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RESEARCH ARTICLE

Influence of Discontinuity Inclination on the Shear Strength of Mont Terri Opalinus Claystones

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Abstract
The shear strength of rocks along discontinuities has the highest influence on rock slope stability; therefore, its accurate determination is crucial. This paper presents a potential solution for the 3D surface detection of the rock discontinuity surfaces by using photogrammetric methods (ShapeMetriX3D), from which one of the most important shear strength influencing parameters can be determined and analyzed. From the determination of the angle enclosed by the plane of the sample surface and the shear plane in the direction of shear, besides the effect of the upslope/downslope shearing further analysis can be carried out in case the examined rock sample contains bedding planes or foliation. The magnitude of the influence on the shear strength for both cases is demonstrated on existing direct shear strength test measurements that were carried out on over-consolidated Mont Terri Opalinus Claystones from the Rock Laboratory of Mont Terri in Switzerland.

Keywords
Mont Terri, Opalinus Claystone, 3D surface detection, shear strength, discontinuities

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1 Introduction

With the development of the infrastructure, it is unavoidable to construct roads and railway lines passing by rock walls and rock slopes. More and more rock mechanical softwares are available for modelling stability problems that require exact input parameters, for instance friction angle, cohesion, Poisson ratio. The optimisation of costs, building the support systems in a more economical way are also among the primery goals; therefore, the more precise determination of the rock mechanical parameters and the better understanding of the rock mass is crucial. Discontinuities happen to be often the weak points of rock materials, since, if movements in the rock mass occur, it tends to happen along these surfaces. The point where the initiation of the movement along the surfaces takes place, depends on the shear strength along the discontinuities, and therefore their investigation is one of the most important topics in rock mechanics [1, 2, 3]. The shear strength of rocks along discontinuities is influenced by several factors, for example, surface roughness of the joint, joint infill material, elevation of the plane of the sample surface in respect to the shear plane in the direction of shear, rock strength, normal stress acting on the sample surface, humidity, bedding, and in situ stress conditions...etc [4, 5, 6, 7, 8, 9]. No standards exist that could take into consideration all these parameters. However, one of the most widespread and optimal methods since 1974 for the determination of the direct shear strength along discontinuities is described in the 'Suggestions of the International Society of Rock Mechanics' (ISRM), only recently published the updated version of their approach [10, 11].

In this paper, only one shear strength influencing parameter is investigated, which usually originates from the frequently occurring inaccurate encapsulation of the rock samples prior to the direct shear strength tests. This inaccuracy can be due to a complex sample surface where the required determination of the parallel encapsulation with the shear plane of the test is almost impossible by the use of simple laboratory methods. However, if the angle between the plane of the sample surface and the shear plane in the direction of shear can be determined, with a back calculation based on the theory of Patton [12], a more accurate value can be given for the shear strength of the rock material along the discontinuity.

In order to determine this angle, a 3D photogrammetric method is presented with which the surface could be precisely described utilizing a point cloud of known coordinates. The image processing was carried out with the Software ShapeMetriX3D. As soon as the surface points were determined, the position of the plane of the sample surface, and the position of the plane of the shear plane could be determined and finally the angle between these planes was calculated. It formed a substantial part of the back analysis.

Eighteen samples of Mont Terri Opalinus Claystones (Rock Laboratory in Mont Terri, Switzerland) were investigated with this method, after which they were sheared along their discontinuity with the constant normal load direct shear strength test method based on the suggestions of the ISRM [10].

In the 2015 edition of the Suggested Methods [11], the importance of the relationship between the plane of the discontinuity surface and the shear plane in the direction of shear is discussed in detail. Nevertheless, the Suggestion does not give a directive as to how it could be determined. The aim of this research is to give a possible working solution.

