5	6.0
Maximum		1.76	89.0	171.0	248.0	39.0	9.7
Minimum		1.39	78.0	152.0	229.0	37.0	2.0
Difference		0.37	11.0	19.0	19.0	2.0	7.7

Table 5. *Rock types within 5 km distance for the six sample sites from rock province C, Precambrian basement, from NGU (2016b).*

Rock province	*Sample no.*	*Rock types*
C	4	Augen gneiss, granite, foliated granite (~18%); Amphibolite, hornblende gneiss, mica gneiss (locally migmatitic) (~62%); Sandstone, slate (~14%); Other (~6%)
	7	Augen gneiss, granite, foliated granite (~84%); Dioritic to granitic gneiss, migmatite (~8%); Amphibolite, hornblende gneiss, mica gneiss (locally migmatitic) (~4%); Other (~4%)
	8	Rhyolite, rhyodacite, dacite, keratophyre (~34%); Quartzite (~40%); Basalt (~26%)
	9	Granite, granodiorite (~88%); Amphibolite, hornblende gneiss, mica gneiss (locally migmatitic) (~7%); Augen gneiss, granite, foliated granite (~4%); Other (~1%)
	28	Gabbro, amphibolite (~24%); Dioritic to granitic gneiss, migmatite (~43%); Augen gneiss, granite, foliated granite (~33%)
	29	Augen gneiss, granite, foliated granite (~3%); Dioritic to granitic gneiss, migmatite (~81%); Gabbro, amphibolite (~16%)

Table 6. *The shear test results for the six till samples from rock province C.*

Rock province	*Sample no.*	*Initial dry testing density, ρ_d (g/cm³)*	*Max. shear stress, τ, with normal stress, σ (kPa)*			*Angle of friction, ϕ (°)*	*Cohesion, c (kPa)*
			σ = 100 (kPa)	*σ = 200 (kPa)*	*σ = 300 (kPa)*		
C	4	1.62	88.0	172.0	247.0	38.5	10.0
	7	1.64	87.0	172.0	256.0	40.0	2.7
	8	1.76	85.0	164.0	248.0	39.0	2.7
	9	1.73	87.0	173.0	259.0	40.5	1.0
	28	1.82	82.0	158.0	231.0	36.5	8.0
	29	1.81	82.0	158.0	235.0	37.5	5.3
Average		1.73	85.2	166.2	246.0	38.7	5.0
Standard deviation		0.08	2.6	7.1	11.1	1.5	3.5
Median		1.75	86.0	168.0	247.5	38.8	4.0
Maximum		1.82	88.0	173.0	259.0	40.5	10.0
Minimum		1.62	82.0	158.0	231.0	36.5	1.0
Difference		0.20	6.0	15.0	28.0	4.0	9.0

Table 7. *Rock types within 5 km distance for the five sample sites from rock province D, Caledonian rocks, overthrust sheets of Precambrian rocks, from NGU (2016b).*

Rock province	*Sample no.*	*Rock types*
D	10	Mangerite to gabbro, gneiss and amphibolite (~96%); Olivine rock, pyroxenite (~3%); Phyllite, mica schist (~1%)
	11	Mangerite to gabbro, gneiss and amphibolite (~100%)
	12	Mangerite to gabbro, gneiss and amphibolite (~74%); Gabbro, amphibolite (~16%); Dioritic to granitic gneiss (~10%)
	13	Anorthosite (~100%)
	14	Mangerite-syenite (~84%); Anorthosite (~12%); Dioritic to migmatitic gneiss (~3%); Other (~1%)

Table 8. *The shear test results for the five till samples from rock province D.*

Rock province	*Sample no.*	*Initial dry testing density, ρ_d (g/cm³)*	*Max. shear stress, τ, with normal stress, σ (kPa)*			*Angle of friction, ϕ (°)*	*Cohesion, c (kPa)*
			σ = 100 (kPa)	*σ = 200 (kPa)*	*σ = 300 (kPa)*		
D	10	1.89	85.0	160.0	242.0	38.0	5.3
	11	2.04	81.0	159.0	229.0	36.5	8.3
	12	1.79	91.0	170.0	269.0	41.5	0.0
	13	1.68	84.0	165.0	246.0	39.0	3.0
	14	1.71	84.0	162.0	251.0	39.5	0.0
Average		1.82	85.0	163.2	247.4	38.9	3.3
Standard deviation		0.15	3.7	4.4	14.6	1.9	3.6
Median		1.79	84.0	162.0	246.0	39.0	3.0
Maximum		2.04	91.0	170.0	269.0	41.5	8.3
Minimum		1.68	81.0	159.0	229.0	36.5	0.0
Difference		0.36	10.0	11.0	40.0	5.0	8.3

Table 9. *Rock types within 5 km distance for the seven sample sites from rock province E, Caledonian rocks, metamorphic and igneous rocks, from NGU (2016b).*

Rock province	*Sample no.*	*Rock types*
E	1	Phyllite, mica schist (~47%); Metasandstone, mica schist (~31%); Amphibolite, hornblende gneiss, mica gneiss (locally migmatitic) (~18%); Other (~4%)
	20	Greenstone, amphibolite (~54%); Slate, sandstone, limestone (~38%); Conglomerate, sedimentary breccia (~7%); Other (~1%)
	21	Phyllite, mica schist (~77%); Quartzite (~17%); Greenstone, amphibolite (~6%)
	22	Greenstone, amphibolite (~29%); Slate, sandstone, limestone (~37%); Unspecified volcanic rocks (~21%); Other (~13%)
	23	Greenstone, amphibolite (~5%); Mica gneiss, mica schist, metasandstone, amphibolite (~65%); Quartzite (~30%)
	24	Mica gneiss, mica schist, meta-sandstone, amphibolite (~97%); Greenstone, amphibolite (~3%)
	33	Mica gneiss, mica schist, metasandstone, amphibolite (~92%); Quartzite (~6%); Greenstone, amphibolite (~2%)

Table 10. *The shear test results for the five till samples from rock province E.*

Rock province	*Sample no.*	*Initial dry testing density, ρ_d (g/cm^3)*	*Max. shear stress, τ, with normal stress, σ (kPa)*			*Angle of friction, ϕ (°)*	*Cohesion, c (kPa)*
			σ = 100 (kPa)	*σ = 200 (kPa)*	*σ = 300 (kPa)*		
E	1	1.70	88.0	171.0	247.0	38.5	9.7
	20	1.67	82.0	163.0	250.0	39.5	0.0
	21	1.41	82.0	163.0	246.0	39.5	0.0
	22	1.54	89.0	164.0	243.0	37.5	11.3
	23	1.55	83.0	157.0	232.0	36.5	8.3
	24	1.44	87.0	158.0	240.0	37.5	8.7
	33	1.53	80.0	155.0	233.0	37.5	3.0
Average		1.55	84.4	161.6	241.6	38.1	5.9
Standard deviation		0.11	3.5	5.4	6.9	1.1	4.7
Median		1.54	83.0	163.0	243.0	37.5	8.3
Maximum		1.70	89.0	171.0	250.0	39.5	11.3
Minimum		1.41	80.0	155.0	232.0	36.5	0.0
Difference		0.29	9.0	16.0	18.0	3.0	11.3

Table 11. *Rock types within 5 km distance for the five sample sites from rock province F, Caledonian rocks, overthrust sheets of sandstone and schist, from NGU (2016b).*

Rock province	*Sample no.*	*Rock types*
F	2	Sandstone (~65%); Metasandstone, mica schist (~22%); Quartzite (~6%); Other (~7%)
	3	Sandstone (~100%)
	25	Sandstone (~100%)
	26	Sandstone (~88%); Quartzite (~10%); Conglomerate, sedimentary breccia (~1%); Other (~1%)
	27	Sandstone (~93%); Conglomerate, sedimentary breccia (~6%); Limestone, dolomite (~1%)

Table 12. The shear test results for the five till samples from rock province F.

Rock province	Sample no.	Initial dry testing density, ρ_d (g/cm^3)	Max. shear stress, τ, with normal stress, σ (kPa)			Angle of friction, ϕ (°)	Cohesion, c (kPa)
			σ = 100 (kPa)	σ = 200 (kPa)	σ = 300 (kPa)		
F	2	1.59	89.0	167.0	249.0	38.5	8.3
	3	1.43	81.0	156.0	232.0	37.0	5.3
	25	1.73	85.0	159.0	237.0	37.0	8.3
	26	1.90	84.0	157.0	230.0	36.0	11.0
	27	1.46	82.0	158.0	240.0	38.5	2.0
Average		1.62	84.2	159.4	237.6	37.4	7.0
Standard deviation		0.20	3.1	4.4	7.5	1.1	3.4
Median		1.59	84.0	158.0	237.0	37.0	8.3
Maximum		1.90	89.0	167.0	249.0	38.5	11.0
Minimum		1.43	81.0	156.0	230.0	36.0	2.0
Difference		0.47	8.0	11.0	19.0	2.5	9.0

Table 13. Rock types within 5 km distance for the five sample sites from rock province G, Caledonian rocks, Precambrian basement, locally affected by the Caledonian orogeny, from NGU (2016b).

Rock province	Sample no.	Rock types
G	15	Dioritic to granitic gneiss, migmatite (~97%); Augen gneiss, granite, foliated gneiss (~3%)
	16	Dioritic to granitic gneiss, migmatite (~100%)
	17	Dioritic to granitic gneiss, migmatite (~99%); Olivine rock, pyroxenite (~1%)
	18	Dioritic to granitic gneiss, migmatite (~100%)
	19	Dioritic to granitic gneiss, migmatite (~92%); Amphibolite and mica schist (~8%)

Table 14. The shear test results for the five till samples from rock province G.

