ECoDiST - Easy Computation of Direct Shear Tests

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Daniel Pötschke, daniel.poetschke1@ifgt.tu-freiberg.de

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Abstract

This manual explains the functions of the ECoDiST software. With it it is possible to predict direct shear tests on a laboratory scale. Right now it allows rectangular shear planes. Basic input are surface scan data which are used to calculate roughness parameters. Different methods to predict peak shear strength or complete shear stress curves are offered which gives the opportunity to compare them.
Standardized data formats in ASCII code are used.

Contents

Symbols

a	Grid constant
φ_b	Basic friction angle
Φ	Material inner friction angle
c	Cohesion of material
JRC	Joint Roughness Coefficient
JCS	Joint Compressive Strength
τ	Shear stress
τ_p	Peak Shear stress
τ_r	Residual Shear stress
σ_n	Normal stress
σ_t	Tensile strength
θ^*_{max}	Maximum dip angle
C	Roughness parameter by Grasselli
A_0	Active part of surface by Grasselli

1 Introduction

1.1 Abstract for EGU 2019 in Vienna

The shear characteristics of rock joints are important in geotechnical engineering. For crystalline rocks with a very low matrix permeability and a high matrix strength they dominate the permeability and form weakness zones. If one wants to make precise predictions about the integrity of a possible host rock barrier a deep understanding of the processes in a single rock joint is necessary. Even after 50 years of research predicting the shear stress and dilation of a rock joint under shear displacement remains a challenge. This is caused by the uniqueness of rock joint.

Direct shear tests are performed on lab scale granite samples. This allows a detailed observation and control of all parameters which might influence the results. Lab data are used to validate the predictions. Surface scan data of the rock joints are used as main input data. Other inputs are basic rock matrix parameters, rock joint parameters and the boundary conditions of the direct shear test.

Small software tools help to achieve an easy prediction of surface roughness, peak and residual shear stress and dilation. Firstly the surface is transformed into a quadratic grid that allows fast computation. Then the surface roughness is characterized using different commonly used roughness definitions. A variation of different shear laws, semi-analytical approaches and numerical simulations found in literature are offered to calculate shear strength and dilation. Simple models to predict the permeability should follow in a next step.

The focus of a new numerical approach is to reduce the non-physical assumptions and parameters without a physical meaning. Fit parameters which are valid just for a specific set of data are not used. Balancing the external normal force with the reaction force due to sample deformation is the key feature of the new model.

These tools allow to perform predictions of direct shear tests in an easy and fast manner. A set of functions or standalone executables will be made accessible to the scientific community.

1.2 Short description

The ECoDiST toolbox is written in MATLAB code. Executables are provided which allow the usage of the functionality without a MATLAB licence. The necessary libraries can be downloaded for free from the MATLAB homepage.
The data in- and output uses ASCII files. The software will create text files with the results and also some figures. ECoDiST should help to make easy predictions of planned direct shear tests on a laboratory scale. Scan data of the rock joint are the most important input. The most valuable result is the comparison of different methods for shear strength calculations. A new method is also included.

1.3 What the software is able to do (or why ”easy”?)

The easy thing about the software is the idea to calculate everything on a quadratic grid. This makes the usage of Matlab efficient and implementations easy.

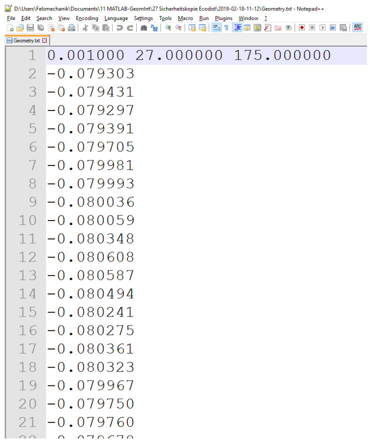
1.4 What the software is not (yet) able to do

The application is limited to rectangular surfaces that are sheared parallel to one of the main axis.
The point cloud has to be rotated into the xy-plane manually before ECoDiST can be used.
Hydraulics are not offered.

2 Input data

2.1 Geometry

To create a geometry file different options are offered: A point cloud from a surface scan can be used. The surface has to be placed in the xy-plane and it needs a rectangular ground size with orientations parallel to the x- and y-axis as well. This can be achieved using open software like CloudCompare or MeshLab.
Another option is to use an stl-file. Basically the programme will simply read the point data from the stl and the further processing is the same as for the point cloud.
The most important parameter to choose is the grid constant a. A quadratic grid of this size will be created and a linear comparison between the grid points and the nearest points from the input point clouds results in the geometry which is used for all following calculations. The new geometry can be represented as a a matrix. The geometry is stored in an ASCII-file as a column vector, see Figure 1.