2 Methodologies

2.1 Patton's theory

Patton was the pioneer in the history of the determination of shear strength along shear surfaces. In his research [12] cut surfaces, samples with irregular, i.e., saw-teeth surfaces were documented (Fig. 1). He found a correlation between the angle *i*, which was the inclination of the saw-tooth with respect to the horizontal shear plane, and the basic friction angle (φ_μ). This was described by:

$$S = N \cdot \tan\left(\varphi_\mu + i\right) \qquad (1)$$

S is the shear load, N is the normal load, φ_μ is the basic friction angle and *i* is the inclination of the saw-tooth with respect to the horizontal shear plane.

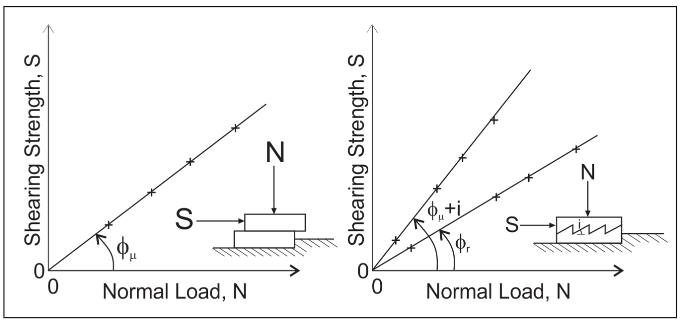

Fig. 1 Shear strength behaviour of samples with a) cut and b) irregular surfaces [9]

This theory was used in the evaluation phase of this paper. In the back calculation of *S, N* and *i* were measured/calculated, from which φ_μ could be calculated. Supposing that $i = 0$, i.e.: the plane of the sample surface is parallel with the shear plane in the direction of shear, without using the calculated φ_μ value, a modified shear strength value *(modAE)*, could be obtained.

2.2 Geology of samples and the procedure of the direct shear strength test

The Mont Terri Opalinus Claystone samples are derived from the underground Rock Laboratory in Switzerland. This is a potential host rock for radioactive waste disposal in Switzerland. Therefore, it is subject to hundreds of small or large scaled experiments and observations. Within the Laboratory area three types of claystones are distinguished, i.e.: shaly facies, sandy facies, and carbonate-rich sandy facies. In this over-consolidated clay a new gallery was under construction in 2012, when the sampling took place for this research. Sample blocks and cores, which derived entirely from the shaly facies zone of the Laboratory, were collected. They are mainly composed of micas, argillaceous and marly shales, layers of marl which are bioturbated and nodular and layers of sandstone with thickness in the order of millimetres [13].

Specimen with 50x50 mm nominal surface area were cut from the sample blocks and cores prior to the encapsulation. The angle *(ß)* between the bedding plane and the specimen surface was measured by a Bevel protactor (Table 1). If this angle was greater than 0, the sample was systematically encapsulated in the sample holder box in a way that the shearing would be upslope (against the direction of the bedding plane) (Fig. 2.).

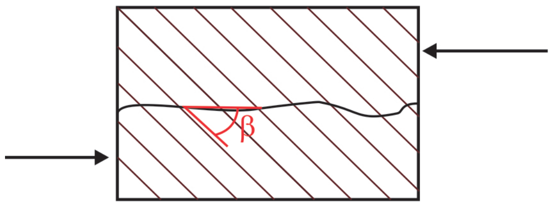

Fig. 2 Determination of the angle ß between the bedding plane of Mont Terri Opalinus Claystones and their natural shear surface

Single-stage direct shear strength tests were carried out along the natural shear discontinuities of the rock samples under low constant normal loading conditions, which were based on the suggestions of the ISRM [7]. Due to the limited amount of rock material, tests were carried out only for 1 MPa normal stress. The tests were carried out in Switzerland, at the École Polytechnique Fédérale de Lausanne (EPFL) – Laboratory for Rock Mechanics (LMR), with a shear machine having a cantilever system, using dead-weight. The top half of the sample was fixed and the bottom half moving. The shear displacement was maximized to 5 mm and the shear was carried out with the rate of 0.8 mm/min.