Rock province	Sample no.	Initial dry testing density, ρ_d (g/cm^3)	Max. shear stress, τ, with normal stress, σ (kPa)			Angle of friction, ϕ (°)	Cohesion, c (kPa)
			σ = 100 (kPa)	σ = 200 (kPa)	σ = 300 (kPa)		
G	15	1.74	89.0	174.0	255.0	39.5	6.7
	16	1.62	86.0	177.0	253.0	40.0	5.0
	17	1.69	86.0	170.0	253.0	40.0	2.7
	18	1.71	84.0	161.0	239.0	38.0	6.3
	19	1.75	84.0	157.0	244.0	38.5	1.7
Average		1.70	85.8	167.8	248.8	39.2	4.5
Standard deviation		0.05	2.0	8.5	6.9	0.9	2.2
Median		1.71	86.0	170.0	253.0	39.5	5.0
Maximum		1.75	89.0	177.0	255.0	40.0	6.7
Minimum		1.62	84.0	157.0	239.0	38.0	1.7
Difference		0.13	5.0	20.0	16.0	2.0	5.0

Table 15. *A summary of the results of the average and the individual highest and lowest values based on all samples regarding initial dry testing density, ρ_d, shear stress, named here as τ_1–τ_3 (for normal stress 100, 200, and 300 kPa, respectively), angle of friction, ϕ, and cohesion, c, sorted into the distinct rock provinces A/B–G with their corresponding values in parenthesis.*

Average ρ_d, high to low (g/cm^3)	*Average τ_1, high to low (kPa)*	*Average τ_2, high to low (kPa)*	*Average τ_3, high to low (kPa)*	*Average ϕ, high to low (°)*	*Average c, high to low (kPa)*
D (1.82)	G (85.8)	G (167.8)	G (248.8)	G (39.2)	F (7.0)
C (1.73)	C (85.2)	C (166.2)	D (247.4)	D (38.9)	A/B (6.1)
G (1.70)	D (85.0)	D (163.2)	C (246.0)	C (38.7)	E (5.9)
F (1.62)	A/B (84.8)	E (161.6)	E (241.6)	E (38.1)	C (5.0)
A/B (1.60)	E (84.4)	A/B (161.4)	A/B (241.2)	A/B (38.0)	G (4.5)
E (1.55)	F (84.2)	F (159.4)	F (237.6)	F (37.4)	D (3.3)

High to low, ρ_d (g/cm^3)	*Low to high, ρ_d (g/cm^3)*	*High to low, τ_1 (kPa)*	*Low to high, τ_1 (kPa)*	*High to low, τ_2 (kPa)*	*Low to high, τ_2 (kPa)*	*High to low, τ_3 (kPa)*	*Low to high, τ_3 (kPa)*	*High to low, ϕ (°)*	*Low to high, ϕ (°)*	*High to low, c (kPa)*	*Low to high, c (kPa)*
D (2.04)	A/B (1.39)	D (91.0)	A/B (78.0)	G (177.0)	A/B (152.0)	D (269.0)	A/B (229.0)	D (41.5)	F (36.0)	E (11.3)	D (0.0)
F (1.90)	E (1.41)	A/B (89.0)	E (80.0)	C (173.0)	E (155.0)	C (259.0)	D (229.0)	C (40.5)	C (36.5)	F (11.0)	E (0.0)
C (1.82)	F (1.43)	E (89.0)	D (81.0)	A/B (171.0)	F (156.0)	G (255.0)	F (230.0)	G (40.0)	D (36.5)	C (10.0)	C (1.0)
A/B (1.76)	C (1.62)	F (89.0)	F (81.0)	E (171.0)	G (157.0)	E (250.0)	C (231.0)	E (39.5)	E (36.5)	A/B (9.7)	G (1.7)
G (1.75)	G (1.62)	G (89.0)	C (82.0)	D (170.0)	C (158.0)	F (249.0)	E (232.0)	A/B (39.0)	A/B (37.0)	D (8.3)	A/B (2.0)
E (1.70)	D (1.68)	C (88.0)	G (84.0)	F (167.0)	D (159.0)	A/B (248.0)	G (239.0)	F (38.5)	G (38.0)	G (6.7)	F (2.0)

Table 16. *A summary of the results for two additional shear tests performed on six of the 33 till samples.*

	Test 2: Max. shear stress, τ, with normal stress, σ (kPa)					*Test 3: Max. shear stress, τ, with normal stress, σ (kPa)*				
Sample no.	*σ = 100 (kPa)*	*σ = 200 (kPa)*	*σ = 300 (kPa)*	*Angle of friction, ϕ (°)*	*Cohesion, c (kPa)*	*σ = 100 (kPa)*	*σ = 200 (kPa)*	*σ = 300 (kPa)*	*Angle of friction, ϕ (°)*	*Cohesion, c (kPa)*
12	94.0	176.0	256.0	39.0	13.3	97.0	177.0	271.0	41.0	7.7
15	97.0	178.0	251.0	37.5	21.3	92.0	176.0	255.0	39.0	11.3
24	81.0	158.0	243.0	39.0	0.0	81.0	155.0	233.0	37.0	4.3
25	80.0	155.0	235.0	38.0	1.7	80.0	156.0	225.0	36.0	8.7
28	85.0	160.0	242.0	38.0	5.3	86.0	167.0	241.0	38.0	9.7
32	90.0	170.0	249.0	38.5	10.7	88.0	170.0	251.0	39.0	6.7

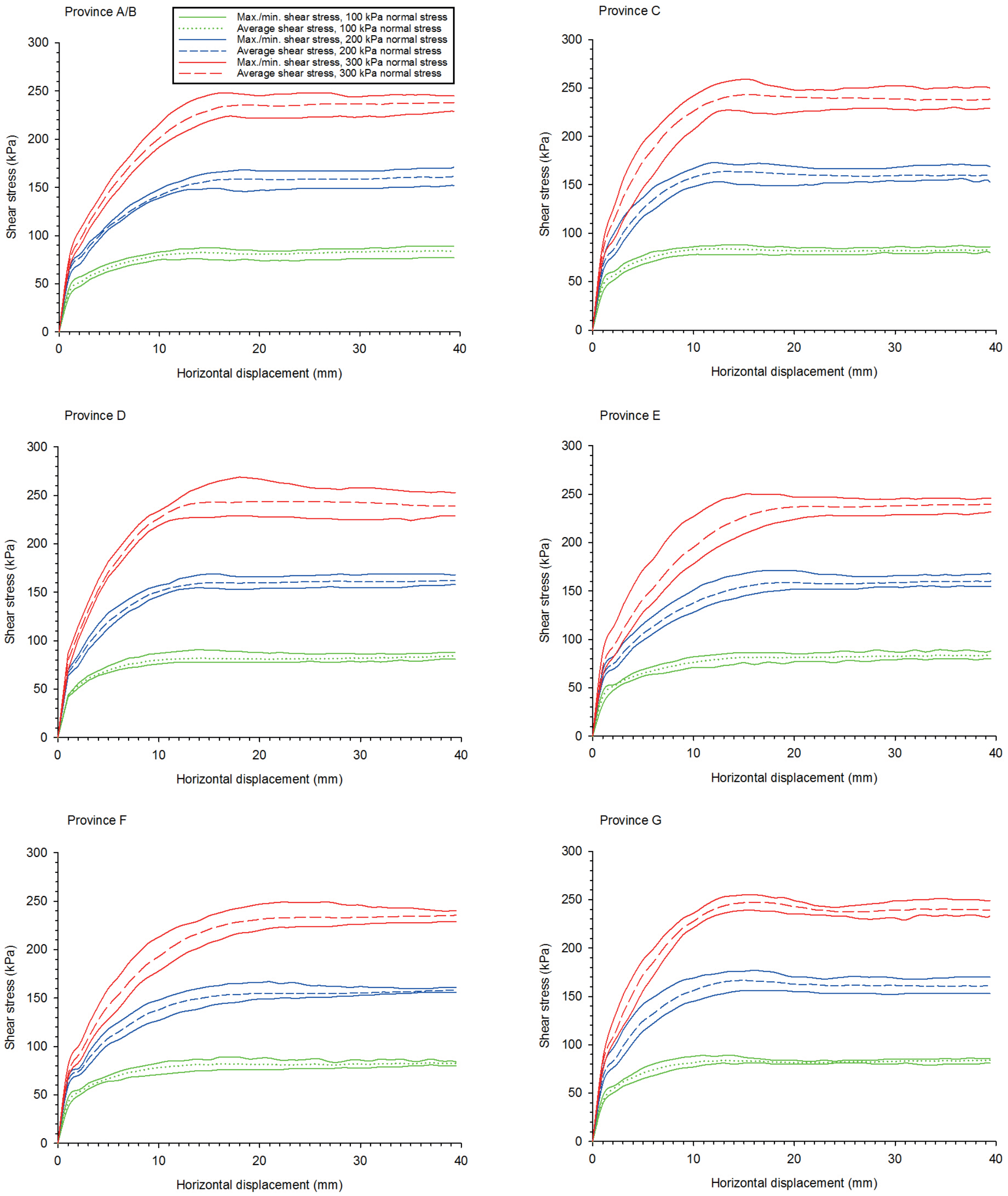

__Figure 6.__ Shear test results for the till samples from each of the six rock provinces, A/B–G.

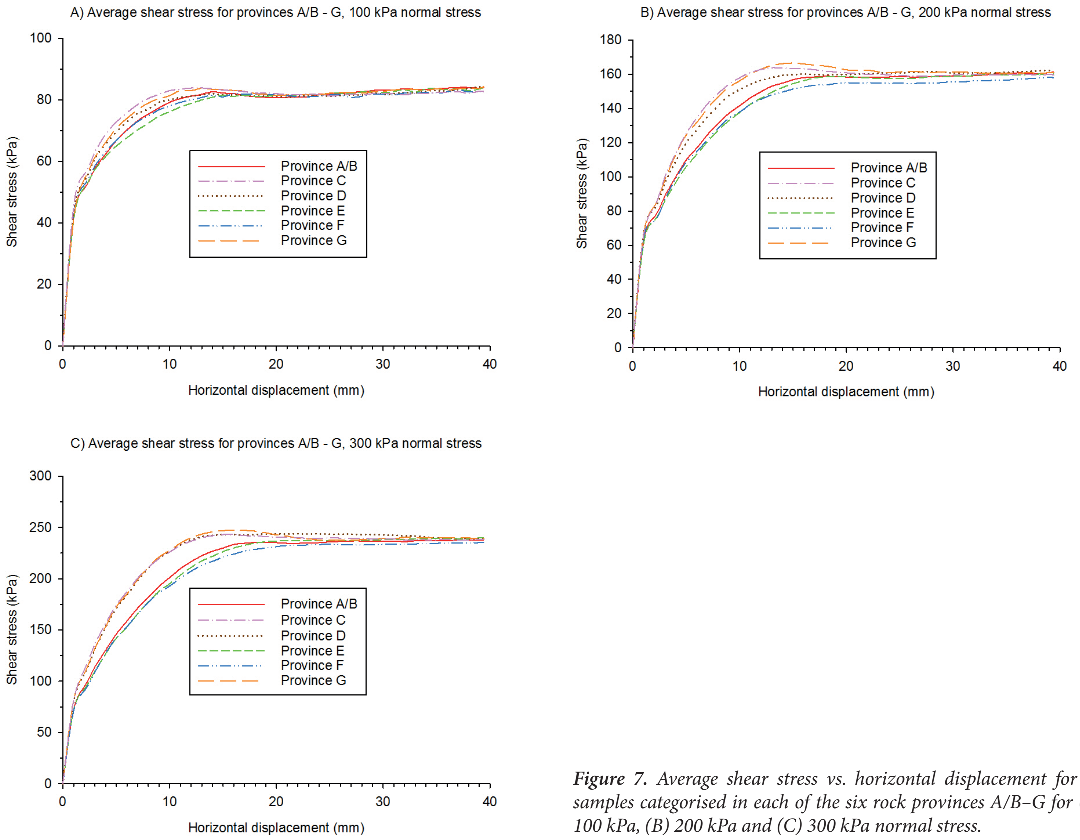

Figure 7. *Average shear stress vs. horizontal displacement for all samples categorised in each of the six rock provinces A/B–G for (A) 100 kPa, (B) 200 kPa and (C) 300 kPa normal stress.*

Discussion

During the fieldwork there were some challenges regarding field interpretation for selecting the ideal sample sites. The tills were, for practical reasons, therefore chosen independently of genesis. However, genesis is known to influence the geotechnical properties of tills through its control on important characteristics such as stress history and particle size distribution. Also, post-depositional processes, such as wetting and drying, freezing and thawing, and downward percolation of fines, may further change the characteristics of the till (Boulton & Paul, 1976). As such variables are not accounted for in the sampling, they are sources of uncertainty for the representativeness of the samples regarding the area from which they are collected and, consequently, for the interpretation of the shear test results.