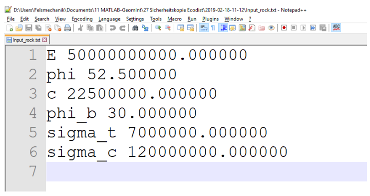
```
0.001000 27.000000 175.000000
-0.079303
-0.079431
-0.079297
-0.079391
-0.079705
-0.079981
-0.079993
-0.080036
-0.080059
-0.080348
-0.080608
-0.080587
-0.080494
-0.080241
-0.080275
-0.080361
-0.080323
-0.079967
-0.079750
-0.079760
```

Figure 1: Geometry file. The first line contains grid constant a, the number of rows (the y-axis) and the number of columns (x-axis). The rest of the file are $m \cdot n$ lines each containing a z-value. All values in meters.

The other options to create a geometry file are: Creating a flat surface, which can be used to check, if the code runs properly. A saw-tooth geometry, cause many publications contain shear tests for this surface type. The last option is to create an arbitrary geometry using fractal dimension. The code for this programme was developed by Mahboob Kanafi et al., 2017.

2.2 Rock parameters

The rock parameters are stored in an ASCII-file like in Figure 2. It is important to use the specified nomenclature. The programme will guide the user through the steps to create this file.



```
E 50000000000.000000
phi 52.500000
c 22500000.000000
phi_b 30.000000
sigma_t 7000000.000000
sigma_c 120000000.000000
```

Figure 2: Input of rock parameters

2.3 Shear tests parameters

The shear test parameters are stored in another file, see Figure 3. Up to three normal stress values can be included in the GUI. But the user can simply add extra lines to the input file and choose it in the next programme run.

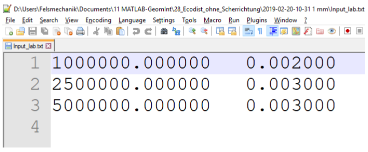


Figure 3: Input of shear test parameters. The first column are the normal stresses. The second column contains the maximum shear displacements for each normal stress value. A repeated shearing on one surface is assumed and the shear diplacement will start at the initial position for every step.

2.4 Lab test results

In case lab tests have been conducted it is possible to include them in the figures to have direct comparison to the predictions (or back calculations) by the different methods. According to the number of normal stress levels as defined in the shear test parameter file (Figure 3) this file also contains data for different normal stresses. An example can be seen in Figure 4.

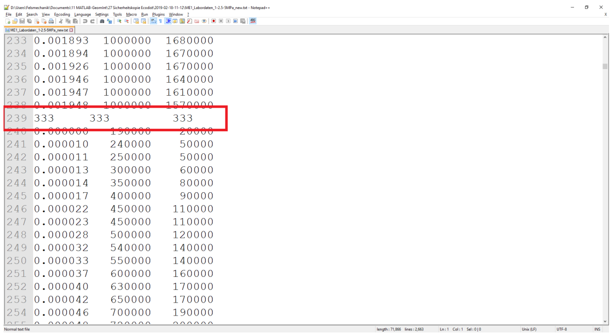


Figure 4: Lab results. The three columns are shear displacement, normal and shear stress. After completing one normal stress level the line [333 333 333] has to be added, also after the last data.

3 Description of formulas

3.1 Surface roughness

A variety of roughness parameters are calculated. For a rock surface the mean of the single profile lines is used as the resulting value.

Z_2 Is the RMS of the first derivative of a profile and its definition is based on Tse and Cruden, 1979:

$$Z_2 = \sqrt{\frac{1}{L}\sum_i \frac{(z_{i+1}-z_i)^2}{(x_{i+1}-x_i)^2}} \tag{1}$$

where L is the projected profile length and Z_2 is an averaged derivative of the profile.

JRC The joint roughness coefficient is a dimensionless parameter. In the original publication by [Barton & Bandis] the scientist had to compare a given profile to a set of profiles. This was quite qualitative and a number of attempts were made to get the JRC value in a quantitative way. The following formula by Tse and Cruden, 1979 was used:

$$JRC = 32.69 + 32.98 \cdot \log_{10}(Z_2) \tag{2}$$

3.2 Closed form solutions

Closed form solutions are easy to calculate. They can predict the peak or the residual shear strength. One prominent formula for the shear strength calculation is the one by Nicholas Barton, 1973

$$\tau_p = \sigma_n \cdot \left(\varphi_b + JRC \cdot \log_{10}\left(\frac{JCS}{\sigma_c}\right)\right) \tag{3}$$

The formula by Xia et al., 2014 uses the 2D roughness parameters definded by Grasselli, Wirth, and Egger, 2002

$$\tau_p = \sigma_n \cdot \left(\varphi_b + \frac{4A_0\Theta^*_{max}}{C+1}\left[1+\exp\left(-\frac{1}{9A_0}\cdot\frac{\Theta^*_{max}}{C+1}\cdot\frac{\sigma_n}{\sigma_t}\right)\right]\right) \tag{4}$$

3.3 Function sets

Using a set of functions allows to calculate shear stress - shear displacement curves. For the different stages of a typical shear process different formulas are used. They provide a better understanding of the process compared to the closed form solutions. Therefore they are often implemented in numerical codes where it is necessary to calculate the shear strength in every calculation step.
One example is the solution by Gui et al., 2018.
Another one is provided by Y. Li, Wu, and B. Li, 2018.
Using the concept of mobilized roughness via look-up-tables a shear curve as set of linear functions was developed by N. Barton, Bandis, and Bakhtar, 1985.

