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Quality aspects in direct shear testing of rock joints

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Abstract

The stability of rock masses is influenced by the occurrence of rock joints. Therefore, the shear strength of rock joints must be considered in dimensioning of underground constructions. One way to predict the shear strength is through usage of failure criteria, which are validated from results of direct shear tests under controlled laboratory conditions. Consequently, the quality of the results from the tests are crucial to the accuracy with which the criteria will be able to predict the shear strength. Since rock joints are unique by nature usage of replicas (man-made copies of rock joins) is of importance in parameter studies. The overall objective of this work is to facilitate the development of improved criteria for predictions of the shear strength of rock joints. To support this objective, two sources of uncertainty have been investigated, namely the geometry of replicas and the influence of the normal stiffness of test systems.

Two quality assurance parameters for evaluation of geometrical differences between replicas and rock joints based on scanning data have been derived. The first parameter describes the morphological deviations. The second parameter describes the deviations in orientation with respect to the shear plane. The effective normal stiffness approach, which compensates for the influence of the normal stiffness of the test system in direct shear testing, has been developed, validated, and applied.

With help of the quality assurance parameters it is demonstrated that it is possible to reproduce replicas within narrow tolerances. Application of the effective normal stiffness approach basically eliminates the normal load error. In all, the results support generation of improved quality of test data and consequently, the development of shear strength criteria with improved accuracy will also be facilitated.

Keywords
rock joints, geometrical quality assurance, replicas, direct shear testing, normal stiffness.

Sammanfattning

Bergmassors stabilitet påverkas av bergssprickor. Bergssprickors skjuvhållfasthet behöver därför beaktas vid fastställandet av vilka laster berganläggningar skall dimensioneras mot. Skjuvhållfastheten predikteras bland annat med hjälp av brottkriterier, vilka valideras med hjälp av resultaten från skjuvtester i kontrollerad laboratoriemiljö. Kvaliteten på resultaten från testerna är därför av avgörande betydelse för med vilken noggrannhet kriterierna kommer att kunna prediktera skjuvhållfastheten. Det övergripande målet med detta arbete är att underlätta utvecklingen av förbättrade kriterier för prediktioner av bergssprickors skjuvhållfasthet. Som ett bidrag till att uppnå detta mål har två osäkerhetsfaktorer undersökts, nämligen geometrin av replikor (kopior) av bergssprickor och inverkan av testsystems normalstyvhet.

Två kvalitetssäkringsparametrar för utvärdering av de geometriska skillnaderna mellan replikor och bergprov baserade på skanningdata har tagits fram. Den första parametern beskriver de morfologiska avvikelserna. Den andra parametern beskriver avvikelserna i orientering med avseende på skjuvplanet. Ett tillvägagångssätt med en effektiv systemnormalstyvhet, vilken kompenserar för inverkan av testsystemets normalstyvhet, har utvecklats, validerats och tillämpats.

Med hjälp av kvalitetssäkringsparametrarna påvisas att det är möjligt att reproducera replikor inom snäva toleranser. Genom tillämpning av tillvägagångssättet med en effektiv normalstyvhet kan felet i normallast i princip elimineras. Sammantaget stödjer resultaten framtagning av testdata med förbättrad kvalitet och därigenom underlättas även utvecklingen av skjuvhållfasthetskriterier med förbättrad noggrannhet.

Nyckelord
bergssprickor, geometrisk kvalitetssäkring, replikor, skjuvhållfasthetprovning, normalstyvhet.

Preface

The work presented in this licentiate thesis was carried out during the period October 2017 – February 2021 at the department of Applied Mechanics at RISE Research Institutes of Sweden in Borås, Sweden and at the Department of Civil and Architectural Engineering at KTH Royal Institute of Technology in Stockholm, Sweden.

I express my gratitude to the supervisors Ass. Prof. Fredrik Johansson at KTH Royal Institute of Technology, Sweden; Adj. Prof. Diego Mas Ivars, SKB, Swedish Nuclear Fuel and Waste Management Co, Sweden and Adj. Prof. Erland Johnson at RISE Research Institutes of Sweden for their dedication, professional guidance and all perspicacious input to our discussions. I also would like to thank the BeFo Rock Engineering Research Foundation reference group for their engagement and valuable input: Christer Andersson (Ramboll), Axel Bolin (The Swedish Transport Administration), Mattias Roslin (The Swedish Transport Administration), Per Tengborg (BeFo Rock Engineering Research Foundation) and Thomas Wettainen (LKAB).

Many colleagues at RISE have been engaged in the in parallel running POST (Parametrization Of STructures) project within which the experimental work was carried out. Mathias Flansbjer and Natalie Williams Portal are acknowledged for the development of the replica manufacturing process, for the manufacturing of the replicas and assistance in the execution of the direct shear tests in the 300 kN equipment, Jörgen Spetz for accomplishment of the scans, Tom Lindström and Pooya Tabib for the assistance in the testing in the 5 MN test setup and Carl-Magnus Jakobsson for assistance in the rigging work in the 5 MN test setup. Lars Jacobsson is gratefully acknowledged for his contribution setting up the POST project and in the application work behind this thesis.

The support and encouragement from friends and relatives have meant a lot, and most of all the love and care from my daughters Rebecka and Emma, my mother Ingrid and my father Johnny.

Borås, April 2021
Jörgen Larsson

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SKB, Swedish Nuclear Fuel and Waste Management Co, Sweden and NWMO, Nuclear Waste Management Organization, Canada) are acknowledged for their financial support of the POST project within which the experimental data were generated being a prerequisite for the thesis work.

List of appended papers

This licentiate thesis is based upon the following scientific articles:

Paper A

Larsson J, Flansbjer M, Portal N W, Johnson E, Johansson F, and Mas Ivars D. (2020) Geometrical Quality Assurance of Rock Joint Replicas in Shear Tests – Introductory Analysis. Paper presented at the *ISRM International Symposium - EUROCK 2020*, physical event not held. https://onepetro.org/ISRMEUROCK/proceedings-abstract/EUROCK20/All-EUROCK20/ISRM-EUROCK-2020-101/451187

Larsson did the analyses and wrote the paper. Flansbjer and Portal developed the replica manufacturing concept and manufactured the replicas. Johansson and Mas Ivars set up the test plan and assisted with comments on the writing and discussions together with Johnson.

Paper B

Larsson J, Johansson F, Mas Ivars D, Johnson E, Flansbjer M and Portal N W. (2021) Rock joint replicas in direct shear testing – Part 1: Extraction of geometrical quality assurance parameters. To be submitted to *Rock Mechanics and Rock Engineering*

Larsson did the analyses and wrote the paper. Flansbjer and Portal developed the replica manufacturing concept and manufactured the replicas. Johansson and Mas Ivars set up the test plan and assisted with comments on the writing and discussions together with Johnson.

Paper C

Larsson J and Flansbjer M. (2020) An Approach to Compensate for the Influence of the System Normal Stiffness in CNS Direct Shear Tests. *Rock Mechancis and Rock Engineering* 53, 2185–2199 https://doi.org/10.1007/s00603-020-02051-0

Larsson and Flansbjer developed the concept behind the approach and designed the experiments. Larsson formalized the concept to a spring model, developed the error estimation procedure and wrote the paper.

Paper D

Larsson J. (2021) Experimental investigation of the system normal stiffness of a 5 MN direct shear test setup and the compensation of it in

CNS direct shear tests. Submitted to *ISRM International Symposium - EUROCK 2021*

Contents

1. Introduction

1.1. Background

From a planning perspective of rock constructions there is a need of societal efficiency and models that can be applied in the design phase. New challenges follow with socio economical changes such as larger and increasingly densely populated cities. These challenges put demands on more efficient usage of the underground space and new types of underground constructions. To meet these challenges knowledge about the load bearing capacity of the rock mass is required. Dams, sites for carbon dioxide storage and nuclear waste repositories are further examples on constructions that require knowledge about the load bearing capacity of the rock mass to be designed. An improved control of the load bearing capacity of the rock mass leads to a more robust infrastructure, a more efficient construction work and a reduced environmental impact through a more efficient usage of the underground space. Consequently, a prerequisite for optimal handling of economic and environmental resources and to have control of the safety margins during construction and operation, is to have access to failure criteria that accurately predicts the load bearing capacity of the rock mass.