Furthermore, to distinguish a till deposit from an old, revegetated debris slide/flow deposit of till material was also rather challenging as the outcrops were commonly limited. According to Cammeraat & Rappol (1987), there is a possibility that till-like resedimentation products (debris flows) may be incorporated in the sampling, as these can be difficult to differentiate from true tills in such cases where the exposure in the field is poor. Additionally, the degree of detailed mapping available from the Quaternary geology map (NGU, 2016c), especially in the transition zone from one deposit type to another, is quite poor in some areas. Although focusing on locations marked on the map as till, one cannot exclude the possibility that some of the samples are, in fact, from e.g., debris slide/flow deposits of till material. Yet, this latter potential source of uncertainty was regarded as having no significant influence, as the sampling itself disturbed the material.

The samples were not tested in their in situ state, as it is regarded as nearly impossible to collect perfectly undisturbed samples of till (e.g., Andresen, 1979). The disturbed samples were also prepared in the laboratory with sieving, splitting, drying and compacting before shear testing. According to Vanapalli et al. (1996), the laboratory preparation of samples must closely represent the physical conditions and the stress state conditions likely to occur in the field if a proper assessment of the shear strength parameters is to be achieved. For example, it is considered as practically impossible to obtain a soil with zero saturation (Budhu, 2015), thus making the dried samples in this study not representable for normal Norwegian field conditions. As water is a main trigger for Norwegian debris slides and flows (e.g., Kronholm et al., 2007; Bargel et al., 2011), shear testing the samples in saturated conditions instead of in a dry condition would clearly be more appropriate for practical applications regarding slope stability assessment. In practice, however, including water in the testing would introduce a variable hard to control. This is due to significant differences of the geological parameters amongst the till samples, such as the particle size distribution, which could lead to, e.g., inhomogeneous saturation in the material and removal of fines. This, in turn, would potentially introduce a significant uncertainty to the results. Moreover, the relatively high levels of applied normal stress do not reflect current field conditions either. Consequently, these results are not likely to replicate the factual in situ/field conditions at the sample sites regarding till shear strength. Nevertheless, and as initially stated, the samples in this study were not tested with the purpose of replicating their field conditions, but with the same procedure for achieving a best possible, equal comparison basis. Hence, the aim of the study was to show if shear strength differences in relation to bedrock geology and the respective rock provinces do exist, regardless of individual field variables such as stress state, density and water content. Excluding these, although highly important, variables was considered necessary to be able to establish equal conditions of testing with a minimum of laboratory variables, and, accordingly, so that the results could be linked to the geological parameters (particle shape, size, etc.) of the samples.

Independently of uncertainties in the sampling and testing procedure, one should also evaluate the apparatus that was used. Regarding the use of a shear box apparatus, Das (2010) pointed out that the direct shear test method has some inherent shortcomings. For example, the reliability of shear box results may, in general, be questioned because the soil is forced to fail along the contact plane of the two halves of the box, rather than along a potentially weaker plane in the sample. However, the disturbed, heterogeneous material tested in this study should be relatively homogeneous when prepared in the sample box, thereby having no significantly weaker planes than the plane of split. Although the shear strength can be found by using other laboratory tests, such as the triaxial test, the direct shear test is considered to be the simplest and most economical for a dry sandy soil (Das, 2010), and, according to Lommler (2012), the commercial laboratory test of choice for granular soils.

Furthermore, according to e.g., Hooke (2005), detailed measurements often show that the variation of yield strength with effective normal pressure is not linear at low effective normal pressures, hereby giving rise to the terms ‘true cohesion’ and ‘apparent cohesion’. While till may have true cohesion (Hooke, 2005; Hungr et al., 2005), Cuffey & Paterson (2010) have pointed out that in shear at critical state the till has no true cohesion. Also, since these samples were prepared from disturbed material, there could certainly be no true cohesion (Hencher, 2012). Thus, the values of cohesion reported here are not true cohesion, but obtained values from the linear regression analysis.

As the reproducibility and repeatability of the results from shear tests may vary (e.g., Bareither et al., 2008a), six of the samples were retested to observe the possible change of results (Table 16). Bareither et al. (2008a) investigated the repeatability and reproducibility of direct shear tests on granular backfill material (sand). In that context, ‘repeatability’ meant testing identical items in the same laboratory by the same operator using both the same method and equipment (intra-laboratory), while ‘reproducibility’ meant testing the identical items with the same method, but in 10 other laboratories by different operators and equipment (inter-laboratory). In summary, the reproducibility varied significantly more than the repeatability. Regarding repeatability, the intra-laboratory tests on the angle of friction led to a SD of 0.1°. On the other hand, the inter-laboratory tests reported an average reproducibility of 8.8°, with a range of variability up to 18.8°. Compared to the present study, where the SD of the angle of friction ranged from 0.3° to 1.3°, the results were considerably better than the reproducibility results reported by Bareither et al. (2008a), although the repeatability was not as good. However, the reason for this diversity of results may be due to factors such as the difference of material used (relatively homogeneous sand vs. heterogeneous till material) as well as the number of tests performed (five vs. three). For these reasons, the results presented in Table 16 were considered satisfactory regarding the assessment of repeatability.

Moreover, on the issue of repeatability, studies by e.g., Feda (2002) and Hattamleh et al. (2010) have reported changes in shear strength due to particle crushing, which initially was also of some concern in this study, especially due to the necessary reuse of samples. Yet, when retesting six of the samples, the results were either equal to, higher and lower than the ones obtained from the main test. This strengthened the initial assumption that the samples would not be noticeably damaged or altered by reuse. Although there were some clear differences in some of the additional tests, it is difficult to isolate the exact reason(s), as these may be due to uncertainties in the shear box apparatus, geological parameters, procedure, operator, or a combination of these. Since the samples consist of gravel, sand and fines, emptying and refilling the sample box gives significantly more combinations of particle arrangements and interactions and, as a result, the repeatability should therefore vary more than retesting, e.g., a homogeneous sand.

Internationally, from shear tests on multiple tills from eastern England, Bell (2002) presented angles of friction mainly ranging from approximately 20° to 30°, although the fraction of fines composed up to 60–80% of these tills. Iverson et al. (1994) reported an angle of friction of 31° in a till from Sweden, while a study by Rathbun et al. (2008) on two tills from Alaska and Ohio, USA, resulted in 31.4° and 29.4°, respectively. Others have reported that the angle of friction for till ranges between 35° and 45° (Koloski et al., 1989). Clearly, the angles of friction for tills may vary significantly. Considering the previously mentioned shear test studies of Norwegian tills, Lund (2013), Langåker (2014) and Langeland (2016) investigated one locality each, i.e., Nesbyen in Nes municipality, Buskerud county, Seim in Granvin municipality, Hordaland county, and Soknedal in Midtre Gauldal municipality, Sør-Trøndelag county, respectively. The angles of friction in the study by Langåker ranged between 38.9° and 42.7°, while the studies by Lund and Langeland resulted in 39.5° and 37.4°, respectively. Although the localities in these Norwegian studies do not overlap with any samples in this study, as well as not being tested with exactly the same procedure, the results are still quite comparable and substantiate the presented results. Especially the angle of friction from Langeland is near identical to the results from the three closest samples presented here, i.e., nos. 22, 23 and 33 (Table 10).

When incorporating bedrock geology into the results, both similarities and differences among the samples are shown within each rock province and when comparing the provinces to one another. It is well known that the compressive strength of different rock types varies (Afrouz, 1992; Nilsen & Palmstrøm, 2000; Waltham, 2009). According to the compressive strength description presented in NS–EN ISO 14689–1 (2004), the terms are 'extremely weak' (<1 MPa), 'very weak' (1–5 MPa), 'weak' (5–25 MPa), 'medium strong' (25–50 MPa), 'strong' (50–100 MPa), 'very strong' (100–250 MPa) and 'extremely strong' (>250 MPa). Accordingly, the tills are composed of rock types of varying compressive strengths. As initially mentioned, this difference in bedrock geology, including rock strength, should to some extent influence the till shear strength as well. In the following, an evaluation of the results is presented for each individual rock province, including a brief description of the typical rock strengths of the dominant rock type(s) within the respective provinces. Note that the compressive strength values given by Nilsen & Palmstrøm (2000) are average values from tests on Scandinavian rocks.

Province A/B: extrusive and plutonic rocks / sedimentary rocks in the Oslo region

When compared to the other provinces, the five samples collected from this province are geographically very close. In addition, the rock types of the respective sites are similar, being mainly dominated by syenite and quartz syenite, as well as granite and granodiorite. Palmstrøm (1997) also presented the compressive strength for several Norwegian rock types, where syenite varies between 100 and 250 MPa. According to Nilsen & Palmstrøm (2000), the compressive strengths for granite and granodiorite are 169 MPa and 171 MPa, respectively, while monzonite has a compressive strength of 106 MPa. According to NS–EN ISO 14689–1 (2004), these rock types are termed as 'very strong'. On the other hand, phyllite and mica schist are listed with compressive strengths of 61 MPa and 71 MPa, respectively (Nilsen & Palmstrøm, 2000), and are termed as 'strong' rocks. However, the compressive strength of both phyllite and mica schist may also be as low as 20 MPa (Palmstrøm, 1997), thereby termed as 'weak' rocks. By solely comparing the compressive strength of these rock types with the till shear test results, in addition to the relatively small geographic area, one should expect intermediate to high shear strength and quite similar results, especially for sample nos. 5, 30 and 31. By comparison, sample no. 6, which contains a significant component of potentially weak mica schist and phyllite, should stand out as the weakest regarding shear strength. The results show a rather intermediate level of average max. shear stresses and angle of friction when compared with the other provinces (Table 15). Actually, the average angle of friction for this province is almost the same as province E. In addition, sample nos. 5, 31 and 32 show the most similar results, whereas no. 30 unexpectedly is the weakest due to the low angle of friction and registered shear stresses, even though the rock types are considered stronger than those in no. 6. This suggests that parameters other than rock (particle) strength may have a larger influence on the results in this particular case.

Province C: Precambrian basement

The six samples in this province are geographically the most scattered, extending from the southeastern part of Norway close to the Swedish border towards the southwestern part of the country. Various gneisses and granites dominate in five of the samples. According to Nilsen & Palmstrøm (2000), the compressive strength is 130 MPa for gneiss and 169 MPa for granite. It is important to note, however, that the designation 'gneiss' is used for rocks with potentially large mineralogical differences (Prestvik, 1995). Thus, the compressive strength for gneiss may vary from 80 MPa to 200 MPa (Palmstrøm, 1997). Due to the compressive strengths of these rock types, termed as 'very strong', one should expect a rather high till shear strength. As expected, on average this province scores quite high regarding max. shear stresses and the angle of friction. The average angle of friction is the third highest of all provinces (Table 15). However, the average is affected by the rather low angles of friction from sample nos. 28 and 29. The results show that sample nos. 4, 7, 8 and 9 are quite similar in having a high angle of friction, clearly differing from nos. 28 and 29, which, in turn, are quite similar to one another by having a lower angle of friction. These two southeastern located samples are geographically close and relatively similar regarding rock types, but they also have some differences when compared to the remaining four samples. The differences of geography and rock types may partly explain the differences of results. For example, one possible explanation could be the fact that this southeastern region is known for having several mylonite zones, where the rocks have been exposed to both plastic deformation and crushing (Oftedahl, 1981). One cannot exclude that such processes may have influenced these two samples regarding geological parameters such as rock strength and particle size distribution. However, only sample no. 29 seems to lie within such a mylonite zone, and it is also slightly stronger than sample no. 28, thereby reducing the likelihood that the mylonite zones have affected the material in a way that influenced till shear strength.