3.4 Numerical methods

Numerical methods use the surface geometry directly and not as roughness parameters. This allows an individual calculation for every rock joint. It is possible to calculate the new surface geometry after shearing took place. Visualizations can help to understand the key factors which influence the shear strength. On the other hand they need ways more data input as the surfaces have to be scanned and more computer power is needed.

One interesting approach is provided by Casagrande et al., 2017.
The apparent dip angles are used to identify the steepest regions in the shear direction. Then forces to slide over this elements are calculated

$$F_{slide} = F_{loc} \cdot \tan(\varphi + \Theta^*) \tag{5}$$

and the forces to shear off the elements

$$F_{shear} = a^2 \cdot (c + \sigma_{loc} * tan(\Phi)) \tag{6}$$

If the force to slide over an element is bigger than the force to destroy it, it will be destroyed. The geometry is adapted to reduce the apparent dip angle. The neighbour z-value will be reduced.
A new approach is based on Casagrande et al., 2017 but uses a different method to determine the active areas of the surface: Instead of using the steepest areas the normal forces are calculated and the geometry data are used to identify the areas in contact. The two surfaces (two identical copies of one) are sheared against each other. In the matrix notation this means a shift by a certain number of pixels. This allows to get shear curves instead of just getting peak shear stress values.
The normal forces are calculated as elastic forces, see Figure 5. The given sample height h of 0.15 m is a typical height of lab scale samples. h_i is the compression of the sample. In geometrical language it is the overlap, that occurs due to shear displacement. After each shear displacement step the surfaces are set to a position where the outer normal force is in balance with the force created by the overlapping surfaces.

$$F_n = \sum_i E * a^2 * \frac{\Delta h_i}{h} \tag{7}$$

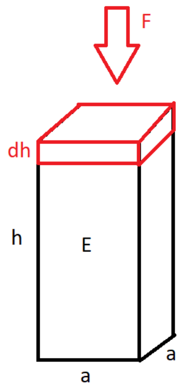


Figure 5: Normal force as a result of elastic deformation.

4 Getting started

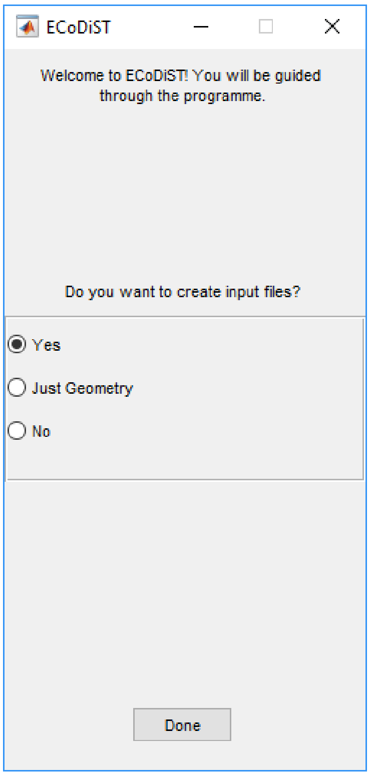
4.1 Installation

Having a valid MATLAB licence it is possible to easily call the function *Ecodist.m*. Customizing the functions to specific tasks can be done.
Without a licence the executables have to be chosen but the free Runtime library by the Mathworks company is needed. Just check the provided readme-file in the folder. This makes code development impossible.

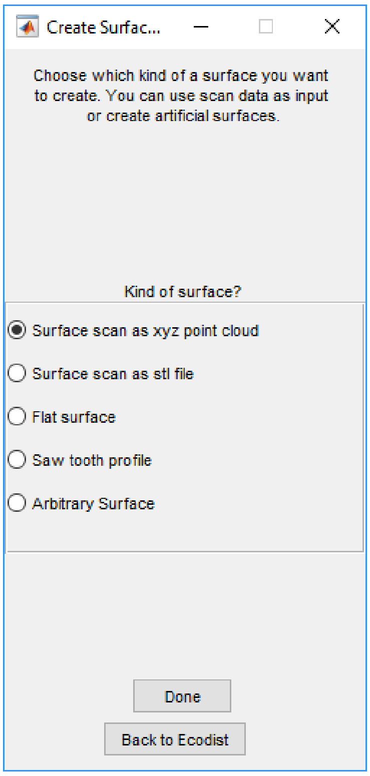
4.2 GUI

The graphical user interface guides the user through the ECoDiST software. It is made for users who wish to make some easy calculations. The programme creates ASCII files as input. Of course it is possible to directly edit this files and re-run the programme using the option not to create input files.