The existence of rock joints influences the stability in rock masses. Thus, they also influence the loads geotechnical structures must be dimensioned to withstand. A critical failure mode in rock masses is shearing of rock joints [1]. It is therefore important to be able to determine the peak shear strength of rock joints. However, in situ experiments are generally of both technical and economic reasons not feasible [2]. The development of shear strength criteria is therefore mainly done based on results from shear testing experiments under controlled laboratory conditions, e.g. [3].

In phase 1 of the POST (Parametrization Of STructures) project [4] executed 2014 – 2016, initiated by SKB, Swedish Nuclear Fuel and Waste Management Co, Sweden; Posiva, Finland; and NWMO, Nuclear Waste Management Organization, Canada one aim was to develop a strategy to describe geological structures and joints in crystalline rock masses. A second aim was to derive knowledge about how to adapt the parameters of shear strength criteria developed from results from laboratory tests to different scales. A conclusion was that numerical modelling certainly is required to understand the behaviour of full-scale rock masses, and the criteria that shall be used to predict shear strength must be validated through experiments. To gain knowledge about the behaviour of real rock masses, the experiments must be carried out under controlled laboratory conditions and on different scales. This is required to add knowledge about averages and variations of the shear strength of rock joints with respect to the scale.

Consequently, the scale of about one square decimetre joint area frequently used in laboratory tests must be completed with tests on larger scales. Based on this conclusion, a subsequent phase of the POST project was launched in 2017 by SKB, Swedish Nuclear Fuel and Waste Management Co, Sweden and NWMO, Nuclear Waste Management Organization, Canada, aiming to add new knowledge about the scale effect. To support the derivation of new knowledge about the scale effect, a new direct shear test equipment was developed in which it is possible to carry out tests in a unique combination of large loads (up to 5 MN normal and shear loading) and large joint areas (up to 400 x 600 mm). The shear test equipment is mounted to a 20 MN loading frame from which the normal load is applied (Figure 1). As an engineer at RISE Research Institutes of Sweden the author also has been engaged in the design, the try-out, and the commissioning of this shear test equipment.

In addition to the need of laboratory tests in different scales, the uncertainties in the interpretation of the results derived from test on rock joints need to be handled. The uncertainties originate from the fact that

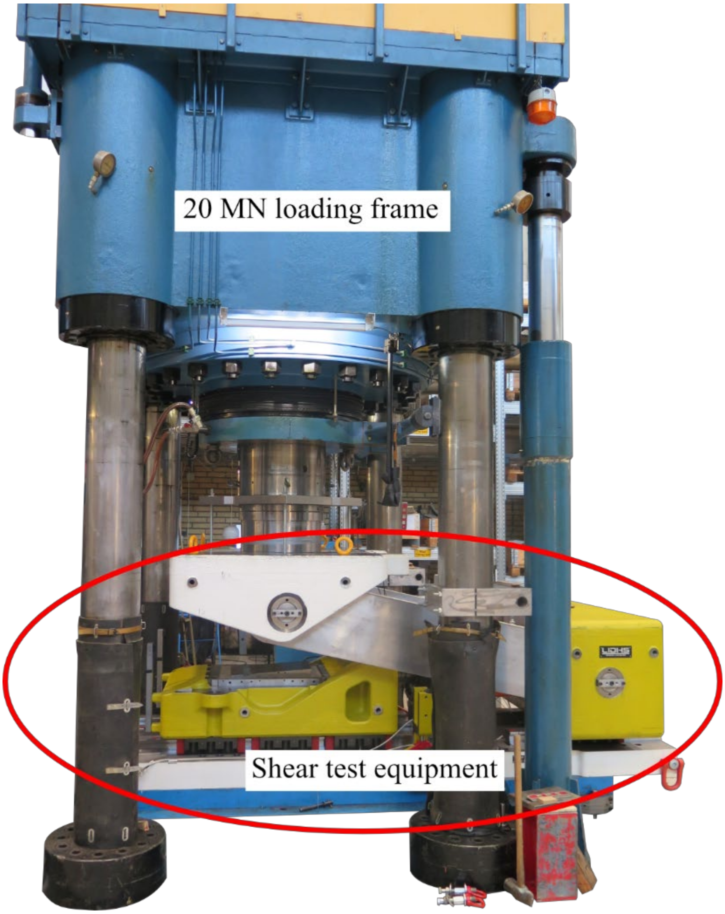

Figure 1. The new direct shear test equipment with 5 MN capacity in the normal loading and shear loading directions, respectively, mounted to the 20 MN loading frame.

each rock joint is unique. Hence, it cannot be stated if observed differences in the results is an effect of differences in input parameters or if it is a result of each rock joint being unique. A way to overcome this issue is to use replicas, i.e. man-made copies of rock joints, in direct shear testing. However, reliable usage of replicas requires knowledge about how well the replicas represent the shear strength characteristics of the rock joint and knowledge about the spread among the replicas.

1.2. Objectives

The overall objective of the doctoral work is to facilitate the development of improved criteria for predictions of the shear strength of rock joints. This will allow for reduction of costs, more efficient usage of the underground space, reduced environmental impact and increased safety related to underground constructions.

The work presented in this thesis supports the overall objective by looking into two quality aspects related to the usage of replicas and the scale effect, respectively. The first aspect deals with geometrical reproducibility of replicas. The second quality aspect takes charge of the influence on the measurements of the normal stiffness of the test system in direct shear test setups. The normal stiffness of the test system causes erroneous measurements of displacements and loads. The usage of replicas and the scale effect are linked to both quality aspects because geometrical reproducibility of replicas is related to the usage of replicas, which also can be used in the study of the scale effect. The influence of the normal stiffness of the test system is relevant to all direct shear tests, which specifically could be a part of a scale effect study using replicas.

These two quality aspects specifically support the overall objective in that they both contribute to more accurate results generated in direct shear testing from which the shear strength criteria are validated. The findings preferably also should be applicable to other research areas than to the studies of rock joints, i.e. the findings of geometrical reproducibility should be applicable to any type of specimens with irregular surfaces, and the findings of the normal stiffness should be generally applicable to tests in which the normal load varies during the test.

1.3. Disposition

Chapter 2 introduces parameters influencing the shear strength of rock joints by an outline of the development of shear strength criteria. This is followed by a description of the design principles of direct shear testing equipment in Chapter 3 since results from direct shear testing frequently are used in the development and validation of shear strength criteria. Various types of uncertainties related to direct shear testing are presented in Chapter 4. Chapter 5 presents the research plan and puts it in the context of the overall objectives. Chapter 6 summarizes the research work and Chapter 7 summarizes and discuss the results. Conclusions are given in Chapter 8 followed by an outlook on future work in Chapter 9.

1.4. Limitations

The thesis is limited to studies of two sources of uncertainties in direct shear testing: the reproducibility of replicas and the influence of the normal stiffness in test set ups. There are other sources of uncertainties that are of potential interest to study. However, they are too many to be covered here, but some of them are mentioned in Chapter 4 to put the two studied sources of uncertainties into context.

The aim of the work on the normal stiffness of test setups has been to secure that correct normal load is applied over the joint. The joint stiffness has not been subject for investigations.

2. Shear strength of rock joints

This chapter outlines why the shear strength of rock joints are of interest to study and the development of shear strength criteria. The intention is not to provide a complete summary, but to provide sufficient information to put the work in this thesis in its context.

Rock joints are of interest to study because they influence the structural integrity of tunnels and caverns excavated in rock and structures founded on rock. The shear behaviour of rock joints is for example of importance in the evaluation of the stability of rock slopes, analysis of the sliding stability of concrete dam foundations, and in the excavations in jointed rock masses. Two frequently used boundary conditions in direct shear testing is constant normal load (CNL) and constant normal stiffness (CNS). CNL simulates the conditions in for example slope stability problems in which sliding occurs under the influence of a constant normal load of the rock mass acting over the joint. CNS on the other hand simulates the conditions in underground excavations. In tests under the CNS configuration, the applied normal load simulates the stiffness of the surrounding rock mass as the joint dilatates during shearing [5].