Province D: Caledonian rocks, overthrust sheets of Precambrian rocks

As for province A/B, the samples from this province are also geographically fairly close. Apart from sample no. 13, which is solely represented by anorthosite, the remaining samples are dominated by mangerite and gabbro, as well as gneiss and amphibolite. Nilsen & Palmstrøm (2000) list the compressive strength as 248 MPa for gabbro and 107 MPa for amphibolite. However, gabbro may have a compressive strength up to 300 MPa (Palmstrøm, 1997), thus classified as 'extremely strong'. Moreover, anorthosite has a compressive strength of 157 MPa (Nilsen & Palmstrøm, 2000). By only focusing on rock strength, the general till shear strength should be high in this case. As expected, the average max. shear stresses and angle of friction are high. The average angle of friction is higher than for province C and ranks second of all provinces (Table 15). However, this province has two rather unexpected extremes. While sample nos. 10, 13 and 14 are relatively similar, no. 11 stands out as clearly weaker and no. 12 as clearly stronger. In addition, sample nos. 11 and 12 are geographically close, and they are also quite alike regarding rock types. This difference can hardly be explained by rock strength and, as suggested for province A/B, such unexpected results imply that geological parameters other than rock strength may have a larger influence on till shear strength.

Province E: Caledonian rocks, metamorphic and igneous rocks

The diversities regarding rock types in this province are larger and more complex than any other province, e.g., mica schist, greenstone, phyllite, amphibolite, quartzite, slate and limestone. Therefore, the span of compressive rock strengths differs accordingly, and one would expect a rather greater variety in the shear test results. Quartzite is significantly stronger than phyllite and mica schist, i.e., 172 MPa, while greenstone is quite similar to amphibolite with a compressive strength of 105 MPa (Nilsen & Palmstrøm, 2000). Slate is listed by Waltham (2009) to have an average compressive strength of 90 MPa. Limestone has a compressive strength of 74 MPa, while mica gneiss is similar to that of slate, i.e., 89 MPa (Nilsen & Palmstrøm, 2000). Hence, this large variation of rock types and corresponding compressive strengths would imply a variation of the shear test results, but preferably in the intermediate to low levels due to the rather large components of potentially weak mica schist and phyllite. Although the results show intermediate to low levels of average max. shear stresses and angle of friction when compared with the other provinces (Table 15), many of the sample results are actually quite similar, thereby making it difficult to link the individual sample results directly and solely to the associated rock strengths.

Province F: Caledonian rocks, overthrust sheets of sandstone and schist

The samples in this province are relatively homogeneous regarding rock types. Sandstone is by far the most dominant, with only smaller amounts of other rock types such as conglomerate, quartzite and mica schist represented. Sandstone has a compressive strength of 147 MPa (Nilsen & Palmstrøm, 2000), although it may vary between 75 MPa and 160 MPa (Palmstrøm, 1997), or even be as low as 30 MPa according to Waltham (2009). Since Norwegian sandstone, which is presumably 'strong' to 'very strong', is dominant in all five samples, this province should show intermediate to high shear strengths and low diversities in the range of results when compared with the other provinces. Although the individual angles of friction and shear stresses are quite similar, the results unexpectedly also show that this province on average has the lowest angle of friction and the lowest max. shear stresses (Table 15). If the till shear strength is to be solely related to the respective rock strengths, the results indicate rock strengths at the lower end of the scale listed by Palmstrøm (1997) or Waltham (2009).

Province G: Caledonian rocks, Precambrian basement, locally affected by the Caledonian orogeny

This province is also quite homogeneous regarding rock types, where various gneisses are dominant. Even though gneisses may vary significantly in composition (Prestvik, 1995), they are generally regarded as 'strong' to 'very strong' rocks (Nilsen & Palmstrøm, 2000; Waltham, 2009). As expected, the angles of friction are both high and similar to one another, and, in fact, they are on average the highest measured of all provinces (Table 15). On average, this province also has the highest registered max. shear stresses. However, the two northwesternmost samples (nos. 18 and 19) are noticeably weaker than the three remaining samples, but at the same time quite similar to each other. An explanation for this difference is uncertain, but may partly be due to geographical and mineralogical variations of the gneisses.

Summary of discussion

When analysing and comparing individual samples to one another within their respective provinces, it is rather difficult to establish a clear and direct relationship between the sample strength and their rock type(s), and, especially, to the associated typical rock strength. However, an important uncertainty on this matter is that the listed compressive strength values from the literature are average values, including a significant range, which are not necessarily representative for the samples in this study. On an individual sample level there are some results that do not relate, as one would expect, to bedrock geology and rock strength. Some samples that are dominated by the same rock type(s) and that are geographically close, show both quite different and similar results, e.g., sample nos. 11 and 12, and nos. 16 and 17, respectively. Consequently, and according to the literature, rock (particle) strength cannot be the only parameter influencing till shear strength. As initially mentioned, this implies that other geological parameters are involved, such as particle size distribution and particle shape, which are also known to have an effect on soil shear strength (e.g., Cornforth, 1973; Yagiz, 2001). If the study rather focused on shear testing the samples in a densely packed state, which most likely would introduce dilatancy and the potential of particle crushing, rock strength would possibly be more directly influential. However, on a more generalised level when comparing each of the provinces to one another, there are noticeable differences and a relation to bedrock geology, e.g., in Fig. 7A–C. For the first half of horizontal displacement, the results show that for all three tests the provinces C, D and G are clearly different from A/B, E and F, which are consistently lower regarding shear stresses in the same displacement interval. This difference may be due to the individual province and sample differences regarding the geological parameters, the fraction size limit (<16 mm), or a combination of these, but it basically seems that provinces C, D and G initially exert more shear resistance than the other three provinces. Such noticeable differences, in turn, may influence the potential of triggering debris slides and flows. The differences, however, are eventually reduced, and the levels of shear stress become more similar towards the end of the displacement. Although the general trend of the shear stress levels of the provinces seems to remain towards the end, the reduction implies that the effect of the different geological parameters in the respective provinces eventually becomes less influential.

Simultaneously, it is necessary to point out the main possible sources of uncertainty regarding the samples. A key aspect to address is that the number of samples may be considered too few to draw a definite conclusion on the levels and differences of shear strength of Norwegian tills, especially with regard to the respective rock provinces. Furthermore, the analysed till samples were independent of their genesis, i.e., no distinction between subglacial till and supraglacial till was made. Another important aspect on this matter is that the changing directions of ice motion and/or climatic fluctuations may have resulted in many tills that are a mixture of glacially eroded rock material and redeposited older sediments (Gillberg, 1977). This is not accounted for, and even if the till material was made solely from erosion of unweathered bedrock material, there is also an unknown variable regarding glacial comminution ('terminal grades') of mineral grains, e.g., between grains from unmetamorphic clastic sedimentary rocks and grains from crystalline rocks. For this example, the latter are to a large extent unstable when subjected to glacial and other mechanical crushing processes (Haldorsen, 1978). Also, due to the relatively passive transport of supraglacial tills, the associated occurrence of comminution is known to be minor (Boulton, 1978). Accordingly, variables such as transport are likely to have influenced both the particle shape and particle size (Clark, 1987), as well as the actual percentage share of different rock-type fragments in the tills. This may especially be the case for samples such as no. 4 in province C, consisting of both sandstone and gneiss. It must be emphasised, however, that the given percentage shares of rock types comprising the till samples are only assumed on a theoretical basis. Consequently, the percentage share of the area of rock type(s) surrounding each sample site is based on an approximate measurement and calculation of the bedrock geology map, which is a planar projection not accounting for topography. Although Ehlers (1983) pointed out that different studies (e.g., Perttunen, 1977) have shown that the Scandinavian tills closely reflect the composition of the local bedrock, the bedrock geology can change over short distances, thus introducing significant uncertainty to this theoretical approach. In addition, the ice-flow directions and the chosen maximum transport distance of five kilometres are also simplifications likely to introduce some uncertainty into the results.

Conclusions

The main shear test performed on 33 near-surface, genetically independent, till samples shows a variation in the registered maximum shear stress up to approximately 16%, whereas the angle of friction varies by 5.5° (36.0°–41.5°) with an average of 38.4°. In general, the results differ more in the main test than in the additional tests for repeatability assessment. When observing the comparison of average angles of friction for the different provinces (Table 15), as well as average shear stresses (Fig. 7A–C), a clear relation to bedrock geology and rock provinces does appear. This is particularly noticeable in the first half of the horizontal displacement length, where the differences of shear stress are the greatest. The average results show that for all three main tests the provinces C, D and G display higher shear stress and angle of friction than A/B, E and F, which are consistently lower. Generally, provinces of 'strong rocks' have a higher registered shear stress level and angle of friction than provinces of 'weak rocks'. However, these relationships are not so clear on an individual sample level when focusing solely on rock strength, suggesting that rock (particle) strength is not directly the governing parameter of till shear strength. Rock strength would possibly be more influential on the results if the study rather focused on shear testing the till samples in a densely packed state, which most likely would introduce dilatancy and potential particle crushing. For this case, it is considered more likely that rock strength, being a result of variations of rock types throughout the rock provinces, rather indirectly influences till shear strength due to its effect on, e.g., particle shape and size distribution, and, furthermore, that these geological parameters are more directly influential when shear testing the samples in such a loosely packed state. For the last half of horizontal displacement, however, all six provinces show a relatively similar level of average shear stress. Even though the general trend regarding the provinces of high shear stress and low shear stress seems to continue towards the end, it appears that the geological parameters influencing the till shear stress of the respective rock type(s) eventually become less influential.

In summary, due to the noticeable differences of shear stress and angle of friction, especially between the 'strongest province', G, and the 'weakest province', F, this study demonstrates a relation between till shear strength and bedrock geology. Although not conclusive, this suggests that some rock provinces may, solely on the basis of bedrock geology and associated geological parameters, be more prone to debris slides and flows than others. However, it must be emphasised that what makes an area prone to debris slides and flows also depends on many other parameters, i.e., the terrain, hydrological conditions, vegetation, etc. (Chatwin et al., 1994; Bargel et al., 2011). In addition, the number of samples tested is relatively few and they are geographically widely scattered. The samples are also independent of genesis, which is known to influence several of the characteristics of tills, and this is not accounted for. Moreover, the testing procedure and results do not replicate individual field/in situ conditions at the sample sites, as the samples were disturbed when collected and prepared for the purpose of achieving a comparison basis with a minimum of laboratory variables. Hence, the presented results should be regarded as preliminary. For this case, additional testing should be performed if one is to improve the statistical base of the shear strength of Norwegian tills and provide a more thorough evaluation of its relation to bedrock geology.

