Effect of sieving height on density and mechanical properties of a brittle analogue material: Ring-shear test data of quartz sand used for analogue experiments in the Tectonic Modelling Lab of the University of Bern (CH) (http://doi.org/10.5880/fidgeo.2020.006)

Timothy Schmid[1], Guido Schreurs[1], Michael Warsitzka[2], Matthias Rosenau[2]

1. Institute of Geological Sciences, University of Bern, Switzerland
2. GFZ German Research Centre for Geosciences, Potsdam, Germany

1. Licence

2. Citation

When using the data set please cite:

Schmid, T., Schreurs, G., Warsitzka, M. & Rosenau, M. (2019a). Effect of sieving height on density and mechanical properties of a brittle analogue material: Ring-shear test data of quartz sand used for analogue experiments in the Tectonic Modelling Lab of the University of Bern (CH). GFZ Data Services, http://doi.org/10.5880/fidgeo.2020.006 -

Table of contents

3. Data Description

This dataset provides densities and mechanical properties of a quartz sand (“A”) based on ring-shear tests (RST). The quartz sand is used in various types of analogue experiments in the Tectonic Modelling Lab of the University of Bern as an analogue for brittle layers in the crust or mantle lithosphere. The material is characterized by means of internal friction coefficient μ and cohesion C. Three sub-datasets document the influence of sieving height on the mechanical properties from 10 cm to 20 cm to 30 cm into a shear cell of type No. 1, following the same protocol. This dataset shows that packing density of quartz sand is dependent on the chosen sieving height and increases with increasing sieving height. However, the effect of the sieving height on internal friction coefficient μ, as well as cohesion C is minor and thus negligible in sandbox experiments.

According to our analysis the material shows for a sieving height of 10 cm a Mohr-Coulomb behaviour characterized by a linear failure envelope and peak, dynamic and reactivation friction coefficients of $\mu_P = 0.70$, $\mu_D = 0.60$ and $\mu_R = 0.65$, respectively. Cohesions C are in the order of 40 – 80 Pa.

For a sieving height of 20 cm, the material shows a Mohr-Coulomb behaviour characterized by a linear failure envelope and peak, dynamic and reactivation friction coefficients of $\mu_P = 0.72$, $\mu_D = 0.61$ and $\mu_R = 0.65$, respectively. Cohesions C are in the order of 50 – 80 Pa.

Data from a sieving height of 30 cm shows a Mohr-Coulomb behaviour characterized by a linear failure envelope and a peak, dynamic and reactivation friction coefficients of $\mu_P = 0.72$, $\mu_D = 0.61$ and $\mu_R = 0.65$, respectively. Cohesions C are in the order of 48 – 90 Pa.

The material’s mechanical properties only show a minor dependency on the sieving height.

3.1. Materials tested

The tested material is an angular to poorly rounded, well-sorted quartz sand with a low sphericity (Zwaan et al., 2016; Table 1). It is sold under the name “Quarzsand A” by the company Carlo Bernasconi AG (http://www.carloag.ch/). The batch from which this sample stems has been purchased in the year 2019. The delivered sand has a grain size distribution between 0.06 and 0.25 mm and a mean grain size of 0.125 mm (Table 1). A more detailed grain size analysis of the tested quartz sand can be found in Zwaan et al. (2018). The bulk density of the sieved material increases from ca. 1510 kg m^{-3} to 1570 kg m^{-3} with increasing sieving height, from 10 to 30 cm.

3.2. Measurement procedures

The data presented here are derived from a SCHULZE RST-01.pc (Schulze, 1994, 2003, 2008) ring shear tester (RST) at the Helmholtz Laboratory for Tectonic Modelling (HelTec) of the GFZ German Research Centre for Geosciences in Potsdam. The RST is specially designed to measure friction coefficients μ and cohesions C in loose granular material accurately at low confining pressures and shear velocities similar to sandbox experiments. In this tester, a sand layer is sheared internally at constant normal stress σ_N and shear velocity v while shear force and lid displacement (corresponds to volume change ΔV) are measured continuously. For more details see Klinkmüller et al. (2016) and Ritter et al. (2016).

3.2.1. Sample preparation and test conditions:

Each sample is carefully prepared by the same person and measured consistently following the same protocol. The measurements presented here correspond to internal friction, i.e. shearing inside the material. Preparation includes sieving from 10 cm, 20 cm and 30 cm height into a shear cell of type No. 1. Normal force, shear force, shear velocity and lid displacement are measured at 100 Hz and then down sampled to 10 Hz. Laboratory conditions are air conditioned during all the measurements (temperature: 23°C, humidity: 45%).

Table 1: Sample overview *(GFZ = German Research Centre for Geosciences in Potsdam, UB = University of Bern). The dataset (GFZ-ID 443) consists of three subsets for each corresponding sieving height (GFZ-ID 443-01, 443-02 and 443-03).*

GFZ-ID	UB-ID	Material	Sieve-ID	Sieving rate [g min^{-1} cm^{-2}]	File name
443-01	quartzsand_10	Quartz sand	GeoMod	29	443-01_UB_Bernsand_10cm_...
443-02	quartzsand_20	Quartz sand	GeoMod	29	443-02_UB_Bernsand_20cm_...
443-03	quartzsand_30	Quartz sand	GeoMod	29	443-03_UB_Bernsand_30cm_...