2.1. Constant normal load

One of the first studies aiming to describe the relation between the shear and normal stress under the CNL boundary condition was done by Patton [6], who used saw-tooth profiles as a model of a rock joint. At lower normal stresses, sliding over asperities and, at higher stresses, shearing of asperities was found to be the predominant failure mode. To calculate the shear stress under a given normal stress, the angle of inclination of the profile and the friction under sliding and shearing, respectively, must be known. Ladanyi and Archambault [7] added the dilatancy, shear area ratio, a statistical average friction, and the degree of interlocking to describe the peak shear strength for joints with irregular surfaces by using energy principles. Barton [1] derived an empirical criterion in which the joint roughness coefficient and the effective joint wall compressive strength were introduced. Zhao [8] pointed out that not only the joint roughness influences the shear strength, but also the matching between the joint surfaces, and therefore introduced the joint matching coefficient.

The introduction of the joint roughness coefficient called for the need of methods to determine the joint roughness. One commonly used method is to characterize the joint surface using fractal theory, e.g. Renard et al. [9]. Another method is by calculation of the apparent dip angles of the individual asperities from 3D scanning data introduced by Grasselli [10], who also presented a constitutive model to which also the influence of the tensile strength of the rock material was included. A prerequisite for employing the model is that the joint surface is accessible, which limits the application of the model to in situ conditions. In addition, the model does not take the influence of the scale and the matching into account.

Ríos-Bayona et al. [11] present a criterion applicable to natural unfilled joints that takes the joint matching into account. This criterion is valid for low normal stresses when sliding is presumed to be the dominant shear mechanism. Casagrande et al. [12] presents an approach from which the peak shear strength can be determined by application of Monte Carlo simulations to generate synthetic joint surfaces from measured joint traces. This approach takes both sliding and shearing into account but presumes a perfect matching of the joints.

Further examples on parameters that are presumed to be of importance to the peak shear strength of rock joints are the influence of interface materials such as in coal-rock interfaces studied by Li et al. [13] and infilling materials studied by e.g. Ram et al. [14].

2.2. Constant normal stiffness

What has been mentioned so far applies for estimation of the shear strength under CNL. Additional parameters need to be incorporated to predict the shear behaviour under CNS. The CNS boundary configuration has so far not been investigated to the same extent as the CNL boundary configuration, but some criteria have been published. Heuze [15] published an analytical expression for calculation of the peak and residual shear strength. In addition to the normal stiffness simulating the constraint of the surrounding rock mass, some other parameters were taken into account: the joint stiffness, the apparent cohesion and the critical normal stress beyond which no dilatation is presumed to occur. Leichnitz [16] derived an analytical expression for calculation of the shear and normal stresses for any given combination of normal and shear displacements instead of an explicitly given stiffness.

In addition to analytical models, graphical methods have been derived. Saeb and Amadei [17] presented a method from which the shear behaviour under constant or varying normal stiffness can be predicted based on curves over the shear and normal displacements for varying normal stresses under the CNL boundary configuration. From this graphical method an analytical model was derived by Saeb and Amadei [18]. For any given increment of normal and shear displacement the corresponding normal and shear stress increments can be calculated by multiplying the displacement increments with normal and shear stiffnesses associated with each type of displacement.

Skinas et al. [19] presented a graphical model from which the shear stress at any instant can be calculated from a set of dilatation curves for various normal stresses under CNL. The model uses the concept of mobilized dilation introduced by Barton [20], which requires introduction of two additional parameters: the damage coefficient and the mobilised joint roughness coefficient. Lastly, assuming that the shear behaviour can be described based on knowledge about the dilation was also adopted by Indraratna et al. [21]. They used a Fourier series to model the normal displacement from shear displacements. The Fourier coefficients are determined based on experimental data.

Consequently, criteria for prediction of the peak shear strength requires input variables derived from testing or measurements (e.g. 3D scanning). Moreover, the validation of the criteria is done by comparisons with the results from direct shear testing. So, if the peak shear strength is the target variable, there are many parameters whose influence needs to be controlled to extract reliable results from direct shear testing.

3. Direct shear testing equipment

In [22] the method is described for determination of the shear strength of rock joints using a direct shear test equipment. Figure 2 illustrates the design principle for a shear test equipment. Each of the two halves of the specimen, which could be made of any rock or replica material, is fixed to a specimen holder by encapsulating material. Before direct shear testing, the specimen holders are mounted to a loading frame whose function is to transfer the normal and shear loads applied by actuators to the joint. After application of the normal load, shearing is accomplished through a relative displacement of the specimen holders. Commonly, one of the specimen holders is fixed except from in the normal loading direction, while the other is subjected to a linear translation through a low friction system, e.g. linear bearings.

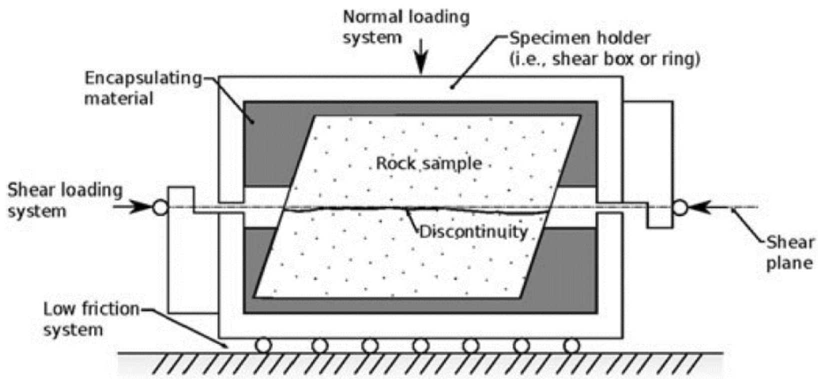

Figure 2. Schematic illustration of the design principle of the direct shear testing equipment. From [22]

The design of a shear test equipment can be done in many ways, but there are some common aspects that need to be considered regardless of design. Of prime concern is that the shear load acts as close as possible to the shear plane. Any offset from the shear plane will add a torque superposed to the shear load. The loading frame then must be designed to withstand this torque, which adds cost and material. However, the most important reason to avoid any external torque to be introduced is to avoid a counteracting internal torque over the joint. Such internal torque will introduce an uneven and uncontrolled normal stress distribution over the joint.

Even though the actuator generating the shear load is placed in the shear plane, the load cannot be transferred directly to the joint for technical reasons. Therefore, the shear loading system (Figure 2) must be designed to be as stiff as possible.

Generally, it is of importance that the shear and normal loads are evenly introduced to the specimen, which requires a robust design of the specimen holders. It is also of importance that the specimen holders can be rigidly fixed to the loading frame. Any movement between the specimen holders and the loading frame will introduce noise and errors in the measured displacements.

Transducers are used to measure displacements in the shear and normal loading directions, respectively. Preferably more than one displacement transducer is used in each direction for evaluation of any obliquity, pitch and roll of the specimen. For proper measurements, the brackets the displacements transducers are mounted to must be robust and allow for a secure fixation to the loading frame. The tips of the transducers that measure the displacement in the normal loading direction will slide during shearing due the relative movement of the specimen holders. Therefore, the surfaces in contact with the tips of the transducers must be plane, parallel with the shear plane and polished for accurate measurements.

The friction between the specimen holder generating the shear displacement and the frame of the test equipment shall be kept as low as possible. The first reason is that as much of the shear load generated by the actuator shall be used to generate shearing of the joint and not to overcome friction in the test equipment. The second reason is the same as the reason for the need of having the shear load to act as close as possible to the shear plane, namely to avoid the need of having the loading frame to be designed to withstand unnecessary loads.