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Article 2

Geological parameters in relation to bedrock geology and shear strength of dry tills: samples from the southern half of Norway

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ORIGINAL PAPER

Geological parameters in relation to bedrock geology and shear strength of dry tills: samples from the southern half of Norway

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Abstract

The shear strength of soils is influenced by various geological parameters. Following the shear strength study of Norwegian tills by Opsal (2017), this study presents test results of a selection of such parameters, i.e., particle size distribution, particle shape, and the mineralogical composition, of 33 till samples (fractions <16 mm) from 6 rock provinces in the southern half of Norway. The mutual correlations between the geological parameters and their correlations to dry till shear strength have been investigated. The results are generally in accordance with expectations regarding the relation of such geological parameters to bedrock geology. The results also indicate that the till shear strength is not specifically governed by one geological parameter, but rather by an interaction of all the parameters combined. Particle size distribution and mineralogical composition are found to relate to the angle of friction, while particle shape is considered to influence the initial shear resistance and may thus be of special importance regarding the potential initiation of debris slides and flows in the respective provinces.

Keywords Till · Particle size · Particle shape · Mineralogical composition · Bedrock geology · Shear strength

Introduction

Due to the glaciations, till deposits are found in many areas, particularly in North America and Northern Europe (e.g., Sladen and Wrigley 1983). In Norway, till is the most dominant Quaternary deposit (Bergersen and Garnes 1972; Haldorsen et al. 1983). Internationally, the descriptions of geological parameters, such as the size and shape of fragments (particles) in tills, have been documented for more than a hundred years (e.g., Hershey 1897; Krumbein 1933; Wentworth 1936; Cammeraat and Rappol 1987). On this matter, it seems like a large part of the studies on Norwegian tills were performed in the 1970s and 1980s (e.g., Garnes and Bergersen 1977; Vorren 1977; Haldorsen 1981). Apart from studies performed on, e.g., genesis and depositional processes, many studies on particle size and shape are in relation to construction work purposes, such as aggregates for concrete and asphalt (e.g., Bulevičius et al. 2013). However, geological parameters such as the particle size distribution and particle shape, including particle angularity (Shin and Santamarina 2013) and particle surface roughness (Duncan et al. 2014), as well as mineralogy (Bolton 1986), also have an influence on soil shear strength (e.g., Yagiz 2001). Thus, even though many previous studies for various aims have been performed on Norwegian tills, the relation of such geological parameters to the shear strength of tills is relatively poorly documented. In addition, available documentation and data supporting 'known relationships' of bedrock geology to such till characteristics seem to be rather poor or based on outdated or non-standardised test methods, thereby resulting in the motivation for this project.

Regarding the influence of geological parameters on soil shear strength, the angle of shearing resistance generally increases with increasing median particle diameter (Li 2013; Wang et al. 2013). The shape of a particle can be expressed in terms of the form (overall shape), the roundness (large-scale smoothness), and the surface texture (small-scale smoothness; Barret 1980; NS-EN ISO 14688-1 2002). For instance,

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sphericity may express the shape, while the roundness provides a summarised expression for certain detailed characteristics of the solid (Wadell 1932). Elongated and cubical-shaped particles are considered to have a low and high sphericity, respectively (McLean and Gribble 1985). Cho et al. (2006) stated that, even though it is recognised that particle shape affects soil behaviour, the geotechnical soil classification systems do not take particle shape into consideration and, consequently, the true role of particle shape on soil response is therefore vague. However, in the context of shear strength, a decreasing particle sphericity is known to cause particle interlocking of different degrees, which in turn restrains slip and rotation (Rong et al. 2013). According to Cho et al. (2006), such decrease in the particle sphericity leads to an increase in the constant volume critical state friction angle. Li et al. (2013) found that increasing convexity increased peak friction angle, but decreased constant volume friction angle, while increasing elongation increased constant volume friction angle, but decreased peak friction angle. Moreover, according to Shin and Santamarina (2013), the presence of angular particles hinders particle mobility, which leads to a higher angle of friction. Shinohara et al. (2000) and Sukumaran and Ashmawy (2001) found that the angle of internal friction increased with increasing particle angularity, i.e., angular-shaped particles usually result in higher shear strength than rounded particles (Chan and Page 1997; Guo and Su 2007). In addition, the interparticle friction generally varies with particle texture (or roughness), which refers to the small asperities present on the surface of the particles (Guo and Su 2007). This microroughness is related to the hardness, texture, and strength of the surface, which are determined by the crystal structure of the minerals and intercrystalline bonding (Terzaghi et al. 1996). Therefore, the interparticle friction increases with surface roughness due to the process of particle slippage, as this is controlled by surface roughness (Santamarina and Cascante 1998). Consequently, the angle of friction at the critical state of cohesionless soils depends on the particle size distribution, particle shape, and mineralogy (Leroueil and Hight 2003).

Furthermore, regarding material differences, it is known that the shape of the broken product, as well as the terminal size of comminution, are determined by the lithology (Goldthwait 1970). Thus, the origin of the rock has a strong influence determining the shape of the particles (Pellegrino 1965), and regarding the composition of till, it is generally made by local rock fragments (Dreimanis et al. 1957). For this case, Ehlers (1983) pointed out that Scandinavian tills closely reflect the composition of the local bedrock. Previous Norwegian studies (e.g., Jørgensen 1977) have shown that parameters such as the particle size distribution of tills may vary significantly throughout the country. The Norwegian bedrock geology also differs greatly, both in terms of formation (igneous, sedimentary, and metamorphic), as well as age, ranging from Precambrian to Permian (e.g., Johnsen 1995). Therefore, the differences regarding such geological parameters in tills should to some extent relate to the bedrock geology and the shear strength parameters obtained in the previous study by Opsal (2017).

Opsal (2017) investigated the critical shear strength of 33 genetically independent till samples from 29 municipalities in 11 counties in the southern half of Norway (Fig. 1; Table 1). In summary, the disturbed, sieved (fractions <16 mm), and dried till samples collected from the upper part of the deposits (Fig. 2) were tested using a large-scale direct shear box apparatus (SB2010, Testconsult Ltd.) to investigate the potential relation of the results to bedrock geology. The main reason for using dried samples was to exclude water as a variable, as it would be hard to control in a large-scale direct shear test due to significant material differences amongst the till samples, which could result in, e.g., inhomogeneous saturation. Although not conclusive, the study indicated a relation of till shear strength to bedrock geology, suggesting that some regional rock provinces may, solely on the basis of their associated geological parameters, be more prone to debris slides and flows than others (Opsal 2017). However, the geological parameters of the samples were unknown, as they were not yet investigated at that point of the study. Hence, this subsequent study investigates a selection of geological parameters known to have an influence on soil shear strength, and thereafter evaluates their relation to the shear strength from the previous study. Also, the geological parameters are evaluated with regard to the general bedrock geology in the respective provinces. Therefore, 6 tests have been performed on the 33 till samples, i.e., 'particle size distribution' (PSD), 'flakiness index' (FI), 'shape index' (SI), 'roundness/angularity' (R/A), 'surface texture' (ST), and 'X-ray diffraction' (XRD).

Methods

Preliminary work

As described by Opsal (2017), when manually collecting the till samples (Fig. 2), particles clearly larger than 20 mm were not included. This was done due to practical reasons (e.g., sample weight), limitations of the laboratory testing equipment, as well as the standard for the shear box apparatus, which recommends not including particles larger than 20 mm. The collected till samples were sieved on a 16-mm sieve, and a portion of material of minimum 2.6 kg (fractions <16 mm) were thereafter randomly selected by splitting. Note that these riffled portions from each sample were used as a basis for all tests done in this study. Also note that due to the relatively small area of rock province B, as well as its overlap with province A, these two provinces were combined as one province, A/B (Opsal 2017).

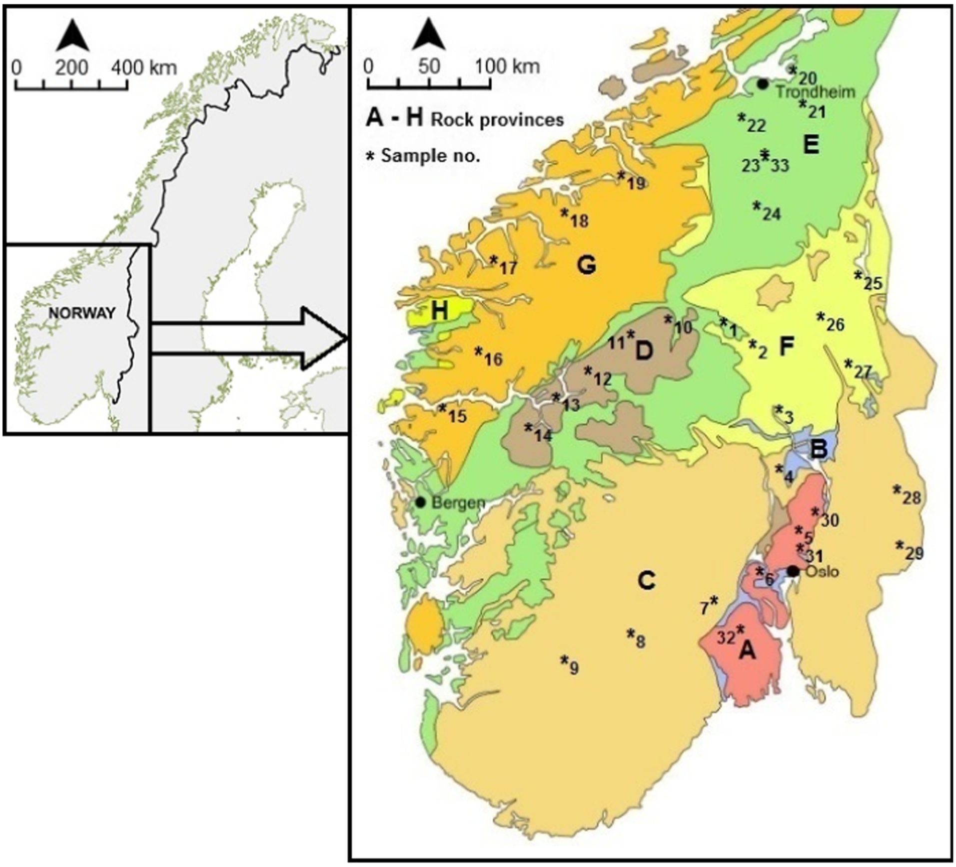


Fig. 1 A simplified bedrock geology map of the southern half of Norway illustrating the major rock provinces (named here as A–H) listed in Table 1, in addition to the approximate locations of the 33 till samples, modified from Norsk Betongforening (NB, 1988, as cited by Haugen and Lindgård 2012)

Table 1 A description of the major rock provinces (named here as A – H) in Norway, as illustrated in Fig. 1, modified from Norsk Betongforening (NB, 1988, as cited by Haugen and Lindgård 2012) and NGU (2017a, b)