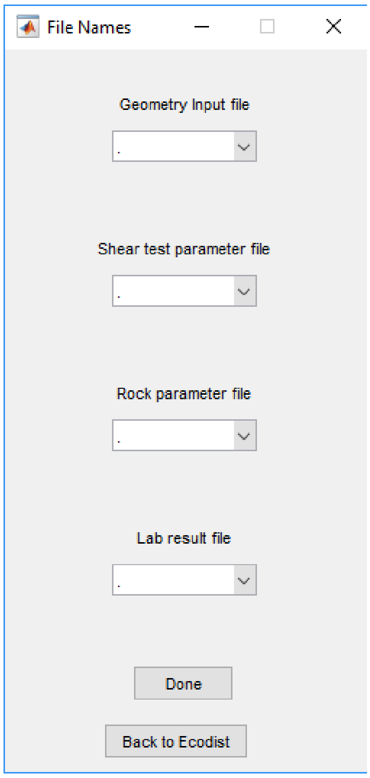
Start the ECoDiST executable, see Figure 6. If the choice is to create input files, the next step will be to choose the kind of surface creation. If no input files have to be created the files in the folder are on offer and the files have to be chosen. If just the geometry is needed, one file less has to be selected.



(a)



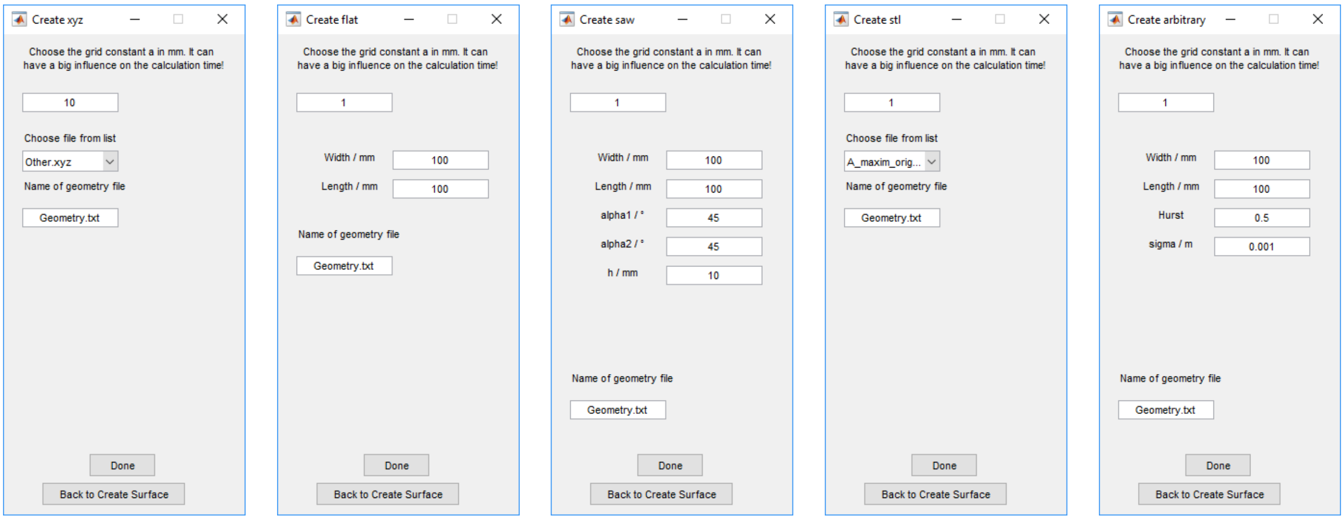
(b)



(c)

Figure 6: (a) Start of ECoDiST (b) Choose surface creation option (c) Choose input files

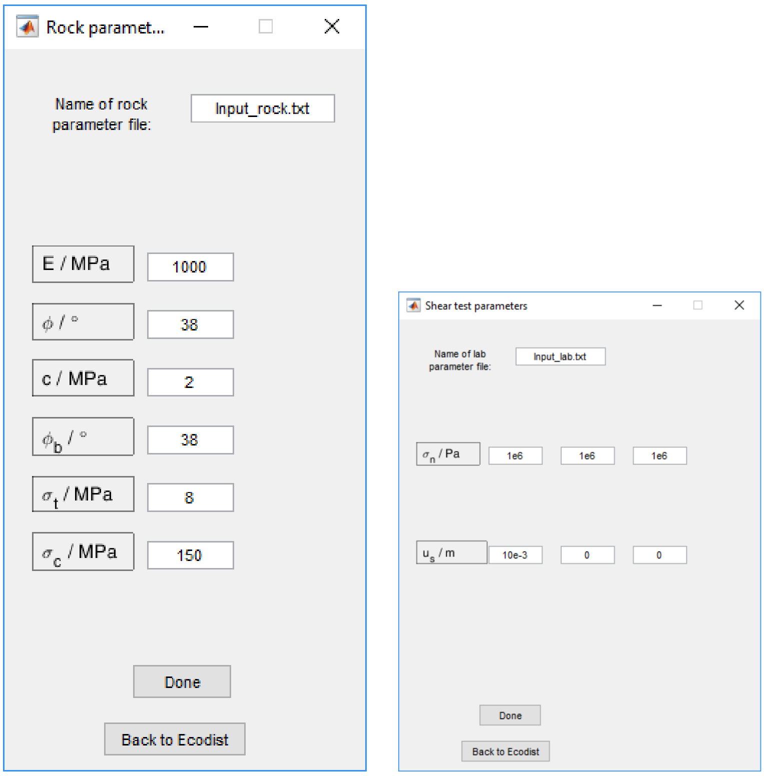
The methods to create a geometry input files can be seen in Figure 7.