4. Sources of uncertainties in direct shear testing

There are many uncertainties related to direct shear testing that potentially can influence the results. This chapter is introduced by an outline of some aspects influencing the uncertainties followed by subsections in which two sources of uncertainties are described more in detail: the usage of replicas and the normal stiffness in direct shear test setups. A complete survey of all possible sources to uncertainties is not given. Examples are presented in Section 4.1 with the intention to put the two sources of uncertainties studied in this work into context.

4.1. General aspects of importance

The following four aspects representing general sources of uncertainties that to a large extent are possible to control with established methods and techniques are here briefly described in the following order: specimen fixation, joint surfaces, control system, and test equipment.

If we omit sources to uncertainties inherent to joints as the influence of infilling material, compressive strength, joint matching etc. and focus on those related to the test setup specifically, one aspect is related to the encapsulating material fixing the specimen relatively to the holder. If the material for some reason e.g. due to shrinkage or adherence, is not fixed to the specimen holder the joint matching could be affected if the joint surfaces are displaced relatively to each other. This risk is higher when the shape of the specimen holder is circular since a circular shape does not provide any constraints against rotation. The joint matching also could be affected if there is no positioning system that relates the specimen halves relatively to each other. If the repositioning of the specimen halves differs from the original position, e.g. after scanning, it does not matter how accurate the scans are; an error could be introduced anyhow. Even with a positioning system between the specimen holders in place, the positioning of the specimen holders relatively to the loading frame must be under control to secure that the shear direction will be as intended.

Some issues directly related to the specimens are also worth mentioning. It goes without saying that loose fragments shall be removed from the joint surface prior to possible scanning and direct shear testing, but in practice it could be more difficult than it appears to be. Fragments that do not come off using e.g. a brush, still could turn out to have no load bearing capacity during shear testing. In such case, the fragments come off at low loads rather than will be subject to wear of asperities. The same type of error could occur in conjunction to breakage in boundaries, which can be observed in some specimens after shear testing. Often it is not known at what instant the breakage occurred. Again, this means that the asperities do not contribute to the shear strength to the extent as expected. In addition, breakage will reduce the joint area, which is not accounted for in the control system. This means that a higher normal stress than intended will be applied over the joint. In many cases a spherical bearing is mounted between the actuator and the specimen holder. This is done to prevent harmful transverse forces to be transmitted to the actuator. It also means that the specimen holder will be free to rotate. Therefore, the individual measurements from the displacement transducers need to be investigated to judge any influence of pitch and roll during shearing.

The control system is a part of the test setup that also requires attention. Tuning the control system is required to get an as quick, and at the same time, as accurate response as possible from an actuator to meet the setpoint, e.g. a certain displacement rate or a certain load. It is also of importance that the control system is able to maintain the specimen halves in the original position during e.g. normal loading test and application of pre-loads prior to shear testing, to not cause any unintended shearing of the joint. Most industrial control systems have three terms that are adjusted in the tuning process: proportional (P), integral (I) and derivative (D). The terms provide different types of contributions aiming to eliminate the error between the setpoint and the measured process variable, and there are various established loop-tuning techniques that can be employed.

Test equipment shall be as stiff as possible. The influence of the normal stiffness of the test system is further described in section 4.3, but generally the loading frame must be stiff enough to allow for an accurate and quick control in the application of loads. In the shear direction, often a constant shear displacement rate is desired, while the shear load required to maintain a constant shear displacement rate will vary with the load bearing capacity of the joint surface. This requires an ability of the control system to react on this type of occurrences, but the control system is not the only factor affecting the response on a sudden need for a lower shear force. At instants when there is a need for an increase in the shear load, energy will be built up within the test setup in terms of elastic deformations. These deformations are present in the hydraulic oil as well as in the loading frame. When the resistance suddenly decreases the stored elastic energy is released, which causes an undesired suddenly lowered shear force. This effect can be seen by plotting the shear displacement over time and observe the fluctuating appearance deviating from the desired linear appearance. Hysteresis in hydraulic valves can also contribute to deviations in loading.

4.2. Replicas

The geometry of the joint surface is a background variable that ideally shall be held fixed under intervention on a target variable. However, this is not possible since each rock joint by nature is unique [10]. Therefore, an alternative is to use replicas, i.e. man-made copies of rock joints. Replicas have the potential of making it possible to carry out controlled parameter studies by offering repeated tests under intervention on a target variable, e.g. studies on the influence of the normal load on the peak shear strength.

Replicas have been used for many different purposes as reported in the literature. Replicas were used in the study of the scale effect by Bandis et al. [2]. Digitally downscaled concrete replicas were produced from 3D printed moulds in a study by Uotinen et al. [23]. Empirical models for the shear strength behaviour were derived from studies of replicas by Zhang et al. [24], Kumar et al. [25] and Lee et al [26]. Koyama et al. [27], Um et al. [28] and Jing et al. [29] investigated the influence of the anisotropy and loading on the shear strength. The effect of infill materials on the shear behaviour was studied by Shrivastava et al. [30]. The influence of asperity and roughness was studied by Shrivastava et al. [31] using replicas with varying triangular profiles. Non-persistent joints in replicas were used in experimental studies by Zhang et al. [32] and Asadizadeh et al. [33]. The shear behaviour of joints with different JRC profiles were studied by Kimuara et al. [34], Jiang et al. [35] and Ghazvinian et al. [36] using replicas. However, the practice in the studies is that only one replica per parameter setting was used in the experiments. This means that the spread in the experiments is not known. This in turn means that it is not possible to state if the observed differences between the results is a consequence of an intervention on a target variable or just an effect of different properties between the replicas.

It is also of importance to know how the spread in the test results of the replicas relates to the result of the mother rock joint. Liu et al. [37] used replicas to derive a shear strength criterion. Xia et al. [38] investigated the influence of the joint roughness, the normal stiffness, and the initial normal stress on the shear mechanical characteristics. In both works it would have been possible to compare the results between the mother rock joint test and the corresponding replica test, but this was nevertheless not done.

One work has been found in which direct comparisons between replicas and the mother rock joint in direct shear testing were presented by Singh et al. [39]. However, also in this study only one replica per parameter setting was tested, disqualifying the possibilities to evaluate the spread of the replicas, and put this in relation to the result from the mother rock joint. Moreover, the possible influence of geometrical differences between the joint surfaces was not discussed.

Obviously, knowledge about the uncertainties in the usage of replicas is missing. This in its turn means that shear strength criteria derived from results from tests with replicas could be faulty. One source of uncertainty is the difference in material properties between the replica material and the rock. Another source is the uncertainty about the geometrical reproducibility of replicas, i.e. the ability to produce replicas with mutually identical properties. In addition, the geometrical deviation between the joint surfaces of the replica and the mother rock joint is also of importance to know.

4.3. The normal stiffness of the test setup

The normal load in direct shear testing can either be applied by a physical spring mounted between the specimen holder and the frame of the test setup (the control system and the complete hardware), or by simulation of a physical spring by the control system in test setups equipped with closed-loop control. In this type of control system, the normal stiffness is entered as input value for the relation between the normal displacement and the normal load. The difference between the true and desired load response is then calculated by the control system. Based on this information the actuator continuously adapts the normal load to account for the effect of the dilatancy [40].

It is difficult to measure the dilatancy directly since the available space around the joint is limited. Therefore, the displacement transducers in many cases cannot be located close to the joint. This means that there is a risk that other normal displacements in addition to those originating from the dilatancy will be measured from the test system (all components between the measuring points of the displacement transducers, which means that the “test system” is a part of the “test setup”). Therefore, test systems shall be as stiff as possible which is stated in the ISRM “Suggested Method for Laboratory Determination of the Shear Strength of Rock Joints” (2014) [22]. It is proposed in this suggested method to use a high stiffness dummy, i.e. a steel specimen, to enable calibration of test systems.