2.3 3D surface detection with ShapeMetriX3D

Although still in use, the existing 2D surface detection measurements are time consuming and out of date. The direction of the attention faces towards the 3D surface detecting methods. Different methodologies exist for 3D surface detection, e.g. laser scanning [6, 14, 15], system based on advanced topometric sensor (ATS) [16], photogrammetric methods [17]. Test results from each method are obtainable in both point cloud and grid mesh, from which surface inclination and surface roughness parameters can be calculated. Some of the quantification of surface roughness is carried out by the joint roughness coefficient (JRC) [16] the shadow area percentage (SAP) [6] or the brightness area percentage (BAP) [14]. The majority of the international research on this matter focuses on the correct assessment of surface roughness [11] and little attention is given to the effect of the global inclination of the joint surface on the shear strength. The present research aims to bridge this gap whereby a 3D photogrammetric method was used. The software for the data processing, ShapeMetriX3D, was developed by the Austrian company 3GSM GmbH [17]. This method has been successfully used for laboratory scale 3D surface detection [18].

Tests were carried out on the Mont Terri Opalinus Claystone samples before and after the direct shear strength tests. The data processing of the ones taken after are not part of this research. Prior to imaging, the samples were already encapsulated, and their position was fixed. In the process of imaging, two photos were taken at a distance *D1* and *D2* from the face of the sample. The machine used was a Canon EOS 400D type digital camera. For the sake of an accurate imaging, by shifting the camera parallel to the sample surface, with a distance *F* between imaging positions *P1* and *P2*, the ratio of *F* and *D1* and *F* and *D2* had to stay in between 1:6 and 1:8. To make this procedure real, a frame was built to which the camera was fixed, and could freely slide between positions *P1* and *P2* (Fig. 3.).

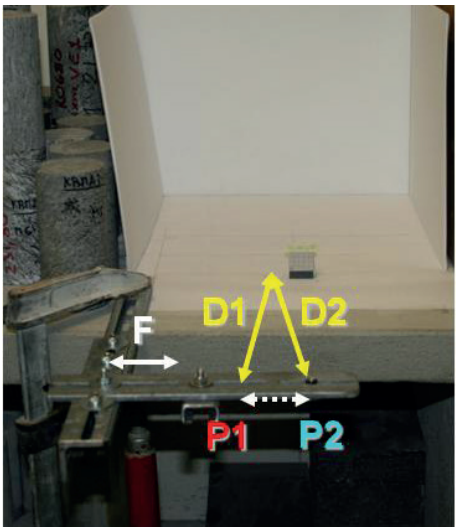

Fig. 3 Camera positions for the imaging of rock sample surfaces with a 3D photogrammetric method. *D1 = D2*

Provided by 3GSM GmbH, the 3D imaging, followed by the processing of data, was carried out with the software ShapeMetriX3D in three steps i.e.: i) 3D image recreation, ii) referencing, iii) data processing.

1. In Step 1, the two images taken from the samples were manually matched together with the software. By defining the area of interest, which, in this case, contained the sample and the surface of the sample holder box, the software generated a 3D photorealistic model.
2. In Step 2, in order to have the 3D image with a correct size and the information of the orientation, the process of referencing was carried out. During the phase of imaging, an object with reference points (at least 3) was placed near the sample (Fig 3). After matching the corresponding reference points (if the *F:D* ratio was correct during the imaging), the software calculated the real distances and orientation in a global coordinate system.
3. In Step 3, which is the data processing, the calculated values with their true magnitude and orientation, were exported in the form of point cloud or grid mesh in a VRML, DXF, CSV and OBJ file format.

2.3.1 Determination of the slope of the sample surface plane in the direction of the shear

From this 3D surface detection approach, the following information could be further calculated and investigated: 1) the elevation of the sample surface in the direction of shear compared to the shear plane, 2) the pre-existing natural shear direction compared to the one used in the laboratory, 3) the surface roughness. This paper focuses only on the first point; the latter two are not part of this work.