(a) (b) (c) (d) (f)

Figure 7: The different methods to create a geometry file.

If the files for the rock parameters and the shear test parameters have to be created the windows seen in Figure 8 will be displayed and the values can be inserted.

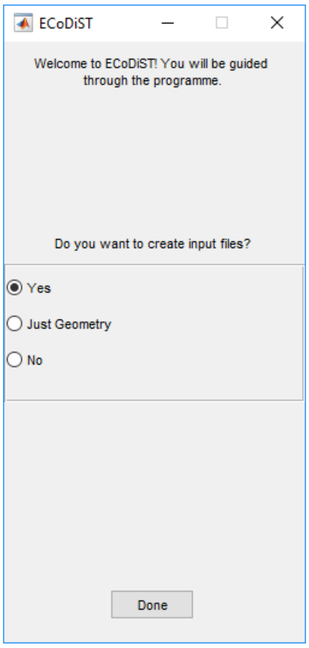


(a) (b)

Figure 8: Input of (a) rock parameters and (b) shear test parameters.

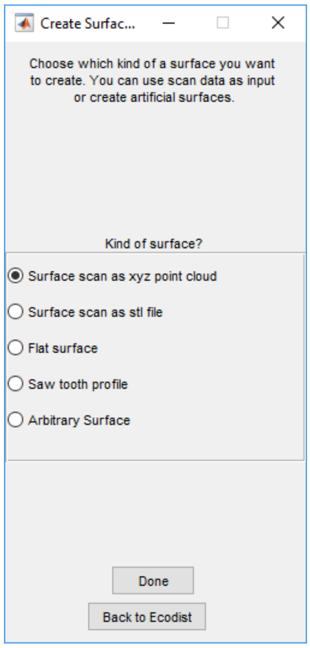
5 Example

The example is a direct shear test conducted on a granite sample. The lab data were provided as excel-sheet and point cloud (thanks to Mr Frühwirt!). The task is to do a back calculation of the data using ECoDiST . The example data can be found in /03 Example-ME1. Put the lab data file and the xyz point cloud file in your current working folder.
Run the ECoDiST programme and complete the following steps:

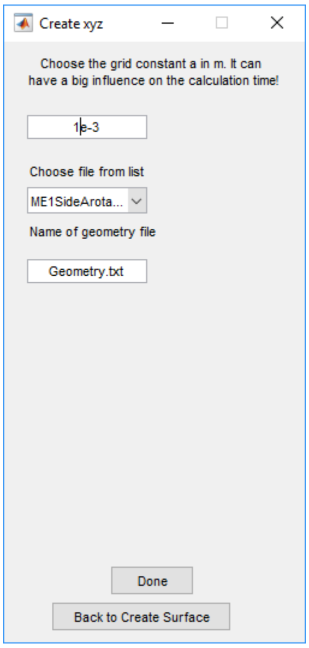


(a) Create input files.

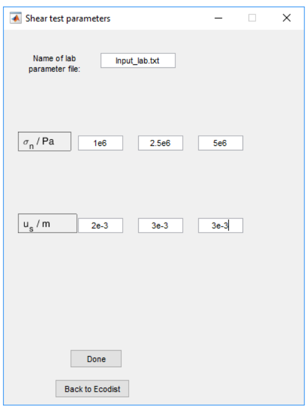
(b) Choose the lab data file.



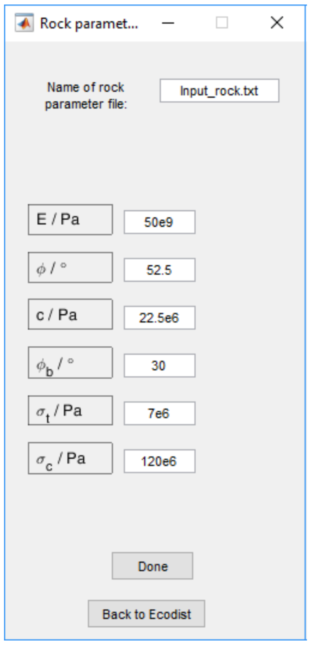
(c) Use a point cloud.



(d) Choose grid constant (1 mm will result in fast and not too bad results) and point cloud. The name of the geometry file can be defined as well.

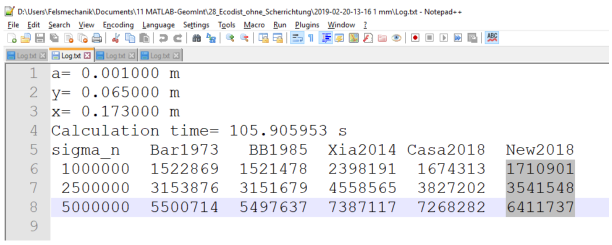


(e) Choose the shear test parameters.



(f) And the rock parameters.