However, the information in the literature is limited about how to carry out calibrations and whether calibrations have been employed to the test systems (Barla et al. [41], Liu et al. [42], Haberfield et al. [43], Moradian et al. [44], Rao et al. [45], Hans et al. [46]). Jiang et al. [39] presented graphs from CNS tests showing the normal stress versus the normal displacement and concluded from comparisons between the slopes of the graphs and the applied stiffness settings that the stiffness was obtained with good accuracy. In a work by Packulak et al. [47], the possibilities to provide guidelines on boundary condition selection in direct shear tests were investigated. They identified different types of potential errors, but the influence of the normal stiffness of the test system was not discussed. Chryssanthakis [48] and Dae-Young et al. [49] used a steel specimen to capture displacements in the test system under the CNL configuration for subsequent calibration of the measured displacements in tests using rock materials. To sum up, even though rarely reported, an approach exists on how to compensate for the normal stiffness of the test system under the CNL configuration. However, there is no information on how to compensate for the influence of the normal stiffness of the test system under the CNS configuration. Therefore, an approach on how to do this was developed in the work presented here.

5. Research plan

Within phase 2 of the POST project, in addition to the development, manufacturing, and try-out of the new direct shear test equipment with 5 MN loading capacity in both the normal and shear directions, several replicas with dimensions 70 x 100 mm were manufactured from a natural rock joint. These replicas and the mother rock joint were then used within this thesis work to study reproducibility of replicas. Two direct shear equipment with normal and shear loading capacities of 5 MN and 300 kN, respectively were used in the study of the influence of the normal stiffness of the test system.

5.1. In the perspective of the overall objective

In experimenting, background variables are controlled under intervention (the action taken whose effect is subject for observation) on the target variable. This is followed by observations of the effect originating from the intervention [50]. An example is an intervention by changing the normal load followed by the observed effect on the peak shear strength (the target variable) keeping all other variables fixed and under control (the background variables). Specifically, the geometry of replicas and the influence of the normal stiffness constitute background variables that need to be controlled. If the joint surfaces differ, so will the shear strength characteristics, and the finite normal stiffness in test setups introduces errors in the applied normal load under the CNS boundary condition. The accuracy with which the criteria derived from laboratory experiments predict the peak shear strength are therefore strongly dependent on the quality of the data from the experiments. However, experimental sources to uncertainties influencing the quality of the data are rarely taken into consideration in studies from which shear strength criteria are derived.

This in turn complicates statements about the accuracy of shear strength criteria. In particular, despite the importance of controlling the geometrical reproducibility of replicas and the influence of the normal stiffness under the CNS boundary condition, control techniques are lacking. Therefore, the research work reported in this thesis aims to answer the question of how the uncertainties of the two identified quality aspects, the geometrical reproducibility of replicas and the influence of the normal stiffness, can be estimated, reduced and kept under control.

The geometrical reproducibility of replicas refers to the fundamental requirement being able to manufacture replica joints with a known and small mutual geometrical spread. This requires ability to quantify the geometrical deviation with respect to the mother rock joint. The geometry of the replica rock joint is a background variable that could affect several target variables, e.g. the shear displacement at peak shear strength, the dilatancy and the residual shear strength.

The normal stiffness of a test set up is a background variable that refers to the undesired, but unavoidable, finite stiffness that exist in all test systems. The normal stiffness of a test setup causes too small dilatancies to be registered by the data sampling system and too low normal loads to be applied under the constant normal stiffness boundary condition.

The normal stiffness of the test setup potentially influences the same target variables as the joint geometry of replicas, but since the character of the two background variables are of different nature they are treated separately in the thesis. Reduction of the uncertainties of these background variables supports the overall objectives not only by enhancement of the prerequisites for an improved accuracy of the developed shear strength criteria, but also by simplifying the way forward to an improved control of the safety margins during construction and operation, which saves time and cost.

5.2. Outline of research plan

Figure 3 illustrates the framework of the work contained in this thesis as well as the planned subsequent work. The illustration in the lower left

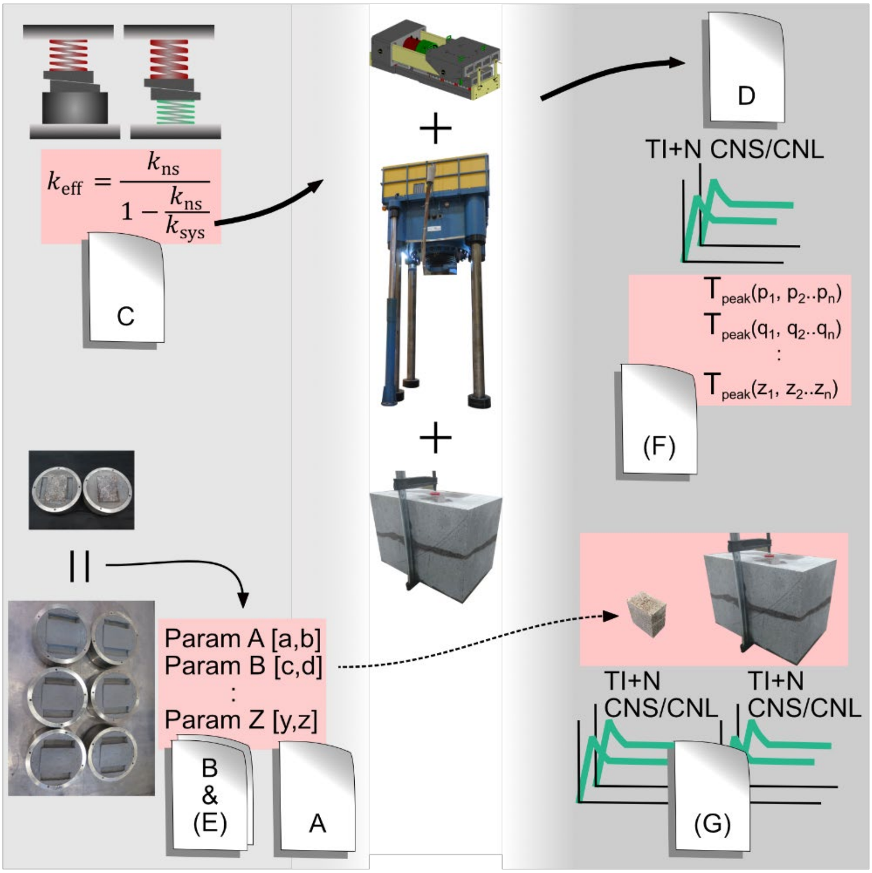

Figure 3. Illustration of the framework comprising the work presented in this thesis (letters without brackets) and the planned continued work (letters with brackets). The middle part illustrates the introduction of the large-scale tests in the 5 MN shear test setup to be used in the planned continued work.

corner represents the work on reproducibility of replicas. The letters refer to papers. Letters within brackets refers to papers planned to be written in continued work, which is described in Chapter 9.

In paper A, an introductory analysis in which the surface comparisons based on 3D scanning data, represented by images illustrating the differences between the mother rock joint and the replicas are quantified to match the visual appearance of the surface comparisons. In paper B, this analysis is deepened and complemented with additional data from which geometrical quality assurance parameters are proposed.

In paper C, an approach is presented on how to compensate for the influence of the normal stiffness in direct shear test setups. The approach is validated in a 300 kN test setup. In paper D, the approach is applied to the new 5 MN shear test equipment as part of the try-out process.

The grey field to the left represents tests on the scale of 70 x 100 mm. The grey field to the right represents test on different scales ranging from 30 x 65 to 300 x 500 mm and is outlined in Chapter 9 describing future work.

6. Summary of appended papers

6.1. Geometrical reproducibility of replicas

The uncertainties related to the geometry of replicas are of fundamental importance to control. In Paper A and Paper B two quality assurance parameters are presented that quantitatively captures the geometrical deviations between replicas and the mother rock joint. The purpose is that the parameters shall be derived for each replica prior to direct shear testing based on 3D scanning data. Replicas having parameter values below certain threshold values will have a shear mechanical behaviour with known deviations from the mother rock joint. It also means that the spread in the shear mechanical parameters among the replicas will be known. In all, this means that the reliability in the usage of replicas in direct shear testing will be improved. The quality assurance parameters and the parameter values were extracted from analyses of a set of replicas and their mother rock joint. The deviations are presented as surface comparisons illustrating the differences between the scanning coordinate points of the replicas and the mother rock joint, respectively. The quality assurance parameters with respect to geometry were derived based on agreement between the qualitative perception through the appearance of the illustrations of the surface comparisons and the quantitative values of the derived quality assurance parameters.