The discontinuity surfaces of the rock samples were perfectly matching, thus, for each pair, only the one encapsulated in the bottom sample holder box was the subject to the analysis; i.e. the one moving during the shear test. The 3D surface of a sample was stored as a point cloud that did not only contain the coordinates of the surface of the image, but also the ones of the encapsulating material around it and the surface of the sample holder box (Fig. 4).

As the top surface of the sample holder box is perfectly parallel with the plane of the shear, it served as a good reference for its determination. Based on the JPG files of the images, the coordinates belonging to the sample surface could be distinguished from the coordinate points of the surface of the sample holder.

With the selected coordinates, the two surfaces (surface of the sample and surface of the sample holder box) were analysed separately in *R*, which is an open-source software for statistical computing [19]. For each surface, a linear regression plane was computed in the coordinate system given by the ShapeMetrix3D software. Accordingly, the (X, Z) plane was parallel to the (X_1, $-Z_1$) plane of the side of the sample holder box, on which it was standing during the imaging. The plane of the top surface of the sample holder box was perpendicular to its side i.e. the (X_1, $-Z_1$) plane (Fig. 5). The direction of shear was parallel to the direction of the longer side of the sample holder box, based on its orientation in the shear machine.

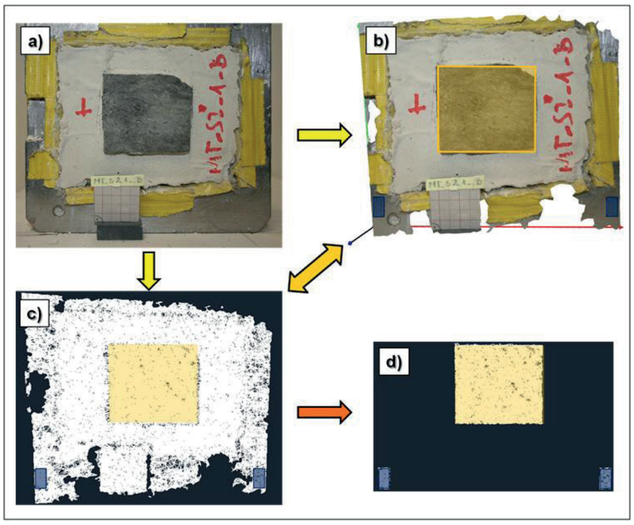

Fig. 4 Procedure of the separation of the coordinates of the sample surface and the surface of the sample holder box, i.e. the shear plane. a) encapsulated bottom half of a specimen; b) 3D JPG image from the ShapeMetriX3D software: the selected zone of the sample and the sample holder boxes are highlighted; c) 3D DXF image from the ShapeMetriX3D software: the selected zone of the sample and the sample holder boxes are highlighted; d) 3D DXF image only with the selected zones

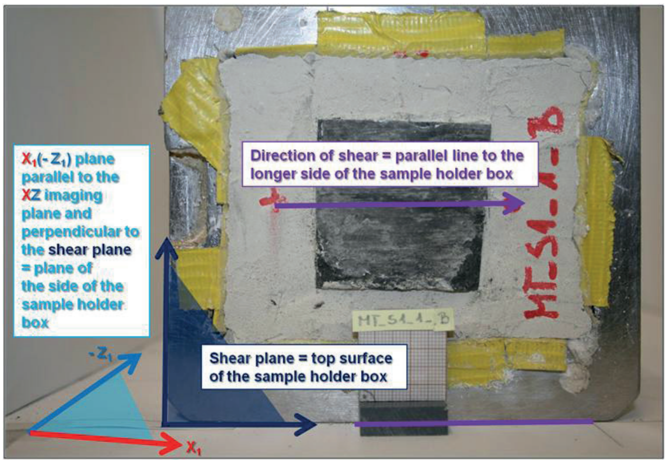

Fig. 5 Localization of the shear plane, direction of shear and the (X, Z) imaging plane

The angle alpha *(α)* has to be determined, which is between the plane of the linear regression plane of the sample surface and the shear plane. In other words, the elevation of the sample surface in the direction of shear compared to the shear plane. Two angles were calculated: a) the angle between the trace of the regression plane of the sample surface and the X axis, and b) the angle between the direction of shear and the X axis. When the plane of the surface of the sample was smaller than the one of the shear plane, it was called as upslope shear (Fig. 6.a), otherwise it was considered as downslope shear (Fig. 6.b). With the two equations corresponding to the two regression planes extracted from *R*, the elevation of the surface of the sample, with respect to the shear plane in the direction of shear, was calculated in *MS Excel* (Table 2).