After completing this steps the calculation should start. The programme will create a new folder with the current date as name. In this folder a couple of png- and text-files can be found once the calculations are finished. The created or used input files are copied to this folder. The Log-file summarizes some basic results, see Figure 9.



```
a= 0.001000 m
y= 0.065000 m
x= 0.173000 m
Calculation time= 105.905953 s
sigma_n    Bar1973    BB1985    Xia2014  Casa2018   New2018
 1000000   1522869   1521478   2398191   1674313   1710901
 2500000   3153876   3151679   4558565   3827202   3541548
 5000000   5500714   5497637   7387117   7268282   6411737
```

Figure 9: The Log-file to compare some shear laws. For a grid constant of 1 mm and a rock surface of 65 mm by 173 mm the calculation time was about 106 seconds using a standard PC.

The results are also graphical displayed, see Figure 10 and Figure 11. For different σ_n values different shear laws make the best predictions. As it can be seen in Figure 9 Barton and Barton-Bandis are basically identical. The minimal differences occur mainly due to numerical issues. The shear law of Xia over-predict the shear stresses for the higher normal stresses. In opposite it is the closest estimation for the lowest normal stress.
The Casagrande and the New shear law are very similar but especially for higher normal stresses the difference is increasing. The New law results in lower shear stresses.

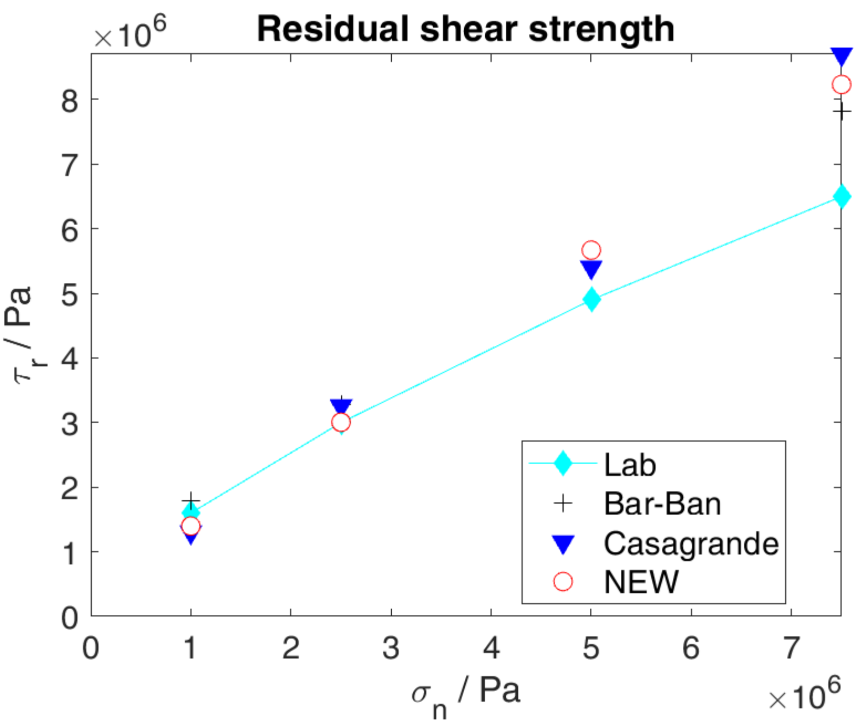


Figure 10: Comparison of residual shear strength using different shear laws.

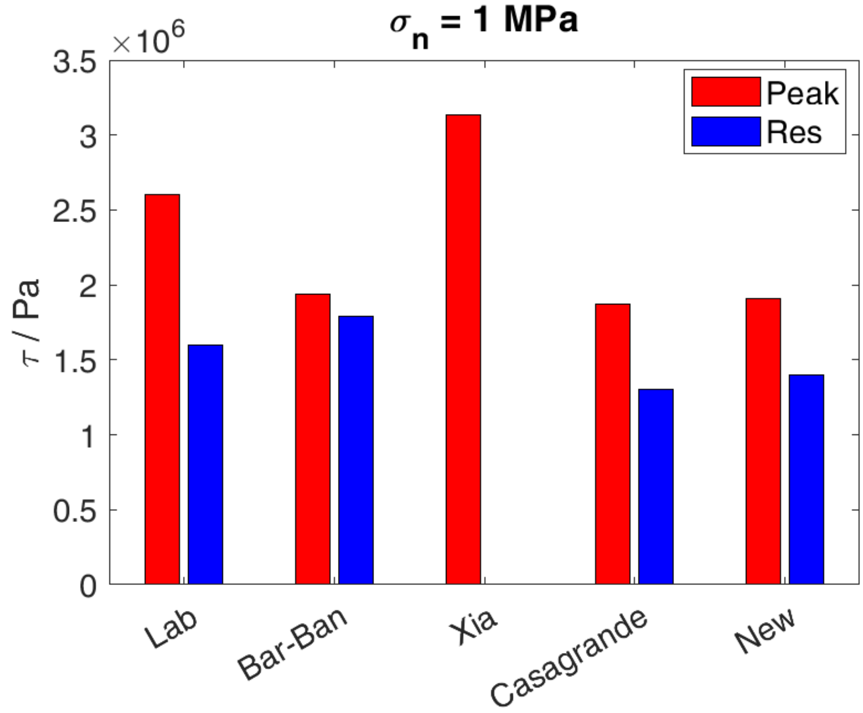


Figure 11: Comparison of peak and residual shear strength for the first step of the shear test using different shear laws.