The geometrical deviations between a replica and the mother rock joint could have different sources of origin. Deviations in morphology are of fundamental interest to capture. In Paper A, an introductory analysis capturing this type of deviation is presented. In addition, an introductory analysis of the relation between the deviations in joint matching and the shear mechanical behaviour in direct shear testing is presented. This analysis serves as a base for establishment of threshold values and

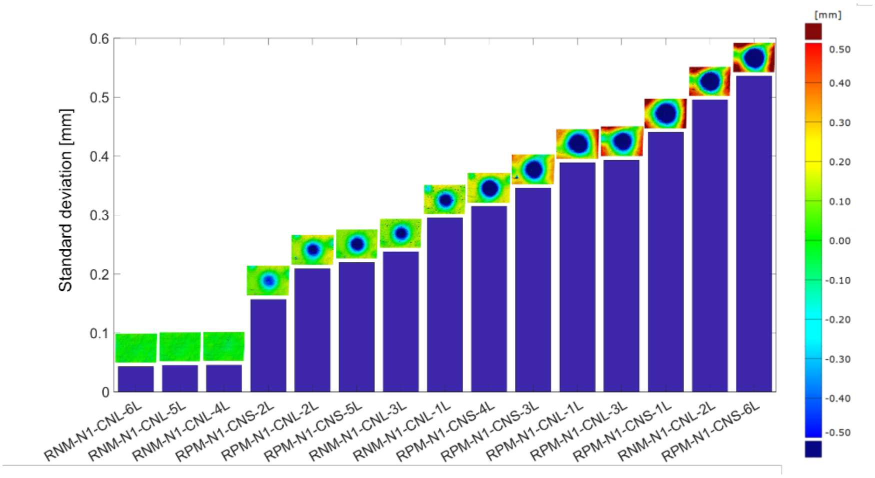

Figure 4. Miniatures of surface comparisons with respect to morphology between the lower joint surface of the mother rock and the replicas along with bars showing σ_{mf}.

evaluations of the ability of replicas to simulate the shear mechanical behaviour of rock joints which is the subject for future work and will be presented in the planned Paper E (Figure 3).

In Paper B, the analysis with respect to morphology presented in Paper A is deepened and complemented with additional data. A parameter denoted σ_{mf} is presented. This parameter captures the morphological deviation between a mother rock joint and its replica. σ_{mf} is the standard deviation of the deviations between the coordinate points of the replica and the rock joint (Figure 4).

The second quality assurance parameter captures deviations in orientation with respect to specimen holder position. The importance of this type of deviation could be imagined in case no morphological deviations between the replica and the mother rock joint exist, but the orientation with respect to the top surface of the specimen holder (corresponding to the shear plane) differ, which potentially has an impact on the shear mechanical behaviour. To capture this type of deviation a parameter that describe magnitudes as well as directions is required and in Paper B a vector denoted $\boldsymbol{V}_{Hp100}$ fulfilling these requirements is presented. $\boldsymbol{V}_{Hp100}$ is the vector obtained after projection of the normal vector with a length of 100 mm of the best-fit plane of the replica joint surface to the corresponding plane of the mother rock joint.

6.2. The influence of the system normal stiffness

The second background variable investigated in this work is the system normal stiffness, which is the sum of undesired, but unavoidable, finite stiffnesses present in test systems. In direct shear tests under the CNS configuration the existence of the system normal stiffness causes application of too low normal loads compared to what should be the case if the dilatancy would only result from the joint stiffness and the specimen material. To compensate for this the effective normal stiffness approach has been developed. To employ the approach, first the system normal stiffness must be determined from a normal loading test using a stiff test specimen. Then, the effective normal stiffness is calculated and set as input to the control system instead of the user-defined intended normal stiffness in the accomplishment of direct shear tests under the CNS boundary condition. The intended normal stiffness is the stiffness normally set as input to the control system that simulates the effect of the stiffness of the surrounding rock mass as the joint specimen dilates during shearing.

In Paper C a mathematical expression of the effective normal stiffness approach is derived by representing the test system with a linear spring model (upper left illustration in Figure 3). Instead of the ideal situation with only the intended normal stiffness present, the test system is modelled to consist of two springs in series. The upper spring represents the system normal stiffness, k_{ns}, and the lower represents the system normal stiffness, k_{sys}. The effective normal stiffness, k_{eff}, is calculated from the relation between the system normal stiffness and the intended normal stiffness. The effective system normal approach was validated in a direct shear test setup with normal and shear load capacities of 300 kN using a steel specimen consisting of two halves forming a planar joint with a known angle of inclination. The steel specimen was first used in the normal loading test from which the system normal stiffness was determined. Then, the steel specimen was used in the validation of the approach by using it in

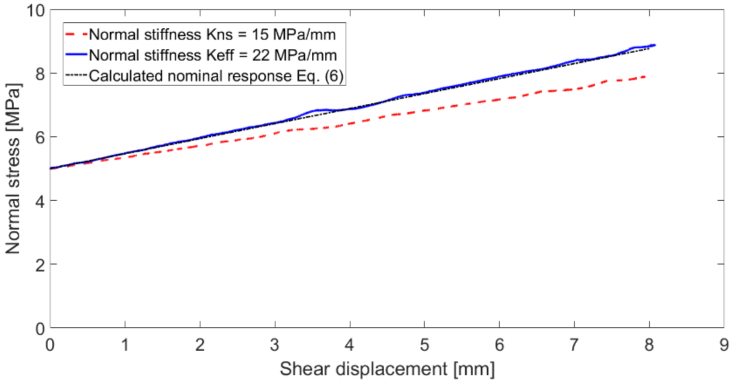

Figure 5. Normal stress over shear displacement from direct shear tests with the intended normal stiffness k_{ns} = 15.0 and the effective normal stiffness k_{eff} = 22.0 MPa/mm respectively as input values for the normal stiffness in the control system. The calculated nominal response according to Eq. (6) in paper C is also shown.

two different direct shear tests under the CNS boundary condition. In the first test the intended normal stiffness, k_{ns}, was set as input to the control system. In the second test the effective normal stiffness, k_{eff}, was used. The approach could be validated by comparing the results from these tests with the calculated nominal response known through the angle of inclination of the steel specimen (Figure 5).

In Paper D the tests in Paper C were replicated as part of the try-out of the new 5 MN direct shear test setup. The tests were executed to determine the system normal stiffness of the 5 MN test setup and to verify that the effective normal stiffness approach could compensate for the influence of the system normal stiffness.

7. Summary and discussion

Two background variables have been studied in this thesis: the geometrical reproducibility of replicas and the system normal stiffness in test setups.

The first background variable concerns geometrical deviations between replicas and the mother rock joint. This is of fundamental importance to control in the usage of replicas. Two quality assurance parameters are presented. The first parameter, σ_{mf}, captures the morphological deviations. In Paper A and in Paper B it is shown that it is possible to reproduce replicas with high accuracy with σ_{mf} < 0.06 mm (Figure 4) after identification and adjustments of deficiencies in the replica manufacturing process (pores, fragments coming loose from the mother rock joint in the mould production process, positioning of the moulds). The second quality assurance parameter is a vector, $\boldsymbol{V}_{Hp100}$, that captures deviations in terms of both magnitude and direction in orientation with respect to specimen holder position. In Paper B it is shown that the deviations of $|\boldsymbol{V}_{Hp100}|$ are small and random with values < 0.36 mm indicating absence of systematic deviations of this type for the replica manufacturing process employed in this study. The obtained parameter values could be perceived to be small numbers. However, frequently in direct shear testing the peak shear strength occurs at shear displacements within tenths of millimetres. This indicates that parameter values corresponding to those obtained in this study could be essential for proper geometrical quality assurance of replicas.