Rock province	Description
A	Extrusive and plutonic rocks in the Oslo region; mainly syenite, granite, monzonite, and rhomb-porphyry
B	Sedimentary rocks in the Oslo region; mainly slate, limestone, and sandstone
C	Precambrian basement; mainly gneiss, granite, metamorphosed volcanic rocks and sedimentary rocks
Caledonian rocks	
D	Overthrust sheets of Precambrian rocks; mainly metamorphosed plutonic rocks, particularly gabbro
E	Metamorphic and igneous rocks; mainly phyllite, mica schist, metamorphosed sandstone, gneiss, and greenstone
F	Overthrust sheets of sandstone and schist; mainly sandstone, conglomerate, and slate
G	Precambrian basement, locally affected by the Caledonian orogeny; mainly gneiss
H	Sedimentary rocks; mainly sandstone and conglomerate

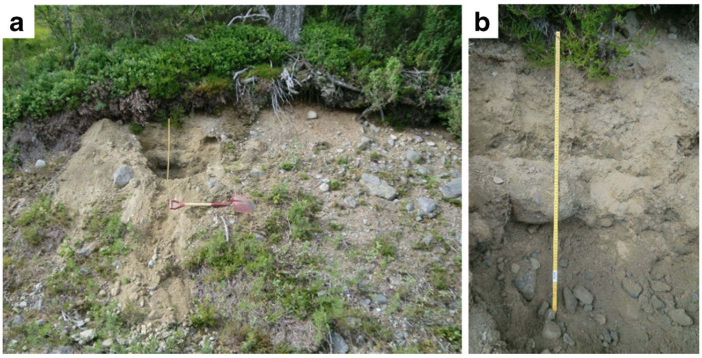


Fig. 2 (a) A typical location for till sampling, here from sample no. 19, province G. (b) Excavation of the sample pit (the carpenter's ruler is 1 m)

Laboratory work

The laboratory work was performed at the Department of Geoscience and Petroleum at the Norwegian University of Science and Technology. Apart from the tests regarding roundness/angularity and surface texture, which included the material retained on the 16-mm sieve, the remaining tests used 16 mm as an upper limit, as in the study by Jørgensen (1977).

Particle size distribution

Sieving was done in two stages, i.e., wet and dry sieving. Only the material larger than the fines (silt and clay) was tested by the use of 12 sieves ranging from 12.5 to 0.063 mm. The sieving was performed mechanically (Fig. 3a) and thereafter manually for each individual fraction (Norwegian Public Roads Administration 2016). PSD is described by the share of fines content (weight %) and D50 (particle size in mm at 50% passing).

Flakiness index

FI gives an indication of the amount of flaky particles in a sample as a percentage of the total mass of the sample (Uthus 2007). Thus, a low flakiness index expresses that the majority of particles are closer to a cubic shape rather than a flaky shape. Following PSD, the material retained on 6 sieves ranging from 12.5 to 4 mm were examined by the use of grid sieves according to NS-EN 933-3 (2012; Fig. 3b).

Shape index

SI determines the elongation of particles, and like FI, SI is performed on sizes equal to or larger than 4 mm (Uthus 2007). The 6 fractions retained on the 12.5- to 4-mm sieves were examined with the use of a customised particle slide gauge (Fig. 3c) to find the percentage share of particles with a length-to-thickness dimension ratio larger than 3 (NS-EN 933-4 2008).

Roundness/angularity and surface texture

Seven sieved fractions from 16 to 4 mm were manually examined to evaluate the particle roundness (angularity) and surface texture (roughness; Fig. 4). Since such characteristics may vary amongst particles due to, e.g., the potential mix of rock types in the tills, these results are therefore the most common particle roundness and surface texture of the samples. The description is qualitative, and four categories for roundness were used, i.e., 'rounded', 'subrounded', 'subangular', and 'angular' (e.g., Holtz and Kovacs 1981), as well as two categories for surface texture, i.e., 'rough' and 'smooth' (NS-EN ISO 14688-1 2002).

Fig. 3 Performing (a) particle size distribution with multiple sieves on dry material, (b) the flakiness index test with a grid sieve, and (c) the shape index test with a customised particle slide gauge

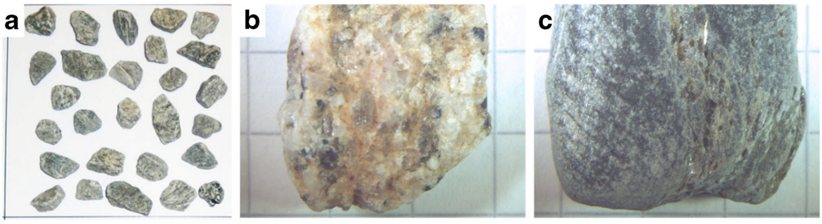


Fig. 4 (a) A sieved fraction (10 mm) of sample material (sample no. 11, province D) used for evaluation of particle roundness. (b) and (c) show surface texture differences between particles (10 mm) categorised as 'coarse' (no. 9, prov. C) and 'smooth' (no. 21, prov. E), respectively (the paper squares are 5 × 5 mm)

Mineralogical composition, X-ray diffraction

Material retained on the 0.5-mm sieve (<1 mm) was split, crushed, and then analysed in the XRD apparatus (D8 ADVANCE, Bruker Corp.). The results were thereafter simplified, i.e., main mineral categories were used in the presentation of results. For example, biotite and muscovite were listed together as mica.

Supplementary work

Two correlation tests, Pearson and Spearman rho, were performed on all samples. This was done to evaluate the relationships between the quantifiable geological parameters, i.e., fines content, D50, FI, SI, and XRD. In addition, the relationships between the geological parameters and the parameters from Opsal (2017) were evaluated, i.e., the initial dry testing density, ρ_d, the maximum shear stresses (named here as τ_1-τ_3 for 100, 200, and 300 kPa normal stress, respectively), as well as the angle of friction, ϕ, and the cohesion, c. Regarding XRD, only the main minerals that were significantly present in (almost) all samples were included in these correlation tests, i.e., quartz, plagioclase, alkali feldspar, mica, amphibole, pyroxene, and chlorite. For both tests, a P value ≤0.05 was used regarding statistical significance. Three categories were used for the strength of association for both tests, which, after Cohen (1988) are 'small correlation' ($0.1 \leq r < 0.3$), 'medium correlation' ($0.3 \leq r < 0.5$), and 'large correlation' ($r \geq 0.5$) for positive correlation. The categories also apply for negative correlation, i.e., 'small correlation' ($-0.3 < r \leq -0.1$), 'medium correlation' ($-0.5 < r \leq -0.3$), and 'large correlation' ($r \leq -0.5$).

Results

The results of the 33 samples are shown in Figs. 5, 6, and 7 and Table 2. The main shear test results from Opsal (2017) are also included in Fig. 6. From the results, rock provinces A/B, D, and G showed a considerably lower variation regarding the fines than provinces C, E, and F. For D50, provinces C, F, and G showed the largest variations, while provinces D, E, and especially A/B had a noticeably lower variation (Figs. 5 and 6a, b).

For particle shape, provinces A/B, D, and G showed a quite similar, as well as a considerably lower, variation of results compared to provinces C, E, and F regarding both FI and SI (Fig. 6b). Considering particle roundness, provinces A/B, C, and D ranged from angular to subangular, provinces E and G were classified solely as subangular, while province F ranged from subrounded to subangular. For particle surface texture, the dominant category was rough for provinces A/B, C, D, and G, and smooth for provinces E and F.

Figure 7 shows that the main minerals in all samples were quartz and plagioclase. Other minerals, such as alkali feldspar, mica, amphibole, and pyroxene, were also represented in most samples. Quartz was clearly dominating in provinces E and F, while provinces D and G were dominated by plagioclase. Provinces A/B and C were also dominated by quartz, although the results varied more than for provinces E and F.

The correlation tests showed that for the angle of friction, D50 had a medium positive correlation, fines had a medium negative correlation, while both FI and SI showed no statistically significant correlation (Fig. 8). Regarding correlation of the mineralogical composition to the angle of friction, quartz had a medium negative correlation, while plagioclase had a medium positive correlation. For the maximum shear stresses, τ_2 and τ_3, there were medium to large positive correlations to D50. Fines had medium negative correlations to τ_2 and τ_3. Furthermore, D50 had a medium negative correlation to FI and SI, while fines showed a medium to large positive correlation to FI and SI. Moreover, chlorite, mica, and quartz had a medium to large positive correlation to FI and SI, and mica also had a medium positive correlation to fines. In contrast, alkali feldspar and plagioclase had a medium to large negative correlation to FI and SI, and alkali feldspar also had a medium negative correlation to fines.

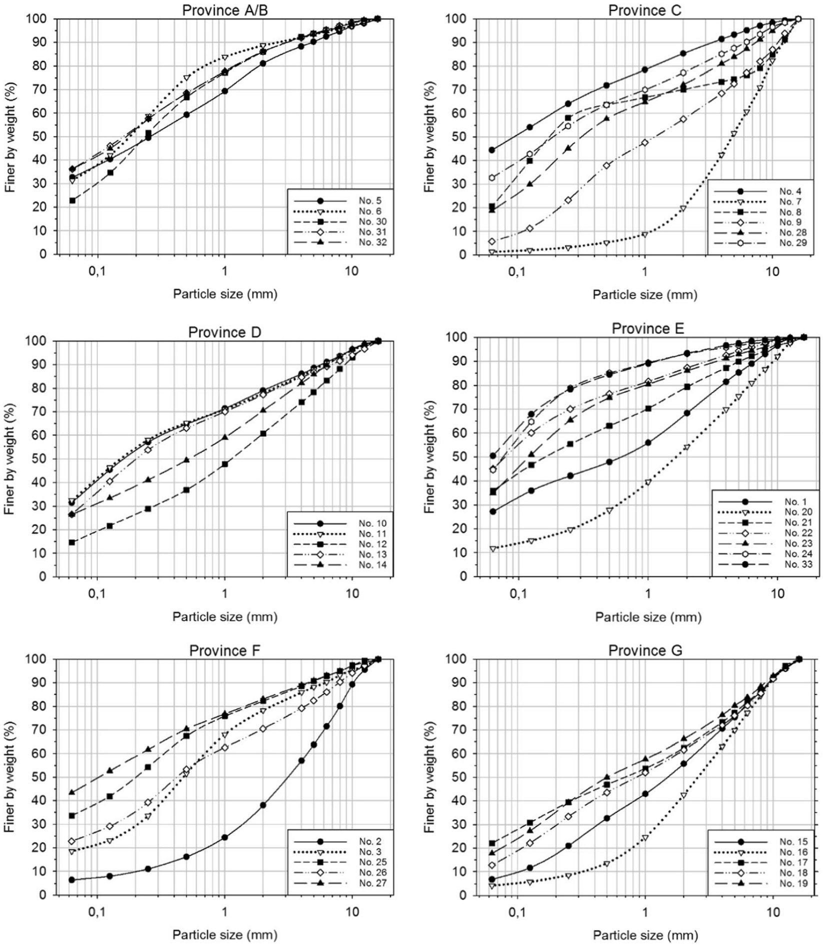


Fig. 5 Particle size distributions for all 33 samples categorised in their respective rock provinces, A/B – G

Discussion

Due to the diversity of both geographical and geological provinces, the presented results show a large range of values. However, there are also similarities amongst the samples, which are noticeable when categorising the results by the 6 rock provinces. As presented by Opsal (2017), the provinces are dominated by different rock types (Fig. 1; Table 1), which seem to correspond quite well to the mineralogical composition of the till samples. For example, province D is represented by rocks such as gabbro, amphibolite, and anorthosite, i.e., rocks mainly constituted by plagioclase, which is a mineral heavily represented in this province (Fig. 7). The high amount of quartz in the samples from province F also correspond to the fact that common sandstones, which dominate in this province, normally consist of a high amount of this mineral (e.g., Prestvik 1995).