The New shear law and the Barton-Bandis model allow to calculate complete shear curves. So for this models a comparison with the lab results is possible and displayed in Figure 12. The New model is limited to shear displacement increments of one pixel which is the grid constant.

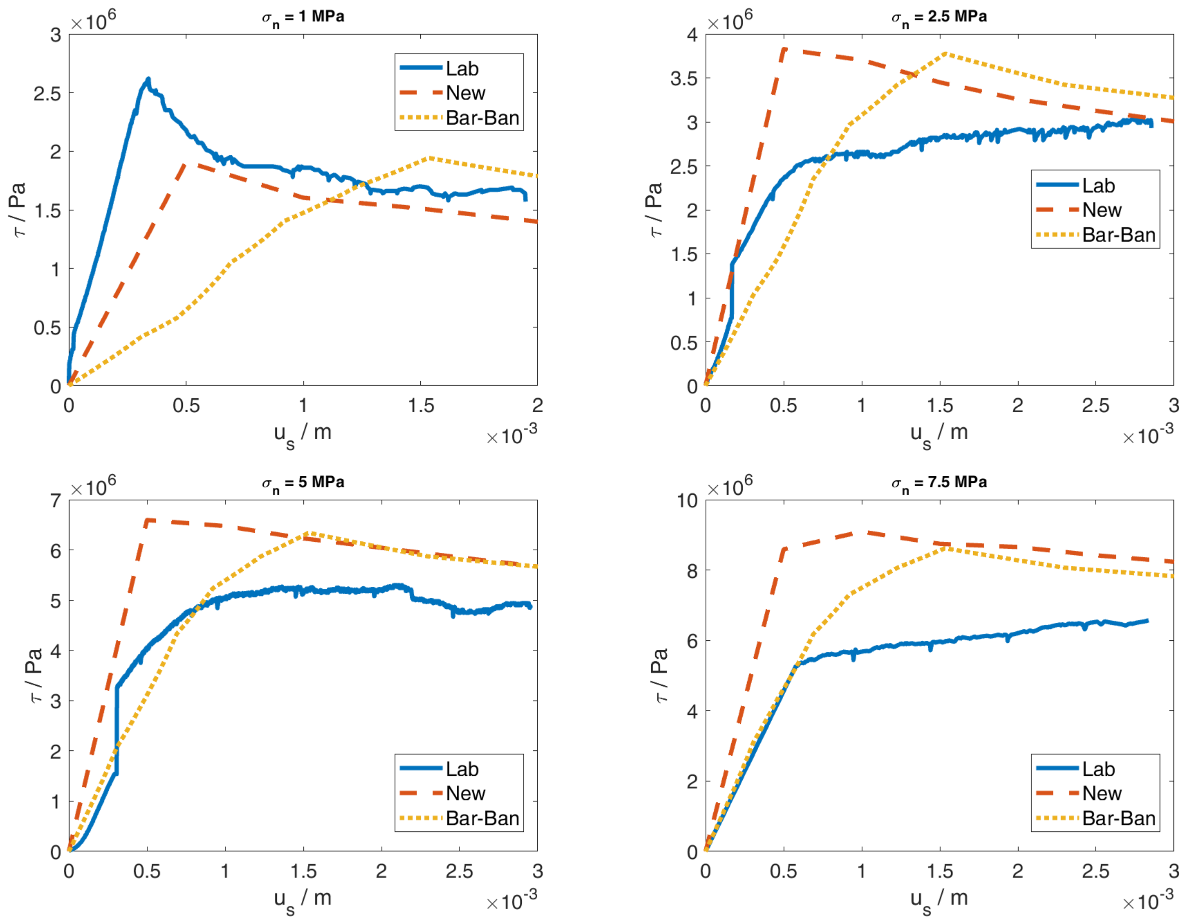


Figure 12: Comparison of lab results with Barton-Bandis and New shear law for $\sigma_n = 1, 2.5, 5, 7.5\,\mathrm{MPa}$ using a grid constant of $a = 0.5\,\mathrm{mm}$.

In the pdf file in the example folder the output of the programme can be found and compared with the own output.

6 Limits, problems and further developments

6.1 Quadratic grid

The quadratic grid allows the fast calculations. On the other hand is has some drawbacks. First it is always a further simplification of the geometry since the scanner output is usually not a perfect quadratic grid. Another problem are steep regions of the surface which play a major role in the shear stress modelling. The grid is easily spoken a projection on the xy-plane. So a vertical part of the surface will be reduced to a big height difference between neighbouring grid elements.
The grid constant is very important for the calculation of the roughness and so for the shear stresses. Choosing a small grid constant is a good approach to capture also details of the geometry. On the other hand if the grid constant is chosen too small the resulting geometry may contain more grid points than the original point cloud contained. This suggests a resolution which is not plausible due to the lack of data. A strategy where the grid constant results in similar grid points as input points is recommended. It is also recommended to choose a quite big grid constant for the first programme calls, because calculation time increases with the decrease of grid constant.
An example for the different results by just modifying the grid constant can be seen in Figure 13. It can be seen, that an increasing grid constant causes an decreasing shear stress. This is plausible because an increase in grid constant results in a decrease of details and a smoother surface is the basis of the calculation.