The second background variable investigated in this work is the system normal stiffness. In the validation of the effective normal stiffness presented in Paper C, the system normal stiffness of the 300 kN direct shear test setup up is found to be equal to 471 kN/mm in the normal loading interval 50 – 100 kN. In the first direct shear test under the CNS boundary condition a user-defined intended normal stiffness equal to 15.0

MPa/mm was set as input to the control system yielding an about 13 % lower normal load than the nominal at the end of the test. In the second test, using an effective normal stiffness equal to 22.0 MPa/mm as input, this deviation basically could be eliminated (Figure 5). In the investigation of the 5 MN setup presented in Paper D, the system normal stiffness is found to be equal to 11 326 kN/mm in the normal loading interval 750 – 3 915 kN. In this test setup, setting an intended normal stiffness equal to 10 MPa/mm as input to the control system yielded an about 11 % error in the normal load. Setting the effective normal stiffness equal to 11.53 MPa/mm basically eliminated this error as well. It is of interest to note that only small system normal displacements, in the order of tenths of millimeters, are required to cause normal load errors of about 10 % for the two studied test systems.

Even though the presented geometrical quality assurance parameters and the effective normal stiffness approach have been derived from replicas manufactured from a specific process and applied to specific direct shear test setups, respectively, they are generally applicable. In addition, it is demonstrated that only small perturbations in the background variables are required to get a negative impact on the test result. As demonstrated, the presented quality assurance parameters and the effective normal stiffness approach can handle these perturbations. Therefore, the quality assurance parameters for geometries of replicas and the effective normal stiffness approach foster development and evaluation of shear strength criteria with improved accuracy. This in turn means that the parameters and the approach support the overall objective of this work, namely cost reduction, more efficient usage of the underground space, reduced environmental impact and increased safety in activities related to underground constructions. The findings are also applicable to other research areas than to studies of rock joints. The geometrical quality assurance parameters are applicable to any type of specimens with irregular surfaces. The effective normal stiffness approach is applicable to other types of test setups with closed-loop control in which the normal load varies during the test.

8. Conclusions

The possibility to improve the control of two background variables in direct shear testing is investigated to improve the accuracy of the resulting experimental data.

The first background variable deals with reproducibility of replicas. Two parameters for geometrical quality assurance of replicas are presented: σ_{mf}, capturing morphological deviations and $\boldsymbol{V}_{\mathrm{Hp100}}$ capturing deviations with respect to specimen holder position. It is demonstrated by using the presented parameters that it is possible to reproduce replicas with small geometrical deviations.

The second background variable is related to the undesired finite normal stiffness present in test systems causing application of too low normal loads in direct shear tests under the constant normal stiffness configuration. It is demonstrated that the normal load error basically could be eliminated by application of the effective normal stiffness approach.

In all, the results support control of these background variables and consequently, the development of shear strength criteria with improved accuracy will be facilitated.

9. Future work

The derived parameters σ_{mf} and $\boldsymbol{V}_{\mathrm{Hp100}}$ used for geometrical quality assurance of replicas are only useful after establishment of threshold values that determine if a replica is approved for usage or not. This will be the subject for future work together with a validation of σ_{mf} and $\boldsymbol{V}_{\mathrm{Hp100}}$ by demonstrating the coupling between these parameters and the direct shear strength characteristics. In addition, the replicability of the replicas will also be studied, i.e. the ability of the replicas to capture the shear strength characteristics of the mother rock joint. With reference to Figure 3 the results will be presented in paper E.

In the upcoming work the second objective, the scale effect, will be investigated. The scale effect will be investigated based on results from direct shear tests on different scales under different configurations. Shear test data derived in phase 2 of the POST 2 project will be complemented with tests that will be executed in a test campaign launched 2021. A part of these tests will be accomplished in the new 5 MN direct shear test equipment.

Initially, the results from the large scale (300 x 500 mm) will be used to evaluate the ability of existing shear strength criteria to predict the shear strength characteristics on this large scale in combination with stresses representing the conditions several hundreds of meters below the surface of the earth. This will be done to identify possible needs for improvements of existing shear strength criteria. The results will be presented in paper F (Figure 3).

Finally, the scale effect will be investigated by analysis of data from direct shear tests on all scales. With reference to Figure 3, the outcome from the analysis will be presented in paper G. The dashed line in Figure 3 refers to the application of the derived quality assurance parameters to different scales of replicas. The reason for making it dashed is to indicate that, although of interest, the execution of this type of investigations is not included in the planned remaining doctoral work.

References

[1] Barton N (1973) Review of a new shear-strength criterion for rock joints. Engineering Geology 7: 287-332. https://doi.org/10.1016/0013-7952(73)90013-6

[2] Bandis S, Lumsden AC, Barton NR (1981) Experimental studies of scale effects on the shear behaviour of rock joints. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 18: 1-21. https://doi.org/10.1016/0148-9062(81)90262-X

[3] Özvan A, Dinçer I, Acar A, Özvan B (2014) The effects of discontinuity surface roughness on the shear strength of weathered granite joints. Bulletin of Engineering Geology and the Environment 73: 801-813. https://doi.org/10.1007/s10064-013-0560-x

[4] L Jacobsson, D Mas Ivars, H A Kasani, F Johansson and T Lam (2021) Experimental program on mechanical properties of large rock joints Submitted to *ISRM International Symposium - EUROCK 2021*

[5] Thirukumaran S, Indraratna B (2016) A review of shear strength model for rock joints subjected to constant normal stiffness Journal of Rock Mechanics and Geotechnical Engineering 8:405-414 https://doi.org/10.1016/j.jrmge.2015.10.006

[6] Patton FD (1966) Multiple modes of shear failure in rock Paper presented at the 1st ISRM Congress, Lisbon, Portugal, September

[7] Ladanyi B, and G Archambault Simulation Of Shear Behavior Of A Jointed Rock Mass Paper presented at The 11th U.S. Symp. on Rock Mechanics (USRMS) June 16–19 1969 Berkeley California USA

[8] Zhao J (1997a) Joint surface matching and shear strength part A: joint matching coefficient (JMC) International Journal of Rock Mechanics and Mining Sciences 34:173-178 https://doi.org/10.1016/S0148-9062(96)00062-9

[9] Renard F, Voisin C, Marsan D, Schmittbuhl J (2006) High resolution 3D laser scanner measurements of a strike-slip fault quantify its morphological anisotropy at all scales Geophysical Research Letters 33 https://doi.org/10.1029/2005GL025038

[10] Grasselli G (2001) Shear strength of rock joints based on quantified surface description. Dissertation at Ecole Polytechnique Federale De Lausanne

[11] Ríos-Bayona, F, Johansson, F and Mas-Ivars D (2021) Prediction of peak shear strength of natural, unfilled rock joints accounting for matedness based on measured aperture rock mechanics and rock engineering https://doi.org/10.1007/s00603-020-02340-8

[12] Casagrande D, Buzzi O, Giacomini A, Lambert C, Fenton G (2018) A New stochastic approach to predict peak and residual shear strength of natural rock discontinuities. Rock Mechanics and Rock Engineering 51: 69-99. https://doi.org/10.1007/s00603-017-1302-3

[13] Li W, Bai J, Cheng J, Peng S, Liu H (2015) Determination of coal–rock interface strength by laboratory direct shear tests under constant normal load. International Journal of Rock Mechanics & Mining Sciences 77: 60-67. https://doi.org/10.1016/j.ijrmms.2015.03.033

[14] Ram BK, Basu A (2019) Shear behavior of unfilled-planar quartzitic rock joints with reference to weathering grade of joint surfaces. Rock Mechanics and Rock Engineering. https://doi.org/10.1007/s00603-019-01815-7

[15] Heuze F (1979) Dilatant effects of rock joints 4th ISRM Congress 2-8 September Montreux Switzerland

[16] Leichnitz W. Mechanical properties of rock joints International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 1985 22(5):313-321

[17] Saeb S, Amadei B. (1990) Modelling joint response under constant or variable normal stiffness boundary conditions International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 27(3):213-217

[18] Saeb S, Amadei B (1992) Modelling rock joints under shear and normal loading International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 29(3):267-278

[19] Skinas CA, Bandis SC, Demiris CA (1990) Experimental investigations and modelling of rock joint behaviour under constant stiffness. In: Barton N, Stephansson O, editors. Proceedings of the International Conference on Rock Joints, Loen Rotterdam: A.A. Balkema 301-308.