Furthermore, there are also similarities and differences regarding PSD for the provinces. Since till may consist of a variable assortment of rock debris ranging from boulders to fine rock flour, one may also have extremes, e.g., tills mainly consisting of sand and gravel, or tills with an excess of clay (Culshaw et al. 1991). Such extremes may explain the difference of PSD between sample no. 7 and 33 (Fig. 5). Jørgensen (1977) concluded that there was a clear influence of bedrock upon the mechanical composition of tills in Norway, and found that tills from Cambro-Silurian rocks (metamorphic) in the Caledonides had a larger content of fines than tills from Precambrian rocks, i.e., generally above 35% and 15–25%, respectively. This corresponds well to the presented results of fines content for provinces C and E. The reason may be that rock types rich in soft minerals, such as mica and chlorite, which are common minerals in phyllite and schist, produce fines at a higher rate than rocks composed of harder minerals

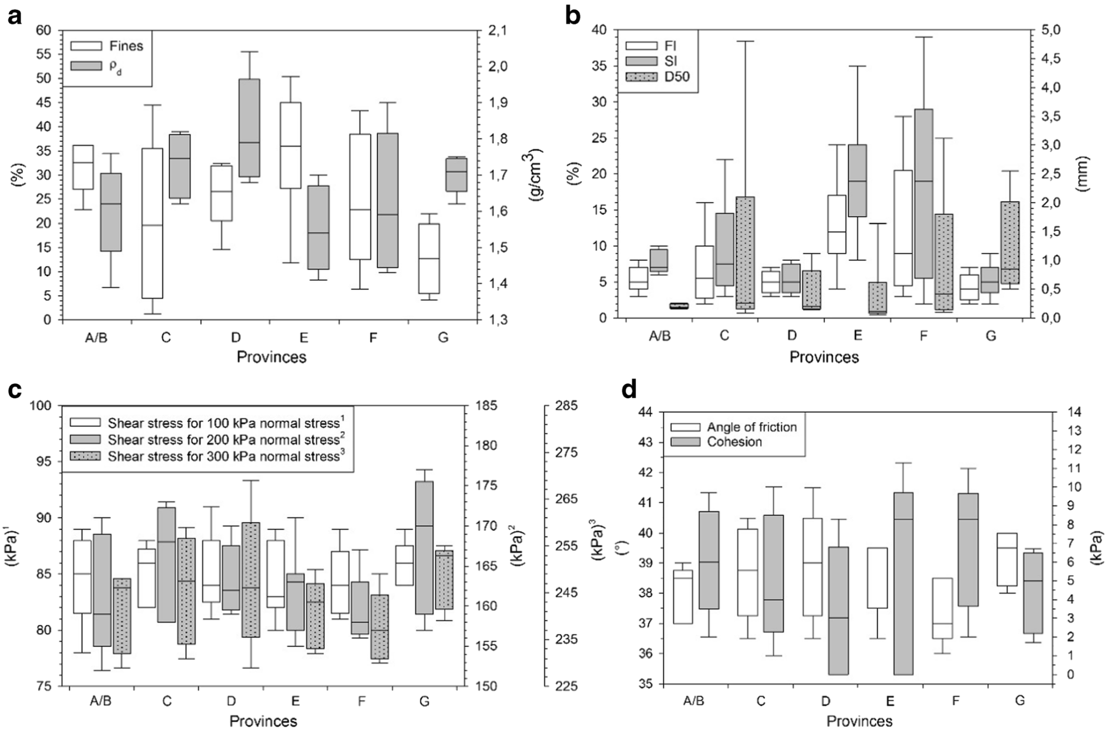


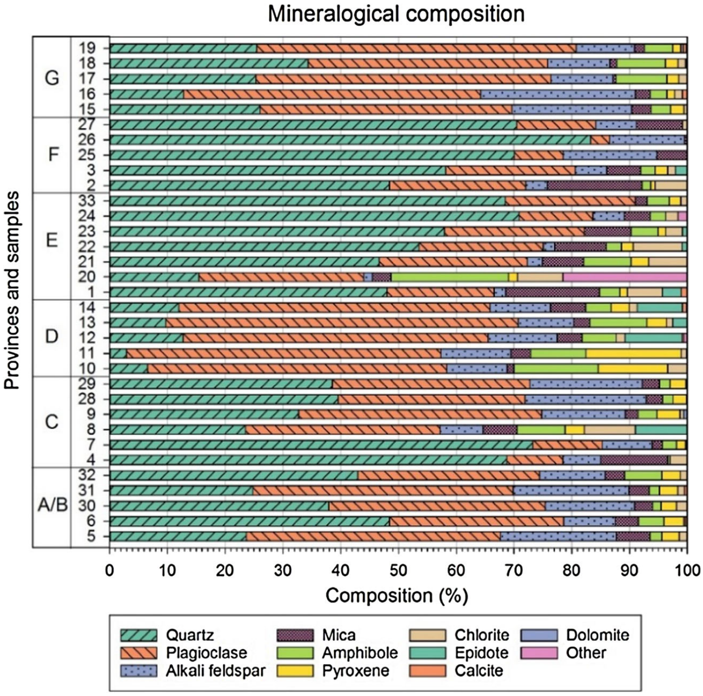
Fig. 6 Box plots for (a) fines content and initial dry testing density, ρ_d (Opsal 2017), (b) flakiness index, shape index, and D50, as well as the shear test results regarding maximum shear stress (c) and the angle of friction and cohesion (d) from Opsal (2017). The results are categorised by the 6 rock provinces, where the boxes represent the 25th and 75th percentiles, and the solid line represents the median. The whiskers above and below the boxes show the maximum and minimum points

(Watters et al. 1987). These rock types are highly represented in province E. Although the relationship between bedrock type and till particle size is complex due to glacial processes, hard rocks, such as gneisses and granites, generally result in coarse soil textures with only minor amounts of rock flour matrix (Derbyshire et al. 1979). According to Haldorsen (1981), coarse-grained tills are characteristic of the greater part of Norway where coarse-grained and/or hard bedrock types dominate. This also corresponds quite well to the presented results of D50, e.g., for province G.

For FI and SI, the results imply that tills in provinces E and F are constituted of more elongated and flaky particles, while the particles in tills from the other provinces are considerably more cubical. Considering roundness, all provinces are dominated by subangular particles, which is a rather normal characteristic for tills (e.g., Thoresen 2000). Since high-strength rocks are normally more abrasion-resistant (e.g., Hudec 2011), this also corresponds to the presented results of roundness showing that samples of angular particles were solely from provinces generally constituted of stronger rocks (compressive strength) compared to the provinces E and F (Opsal 2017). In addition, for surface texture there is a clear difference between the provinces too, as four of seven samples in province E, as well as three of five samples in province F, were categorised as smooth. In contrast, 25 samples categorised as rough were mainly from areas represented by, e.g., gabbro and various gneisses and granites, which are typically medium- to coarse-grained rocks. The samples from provinces E and F categorised as smooth were from areas represented by, e.g., mica schist, sandstone, amphibolite, phyllite, and slate, which are typically medium- to fine-grained rocks (NS-EN ISO 14689-1 2004).

On the relationship between mineralogy and particle form, high contents of flaky minerals are known to favour a high material flakiness (Brattli 1992). As mica and chlorite are flaky minerals, the content of these minerals corresponds well to the results for FI and SI. These minerals are considered major minerals in rocks such as phyllite, mica schist, and slate (e.g., Prestvik 1995), which are heavily represented in province E having high FI and SI. The lowest averages of FI and SI are found in provinces D and G, heavily represented by feldspars, which in contrast to the plate structure of mica, produces blocky fragments (Christiansen and Hamblin 2014). Also, samples categorised as smooth generally have a

Fig. 7 A stacked horizontal bar diagram displaying the results from the XRD analysis, i.e., the mineralogical composition in each of the 33 samples distributed by the respective rock provinces



relatively large share of chlorite and mica, i.e., soft minerals commonly present in metamorphic rocks such as slate, phyllite, and schist, which are often associated with smooth particle surfaces (Watters et al. 1987). When excluding, e.g., glacial processes, which are not accounted for, the differences regarding bedrock geology in the respective provinces are considered likely to explain the presented geological parameters.

From Opsal (2017), the shear strength differences between the provinces, especially between the 'weakest' and 'strongest' provinces, i.e., F and G, respectively, were assumed to be related to the differences of bedrock geology and associated geological parameters. Regarding these provinces, province G has on average a lower fines content than province F, as well as a higher D50. These parameters were found to have a medium negative and positive correlation to the angle of friction, respectively. This is also in accordance to Li (2013), which stated that the angle of shearing resistance is normally increasing with increasing median particle diameter. In addition, province G is constituted of rough particles, which is also known to increase the shear strength. This stands in contrast to province F, generally having smooth particles. Furthermore, quartz is the main mineral in province F, while plagioclase is the main mineral in province G. For this case, quartz and plagioclase were found to have a medium negative and positive correlation to the angle of friction, respectively, thereby corresponding to other studies. For example, Koerner (1970) prepared quartz and feldspar soil samples for shear testing, and found that feldspar showed greater strength than quartz. Bolton (1986) also presented results showing that quartz sands had a lower angle of friction than feldspathic sands. Moreover, Terzaghi et al. (1996) listed the interparticle angle of friction for some common minerals, where quartz was significantly lower than feldspar. Therefore, the differences of quartz and plagioclase also support the higher shear strength of province G.