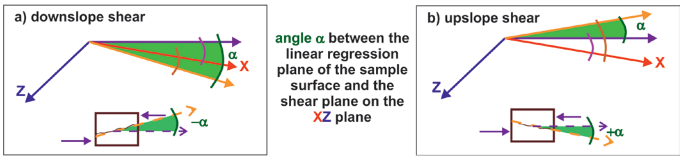

Fig. 6 Calculation of the elevation of the sample surface in the direction of shear compared to the shear plane: a) situation for upslope shear, b) situation for downslope shear.

2.3.2 Relation of the bedding plane vs. shear plane after encapsulation

In Section 2.2 the angle between the bedding plane and the natural shear surface was determined *(ß)* prior to the encapsulation of the sample. However, the relation between the bedding plane and the shear plane is more relevant. Since the natural shear plane was not always parallel to the shear plane of the shear strength test, the value of ß had to be modified *(γ)* (Fig. 7).

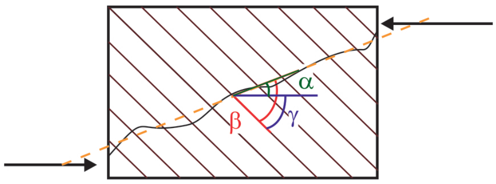

Fig. 7 Determination of the angle γ, the angle between the bedding plane and the shear plane

The angle gamma was calculated by adding to it or subtracting from it α, the angle defining the orientation of the natural shear plane compared to the shear plane of the shear strength test.

Table 1 Relation between the bedding plane of the Mont Terri Opalinus Claystone samples and their natural shear surfaces

Sample	ß [deg]	γ [deg]	Direction of shear
MT_S3_3	0.0	-3.4	downslope
MT_S9_2	0.0	-2.3	downslope
MT_S2_1	0.0	-1.6	downslope
MT_S9_1	0.0	-1.3	downslope
MT_S8_3	8.0	3.6	upslope
MT_S1_2	12.5	4.9	upslope
MT_S8_1	9.0	6.3	upslope
MT_S3_2	14.0	6.4	upslope
MT_S2_2	10.0	8.2	upslope
MT_S8_6	9.7	9.6	upslope
MT_S8_4	11.0	10.7	upslope
MT_S1_1	22.5	19.6	upslope
MT_S5_1	23.0	21.0	upslope
MT_S6_2	48.0	47.3	upslope
MT_S6_1	48.0	47.6	upslope
MT_S7_1	49.0	48.0	upslope
MT_S7_3	49.0	49.0	upslope
MT_S7_2	49.0	49.0	upslope

According to the original assumption (as mentioned before), the samples were encapsulated in a way that shearing would be always upslope. However with the encapsulation and the reconsideration of the relation between the bedding plane and the shear plane, some of the samples were sheared in fact downslope (Table 1).