[20] Barton N (1982) Modelling rock joint behaviour from in situ block tests: implications for nuclear waste repository design. Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH, USA

[21] Indraratna B, Oliveira DAF, Brown ET (2010) A shear-displacement criterion for soil-infilled rock discontinuities Géotechnique 60:8 623-633 https://doi.org/10.1680/geot.8.P.094

[22] Muralha J, Grasselli G, Tatone B, Blümel M, Chryssanthakis P, Yujing J (2014) ISRM Suggested Method for Laboratory Determination of the Shear Strength of Rock Joints Revised Version Rock Mechanics and Rock Engineering 47:291-302 https://doi.org/10.1007/s00603-013-0519-z

[23] Uotinen, LKT, Korpi E, Hartikainen A, Yorke R, Antikainen J, Johansson F, Rinne M. (2015) A Method to Downscale Joint Surface Roughness and to Create Replica Series using 3D Printed Molds. Paper presented at the 13th ISRM International Congress of Rock Mechanics, Montreal, Canada, May.

[24] Zhang X, Jiang Q, Chen N, Wei W, Feng X (2016) Laboratory investigation on shear behaviour of rock joints and a new peak shear strength criterion. Rock Mechanics and Rock Engineering 49: 3495-3512. https://doi.org/10.1007/s00603-016-1012-2

[25] Kumar R, Verma AK (2016) Anisotropic shear behavior of rock joint replicas. International Journal of Rock Mechanics & Mining Sciences 90: 62–73. https://doi.org/10.1016/j.ijrmms.2016.10.005

[26] Lee YK, Park JW, Song JJ (2014) Model for the shear behaviour of rock joints under CNL and CNS conditions. International Journal of Rock Mechanics & Mining Sciences 70: 252:263. https://doi.org/10.1016/j.ijrmms.2014.05.005

[27] Koyama T, Li B, Jiang Y, Jing L (2008) Coupled shear-flow tests for rock fractures with visualization of the fluid flow and their numerical simulations. International Journal of Geotechnical Engineering, 2:3, 215-227. DOI: 10.3328/IJGE.2008.02.03.215-227

[28] Um J (1997) Accurate quantification of rock joint roughness and development of a new peak shear strength criterion for joints. Dissertation at The University of Arizona

[29] Jing L, Nordlund E, Stephansson O (1992) An experimental study on the anisotropy and stress-dependency of the strength and deformability of rock joints. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 29: 535 – 542.

[30] Shrivastava AK, Rao KS (2018) Physical modelling of shear behaviour of infilled rock joints under CNL and CNS boundary conditions. Rock Mechanics and Rock Engineering 51: 101-118. https://doi.org/10.1007/s00603-017-1318-8

[31] Shrivastava AK, Rao KS (2015) Shear behaviour of rock joints under CNL and CNS boundary conditions. Geotechnical and Geological Engineering 33: 1205-1220. https://doi.org/10.1007/s10706-015-9896-2

[32] Zhang, Y., Jiang, Y., Asahina, D. et al. (2020) Experimental and Numerical Investigation on Shear Failure Behavior of Rock-like Samples Containing Multiple Non-Persistent Joints. Rock Mechanics and Rock Engineering 53: 4717–4744. https://doi.org/10.1007/s00603-020-02186-0

[33] Asadizadeh M, Moosavi M, Hossaini MF, Masoumi H (2018) Shear strength and cracking process of non-persistent jointed rocks: an extensive experimental investigation. Rock Mechanics and Rock Engineering 51: 415-428. https://doi.org/10.1007/s00603-017-1328-6

[34] Kimura T, Esaki T (1995) A new model for the shear strength of rocks joints with irregular surfaces. Mechanics of Jointed and Faulted Rock. Rossmanith, Balkerna, Rotterdam. ISBN 90 5410 5410

[35] Jiang Y, Wang Y, Yan P, Luan H, Chen Y (2019) Experimental investigation on the shear strength properties of heterogeneous discontinuities. Geotechnical and Geological Engineering. https://doi.org/10.1007/s10706-019-00955-5

[36] Ghazvinian AH, Azinfar MJ, Vaneghi RG (2012) Importance of tensile strength on the shear behaviour of discontinuities. Rock Mechanics and Rock Engineering 45: 349-359 https://doi.org/10.1007/s00603-011-0207-9

[37] Liu Q, Tian Y, Ma H (2018) Experimental investigation of the peak shear strength criterion based on three-dimensional surface description. Rock Mechanics and Rock Engineering 51: 1005-1025. https://doi.org/10.1007/s00603-017-1390-0

[38] Xia C, Yu Q, Gui Y, Qian X, Zhuang X, Yu S (2018) Shear behaviour of rock joints under CNS boundary condition. Proceedings of GeoShanghai 2018 International Conference: Rock Mechanics and Rock Engineering, Shanghai, May 27–30

[39] Singh HK, Basu A (2018) A comparison between the shear behaviour of ‘real‘ natural rock discontinuities and their replicas. Rock Mechanics and Rock Engineering 51: 329-340. https://doi.org/10.1007/s00603-017-1334-8

[40] Jiang Y, Xiao J, Tanabashi Y, Mizokami T (2004) Development of an automated servo-controlled direct shear apparatus applying a constant normal stiffness condition International Journal of Rock Mechanics & Mining Sciences 41:275-286 https://doi.org/10.1016/j.ijrmms.2003.08.004

[41] Barla G, Barla M, Martinotti ME (2010) Development of a new direct shear test apparatus Rock Mechanics and Rock Engineering 43:117-122 https://doi.org/10.1007/s00603-009-0041-5

[42] Liu Y, Xu J, Yin G, Peng S (2017) Development of a new direct shear testing device for investigating rock failure Rock Mechanics and Rock Engineering 50:647-651 https://doi.org/10.1007/s00603-016-1099-5

[43] Haberfield CM, Szymakowski J (2003) Application of large scale direct shear testing Journal and News of the Australian Geomechanics Society 38:29-39 https://search.informit.org/doi/10.3316/informit.814329096425742 (Original work published March 2003)

[44] Moradian Z, Gravel C, Fathi A, Ballivy G, Rivard P (2013) Developing a high capacity direct shear apparatus for the large scale laboratory testing of rock joints Paper presented at the ISRM International Symposium - EUROCK 2013, Wroclaw, Poland, October

[45] Rao KS, Shrivastava AK, Singh J (2009) Development of an automated large scale direct shear testing machine for rock IGC Guntur https://www.researchgate.net/publication/265407964

[46] Hans J, Boulon M (2003) A new device for investigating the hydro-mechanical properties of rock joints International Journal for Numerical and Analytical Methods in Geomechanics 27:513-548 https://doi.org/10.1002/nag.285

[47] Packulak RMT, Day JJ, Diederichs MS (2018) Practical aspects of boundary condition selection on direct shear laboratory tests Geomechanics and Geodynamics of Rock Masses Selected papers from the 2018 European Rock Mechanics Symposium Saint Petersburg 22-26 may 2018

[48] Chryssanthakis P. Oskarshamn site investigation, Drill hole: KSH01A The normal stress and shear tests on joints SKB Report No. P-04-185 SKB Stockholm 2004 pp 15-16.

[49] Dae-Young K, Byung-Sik C, Jin-Suk Y (2006) Development of a direct shear apparatus with rock joints and its verification tests Geotechnical Testing Journal 29 No. 5 Paper ID GTJ12553 https://doi.org/10.1520/GTJ12553

[50] Montgomery DC (2017) Design and analysis of experiments. Ninth edn. Wiley, Hoboken