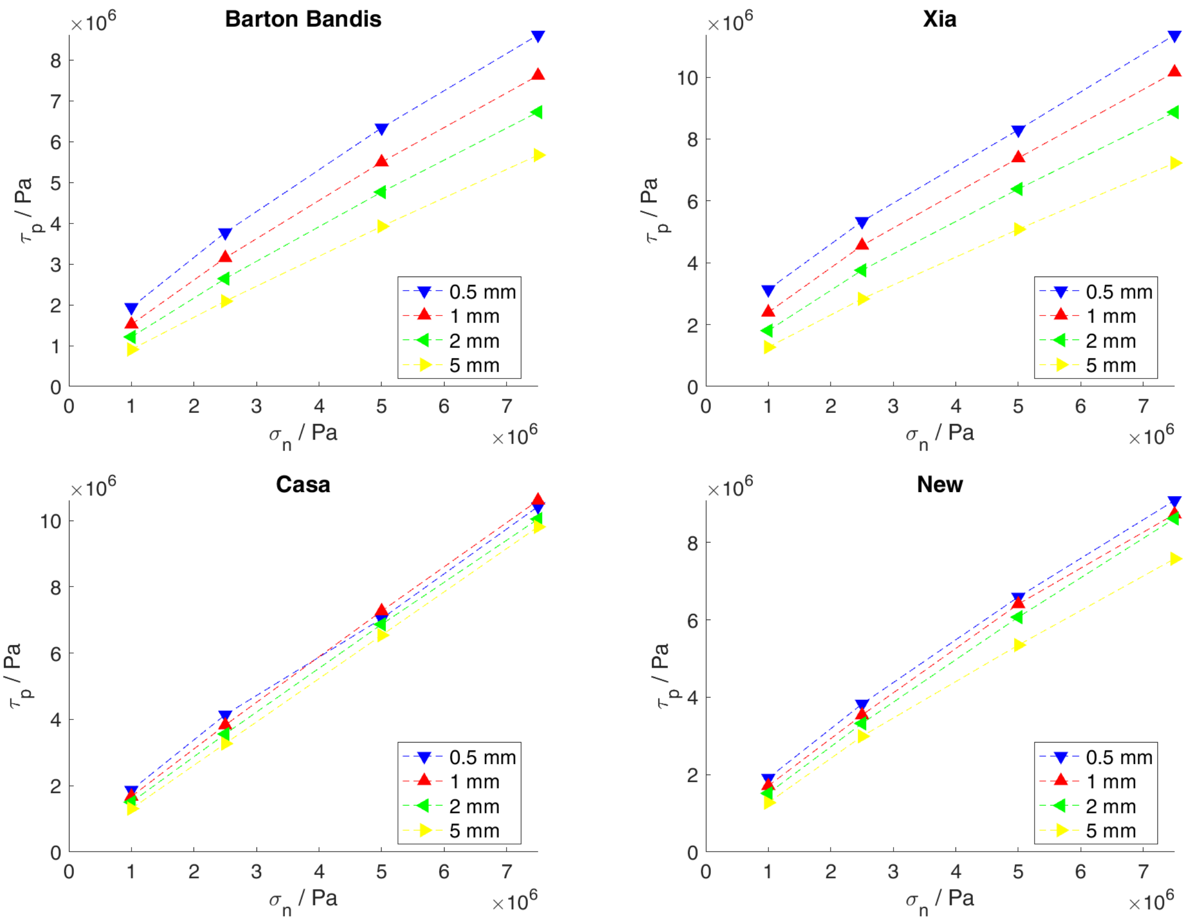


Figure 13: Influence of grid constant on the shear stress calculations.

The influence of the grid constant is more pronounced for the shear laws by N. Barton, Bandis, and Bakhtar, 1985 and Xia et al., 2014 than for the New law and the algorithm by Casagrande et al., 2017.

The reason for this behaviour is that the closed form solutions are dominated by the roughness which is strongly determined by the resolution of the surface. On the other hand the algorithms destruct the surface. The very steep surface parts will be flattened. So the loss by using a bigger grid constant is not too big.
Nevertheless the influence of the grid constant is big. It is necessary to find a good compromise between calculation time and quality of the results. In the given example lab data were available. If no lab data are available in advance and it is really necessary to make a prediction a strategy is needed. The recommendation is to use a small grid constant, as long if the calculation time is not increasing too much and the number of grid points is not bigger than the number of input points. In the example case the smallest grid constant would be a good choice. The calculation time is about 30 minutes.

6.2 Next steps

To add hydraulics and the possibility to simulate constant normal stiffness (CNS) tests, it is necessary to calculate normal displacements first.
By now, the code uses one surface and in case of the New model a copy of this surface. It might be more sophisticated to use the two sides of a rock surface scan which are slightly different.

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