Table 2 Slope of the plane of the rock sample surfaces in the direction of shear

Sample	α [deg]	Direction of shear
MT_S3_3	-3.4	downslope
MT_S8_1	-2.7	downslope
MT_S5_1	-2.0	downslope
MT_S2_2	-1.8	downslope
MT_S7_1	-1.0	downslope
MT_S8_4	-0.3	downslope
MT_S7_3	0.0	straight
MT_S7_2	0.0	straight
MT_S8_6	0.1	upslope
MT_S6_1	0.4	upslope
MT_S6_2	0.7	upslope
MT_S9_1	1.3	upslope
MT_S2_1	1.6	upslope
MT_S9_2	2.3	upslope
MT_S1_1	2.9	upslope
MT_S8_3	4.4	upslope
MT_S1_2	7.6	upslope
MT_S3_2	7.6	upslope

3 Results and discussion

During the direct shear strength tests data such as shear displacement, shear load, and normal load were measured. In the case of the Mont Terri Opalinus Claystones, due to their squared shape surface, the area change could be calculated. From this information, the shear strength for both peak and residual values could be calculated [10, 11]. However, the calculations do not include the shear strength modifying effect of neither the relation of the bedding plane with the shear plane, nor the relation of the plane of the sample surface to the shear plane. Four samples (MT_S1_2, MT_S3_2, MT_S7_2 and MT_S8_3) were excluded from the further evaluation, due to their unsatisfactory failure during the shear test (clogging of corners, presence of other forces besides shear).

The true shear strength for both peak and residual cases was calculated from the equation of Patton (Section 2.1), by knowing the value of i, which in this research is noted by α. From these new results, the difference between the original and the modified shear strength values was calculated. The results were presented in percentages, e.g., if the shear direction was upslope, the value taking into consideration the effect of slope was 100%, but in reality the value should be modified to 80%, as for the upslope shear has a shear strength increasing effect (Fig. 8.).

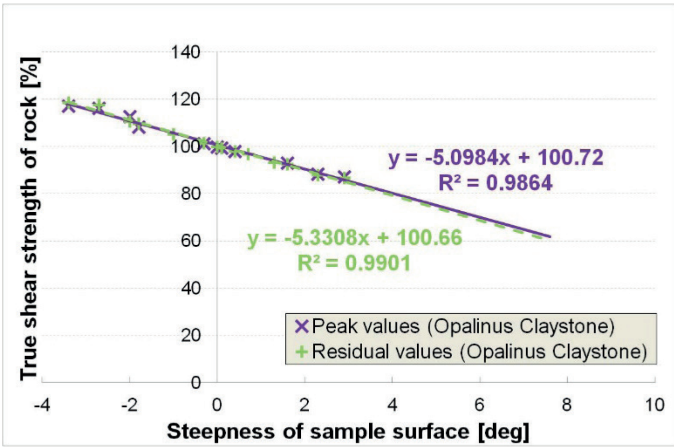

Fig. 8 Effect of the slope of the sample surface plane in the direction of shear. Negative steepness values refer to downslope, positive to upslope shear

There is a linear tendency to be observed between both peak and residual values modified by the effect of the inaccurate encapsulation. Only a 4 degrees tilt can result in a 20 % shear strength difference.

In the current research, 14 samples were evaluated. From an approximately even distribution of the values represented on Fig. 8., it is to be seen that both upslope and downslope shearing took place in the interval of ± 4 degrees (Table 3). Average values are calculated for peak and residual shear strength for both cases (slope of sample surface is taken or not taken into consideration). For peak shear strength in case of upslope shear if the effect of the inclination is not taken into consideration, the values are by 8.8 % overestimated, for downslope shear, 9.3 % underestimated. In case of residual conditions these values change to 6.8 % and 9.4 % respectively (Table 3).

Table 3 Effect of the slope of the sample surface plane in the direction of shear on the shear strength values for peak and residual conditions.

	Upslope shear			
	Peak shear strength (original) [MPa]	Peak shear strength (modified) [MPa]	Residual shear strength (original) [MPa]	Residual shear strength (modified) [MPa]
Minimum	0.412	0.364	0.389	0.363
Maximum	0.550	0.512	0.550	0.533
Average	0.470	0.432	0.469	0.439
Change in average [%]	+ 8.8		+ 6.8	
	Downslope shear			
	Peak shear strength (original) [MPa]	Peak shear strength (modified) [MPa]	Residual shear strength (original) [MPa]	Residual shear strength (modified) [MPa]
Minimum	0.338	0.393	0.321	0.378
Maximum	0.495	0.537	0.416	0.482
Average	0.437	0.482	0.396	0.437
Change in average [%]	- 9.3		- 9.4	

When the effect of the bedding (calculated with the modified γ value) is also taken into consideration, and the slope fitted over the peak and residual shear strength values are analyzed, the inclination of the slopes in the direction of increasing magnitude is 0.14° (Fig. 9). The bedding plane influenced the shear strength of Mont Terri Opalinus Claystones, (28.5 % in the peak, and 20.5 % in the residual domain).