From the literature, the angle of friction should increase with increasing particle angularity, but for this study such a relationship has not been demonstrated. However, if the samples were more diverse regarding roundness, it would possibly be easier to evaluate the real influence of this parameter. Furthermore, there were no significant correlations between FI and SI to the angle of friction. When comparing the provinces, though, the 'strongest' province G is generally constituted of subangular particles having low FI and SI, and rough surface texture. On the other hand, provinces E and F are mainly constituted of subrounded to subangular particles having higher FI and SI, and smooth surface texture. From Opsal (2017), 'strong' provinces such as G initially exerted more shear resistance than provinces E and F. Although there were no significant correlations regarding the particle shape to the angle of friction, it is

Table 2 The results from all samples regarding fines, D50, flakiness index (FI), shape index (SI), roundness/angularity [R/A, angular (A), subangular (SA), subrounded (SR), and rounded (R)], surface texture [ST, rough (Ro) and smooth (Sm)], and the XRD analysis [simplified notification according to Siivola and Schmid (2007)]

Rock province	Sample no.	Fines (%)	D50 (mm)	FI (%)	SI (%)	R/A	ST	XRD - the three most dominating minerals (%)
A/B	5	32.6	0.26	5.0	6.0	SA	Ro	Pl (44%); Qtz (24%); Afs (20%)
A/B	6	31.3	0.18	5.0	7.0	SA	Ro	Qtz (48%); Pl (30%); Afs (9%)
A/B	30	22.8	0.23	3.0	7.0	A	Ro	Qtz (38%); Pl (37%); Afs (15%)
A/B	31	36.1	0.16	6.0	9.0	SA	Ro	Pl (45%); Qtz (25%); Afs (20%)
A/B	32	36.2	0.17	8.0	10.0	SA	Ro	Qtz (43%); Pl (32%); Afs (11%)
C	4	44.5	0.09	16.0	22.0	SA	Ro	Qtz (69%); Mca (12%); Pl (10%)
C	7	1.2	4.81	4.0	5.0	SA	Ro	Qtz (73%); Pl (12%); Afs (9%)
C	8	20.5	0.18	7.0	12.0	SA	Sm	Pl (34%); Qtz (24%); Ep (9%)
C	9	5.6	1.20	2.0	3.0	SA	Ro	Pl (42%); Qtz (33%); Afs (15%)
C	28	18.7	0.32	3.0	5.0	A	Ro	Qtz (40%); Pl (32%); Afs (21%)
C	29	32.6	0.19	8.0	10.0	A	Ro	Qtz (39%); Pl (34%); Afs (19%)
D	10	31.5	0.16	3.0	4.0	SA	Ro	Pl (52%); Am (15%); Px (12%)
D	11	32.4	0.15	5.0	8.0	SA	Ro	Pl (54%); Px (16%); Afs (12%)
D	12	14.6	1.12	7.0	7.0	SA	Ro	Pl (53%); Qtz (13%); Afs (12%)
D	13	26.5	0.20	6.0	5.0	SA	Ro	Pl (61%); Am (10%); Qtz (10%)
D	14	26.4	0.52	4.0	3.0	A	Ro	Pl (54%); Qtz (12%); Afs (10%)
E	1	27.2	0.62	14.0	24.0	SA	Sm	Qtz (48%); Pl (19%); Mca (16%)
E	20	11.8	1.64	4.0	8.0	SA	Sm	Pl (28%); Czo (22%); Am (20%)
E	21	36.0	0.16	17.0	24.0	SA	Sm	Qtz (47%); Pl (26%); Am (8%)
E	22	45.0	0.08	24.0	35.0	SA	Sm	Qtz (54%); Pl (21%); Mca (9%)
E	23	34.9	0.12	9.0	14.0	SA	Ro	Qtz (58%); Pl (24%); Mca (8%)
E	24	44.6	0.08	12.0	19.0	SA	Ro	Qtz (71%); Pl (13%); Afs (5%)
E	33	50.4	0.06	9.0	16.0	SA	Ro	Qtz (69%); Pl (22%); Am (4%)
F	2	6.4	3.12	28.0	39.0	SA	Sm	Qtz (48%); Pl (24%); Mca (16%)
F	3	18.5	0.48	13.0	19.0	SR	Sm	Qtz (58%); Pl (22%); Mca (6%)
F	25	33.6	0.20	6.0	9.0	SA	Ro	Qtz (70%); Afs (16%); Pl (8%)
F	26	22.8	0.42	3.0	2.0	SA	Ro	Qtz (83%); Afs (13%); Pl (3%)
F	27	43.4	0.10	9.0	19.0	SA	Sm	Qtz (70%); Pl (14%); Mca (8%)
G	15	6.7	1.49	2.0	2.0	SA	Ro	Pl (44%); Qtz (26%); Afs (21%)
G	16	4.2	2.55	5.0	5.0	SA	Ro	Pl (52%); Afs (27%); Qtz (13%)
G	17	22.0	0.69	7.0	9.0	SA	Ro	Pl (51%); Qtz (25%); Afs (11%)
G	18	12.7	0.85	3.0	5.0	SA	Ro	Pl (42%); Qtz (34%); Afs (11%)
G	19	17.8	0.50	4.0	5.0	SA	Ro	Pl (55%); Qtz (25%); Afs (10%)
Average		25.8	0.70	7.9	11.4			
Median		26.5	0.23	6.0	8.0			
Standard deviation		13.2	1.03	6.1	9.2			
Maximum		50.4	4.81	28.0	39.0			
Minimum		1.2	0.06	2.0	2.0			
Difference		49.2	4.75	26.0	37.0			

Pl plagioclase, *Qtz* quartz, *Afs* alkali feldspar, *Mca* mica, *Am* amphibole, *Px* pyroxene, *Czo* clinozoisite, *Ep epidote*

considered likely that these parameters still have an influence on the obtained results. In general, it may seem that provinces with low FI and SI, in combination with more angular particles with rough surfaces, promote a higher initial shear resistance than provinces with higher FI and SI, in combination with less angular particles with smooth surfaces (Fig. 9).

As can be seen from Fig. 9 and Opsal (2017), the shear stress levels eventually become quite similar, thus indicating that the differences of geological parameters also eventually

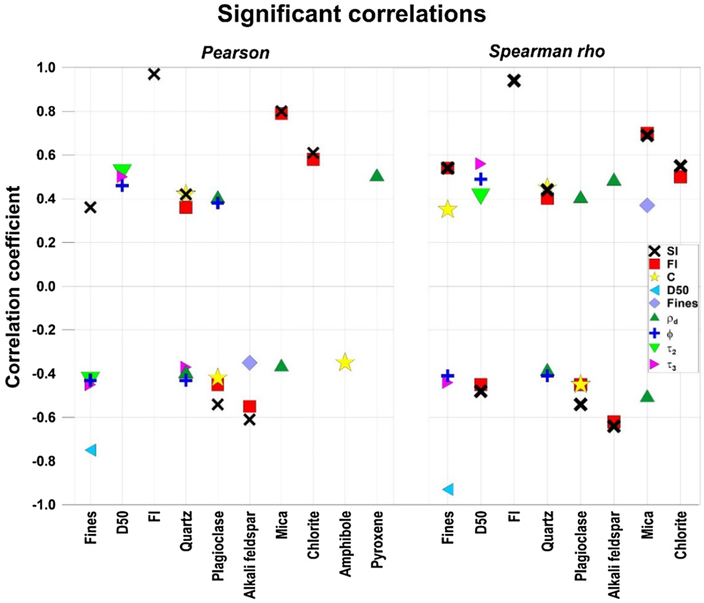


Fig. 8 The statistically significant results from Pearson and Spearman rho regarding the relationships between the geological parameters, as well as their relation to the shear strength results by Opsal (2017)

become less influential. However, in the context of landslides, the presented results suggest that the particle shape may be of special importance for till deposits regarding the potential initiation of debris slides and flows due to its indicated influence on the initial shear resistance. Thus, till-covered valley slopes with a large share of flaky/elongated, smooth, and less angular particles may potentially be more prone to initiation of such landslides. For this case, provinces E and F may be more prone to debris slides and flows than the other provinces, although it must be emphasised that what makes an area prone to such landslides depends on many other parameters as well, e.g., hydrological conditions, characteristics of the terrain, vegetation, etc. (e.g., Chatwin et al. 1994). Furthermore, the Norwegian bedrock geology is in some areas similar to other countries, such as Sweden with regard to the Caledonides (e.g., Lahtinen 2012). Since the tills in Scandinavia are also known to closely reflect the composition of the local bedrock, the presented results may be quite similar amongst the countries in such comparable areas.

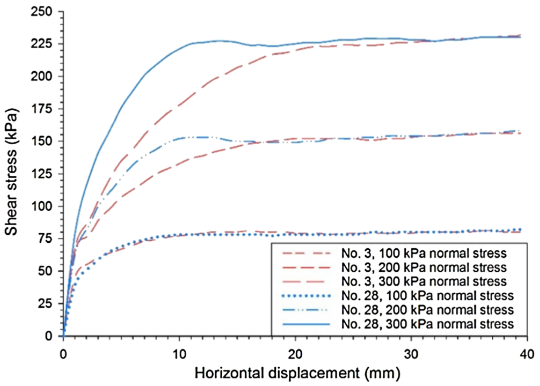


Fig. 9 A shear test comparison between two till samples, i.e., no. 3 (province F) and no. 28 (province C), that are very similar with regard to fines, D50, maximum shear stresses, and angles of friction, but very different with regard to the particle shape, i.e., FI, SI, roundness, and surface texture. No. 3 has an FI of 13.0, an SI of 19.0, and is subrounded with a smooth surface texture. In contrast, no. 28 has an FI of 3.0, an SI of 5.0, and is angular with a rough surface texture. Such noticeable variations of initial shear resistance may therefore be due to differences of particle shape

However, it is necessary to address the uncertainties. Glacial processes are not accounted for, and the number of till samples is relatively small. Since they are individual samples, they do not necessarily represent the area from which they are collected. It must also be added that the samples are collected from the upper part (surface) layer of the till deposits. Thus, e.g., PSD may not be fully representative for the deposits. This may be due to post-depositional processes, such as downward percolation of fines (Boulton and Paul 1976). The process of percolation of fines may partly explain the low amount of fines in some of the samples, such as no. 7. Alternatively, the changed direction of ice motion and/or climatic fluctuations may have resulted in many tills that are a mixture of glacially eroded rock material and redeposited older sediments (Gillberg 1977). Moreover, due to sampling and apparatus limitations, only the particle sizes retained on the 16-mm sieve and below have been included in the study. The discarded larger particles may have different characteristics than the smaller particles. By excluding these larger fractions one thereby introduces a significant uncertainty regarding, e.g., how the obtained laboratory results reflect the actual characteristics of the till deposits. Other key aspects to address are that the roundness and surface texture are qualitatively evaluated, and that merely one fraction size was tested in the XRD analysis. For this latter case, one cannot exclude the possibility that testing both smaller and larger fractions could give somewhat different results.

Conclusions

This study has performed tests on the material from the 33 till samples previously shear tested by Opsal (2017), which were collected from 6 regional rock provinces in the southern half of Norway. In general, the results are as expected regarding the relation to bedrock geology amongst the different provinces, although some samples may be considered as extremes. For example, province E, which is dominated by rocks such as phyllite and mica schist, had on average a significantly higher fines content and a higher share of flaky/elongated particles than province G, which is dominated by gneisses.

According to the literature, all the investigated geological parameters should have an influence on the till shear strength. For this study, PSD and mineralogical composition seem to relate to the angle of friction, while no such relationship was demonstrated for particle shape. However, provinces with generally low FI and SI and more angular and rough particles may seem to promote a higher initial shear resistance than provinces with generally high FI and SI and less angular and smooth particles. This difference of particle shape may influence the initiation of debris slides and flows. For this study, provinces E and F may be more prone to such landslides than the other provinces. In summary, the results indicate that the till shear strength is not specifically governed by one geological parameter, but rather by an interaction of all the parameters combined. The study demonstrates several relationships, which may potentially also apply to tills in other (Scandinavian) countries with similar bedrock geology. However, the presented results should be regarded as preliminary due to the relatively few samples tested. For this case, additional till samples should be tested if one is to improve the statistical base of the presented relationships.

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