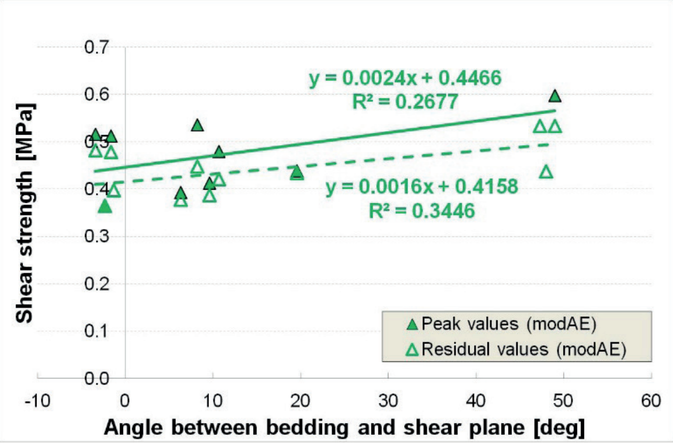

Fig. 9 Effect of angle between bedding and shear plane on shear strength of Opalinus Clay

The previously published research papers dealt with either discontinuity surfaces of in-situ rock faces [14] or corresponded to other lithotypes [15,16]. Although Grasselli et al. [15] experimented on several types of rock joints in laboratory scale, i.e., limestone, granite, marble, sandstone gneiss and serpentinite, they focused on the joint surface roughness quantification from the 3D surface detection measurements. The quantification of joint roughness from 3D surface detection is still very complex and time consuming process, thus it is not part of a daily practice. Different approaches exist in the field of 3D surface detection. The present paper introduced a method that is less time consuming and more reliable than the quantification of surface roughness, as a consequence it gives more consistent shear strength results than not considering the inclination of the joint surface in the direction of shear. The method is easily applicable in the interpretation of the results from laboratory direct shear strength tests along discontinuities.

4 Conclusions

From 3D surface detection methods several shear strength influencing parameters can be determined. The paper primarily focused on the relation between the plane of the encapsulated sample surface prior to direct shear strength test and the plane of the shear in the direction of shear. In the current research, Mont Terri Opalinus Claystones (Switzerland) were used, and the results revealed important information about them. Within a few degrees tilting may it be with or against the slope of the plane of the sample surface, with the use of Patton's theory it was calculated that 20% change can be obtained. This is considered to be a very high number when it comes to design, all due to inappropriate encapsulation. From the tested samples, an average of approximately 9% change in the peak and residual shear strength was calculated if the inclination of the plane of the sample surface was considered.

The second part of the research focused on the relation between the bedding plane of the Opalinus Claystones and the shear plane in the direction of shear. The shear strength values showed an increase with the increase of the angle between the bedding plane and the shear plane. Therefore for Mont Terri Opalinus Claystones from the shaly facies zone the effect of bedding can be considered significant for direct shear strength tests under low 1 MPa constant normal stress conditions.

It would be advisable to continue this research and extend it to other normal loading intervals at least up to the in-situ stress conditions of the Mont Terri Rock Laboratory. This would allow to gain more information on the possible shear behaviour of the host rock, and to better observe the influence of the orientation of the bedding plane on the mechanical parameters. Examination of other rock types is also recommended to find a correlation between the inclined surface plane and the shear plane, in order to draw global consequences. The present research was a first step to create a system from which it would be possible to determine how much the correct sample encapsulation modifies the direct shear strength data.

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