3.2.2. RST (Ring-shear test) procedure:

In a RST a shear velocity of v = 3 mm min^{-1} is imposed. 10 measurements are done at normal stresses of σ_N = 250, 500, 1000, 1500, and 2000 Pa (2 repetitions per stress level). During the measurement the material is sheared for initially 5 minutes. During this period the shear stress τ reaches a peak (= peak friction) and then drops to a plateau indicating shear has localized into a shear zone (= dynamic friction). The sample is then unloaded by shortly reversing rotation and immediately re-sheared for 5 minutes during which shear stress τ reaches a second peak (= reactivation friction) simulating reactivation of an existing shear zone (Figure 1).

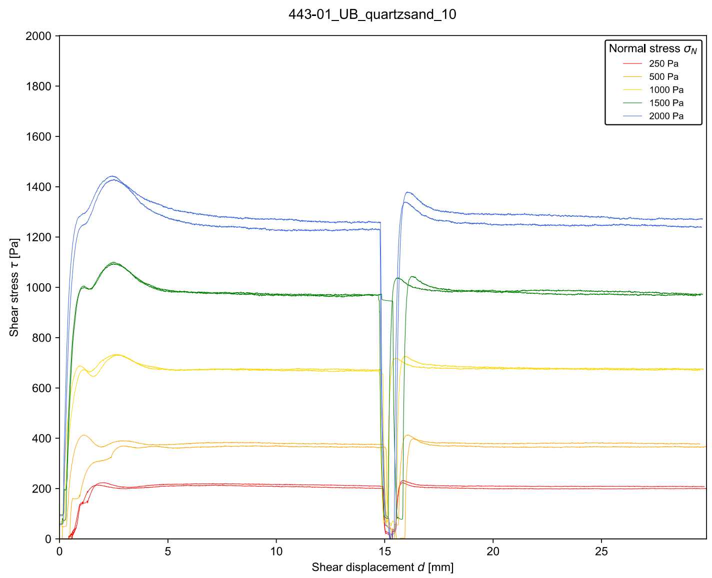

Figure 1: Shear curve plot (443-01). *Y-axis is shear stress τ, x-axis is shear displacement d. Each data set consists of 10 shear curves corresponding to 5 levels of normal stress σ_N with 2 repetitions for each stress level (UB = University of Bern).*

3.3. Analysis method

3.3.1. RST analysis: Friction coefficients and cohesion

From the resulting shear stress curves (see e.g. Figure 1) three characteristic values (strengths) have been picked manually:

(1) The shear strength τ^* at ***peak friction*** corresponding to the first peak in the shear curve reflecting hardening-weakening during strain localization
(2) the shear strength τ^* at ***dynamic friction*** corresponding to the plateau after localization and representing friction during sliding
(3) the shear strength τ^* at ***reactivation friction*** corresponding to the second peak and representing static friction during reactivation of the shear zone.

We performed regression analysis of these friction data by means of linear regression in two ways:

(1) A linear regression through all data pairs of shear strength τ^* and normal stress σ_N. The slope of the linear regression corresponds to the friction coefficient μ and the y-axis intercept to the cohesion C (see e.g. Figure 2). This method assumes that the material behaves strictly as a Mohr-Coulomb material, i.e. has a linear failure envelope.

(2) Calculating all possible two-point slopes (friction coefficient μ) and y-axis intercepts (cohesion C) for mutually combined data pairs of shear strength τ^* and normal stress σ_N. These data (i.e. all individual μ and C) are then evaluated by means of univariate statistics by calculating mean and standard deviation and comparing the probability density function (pdf) to that of a normal distribution (see e.g. Figure 3). This method overcomes the limitation of the analysis to Mohr-Coulomb material and allows for non-linear failure envelopes (Santimano et al., 2015).

In case values for μ and C as derived from the two methods are identical (within standard deviation), the material is properly characterized by a straight Mohr-Coulomb failure envelope.

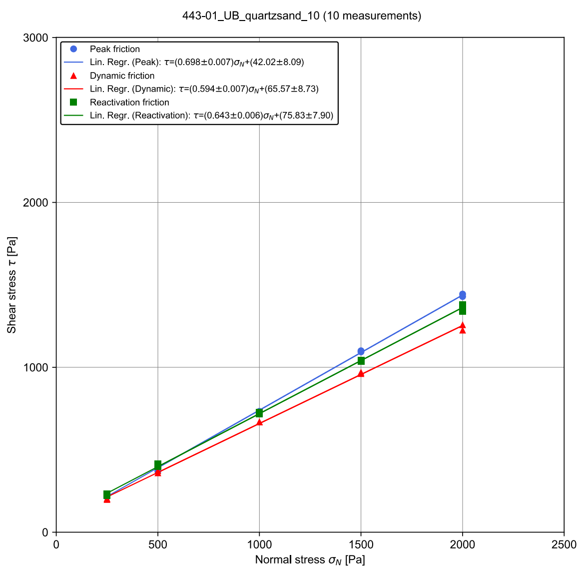

Figure 2: Friction plot (443-01). *Plot of all data pairs in the Mohr space (normal stress σ_N vs. shear stress τ) including curves of the corresponding linear least-squares regression (UB =University of Bern).*

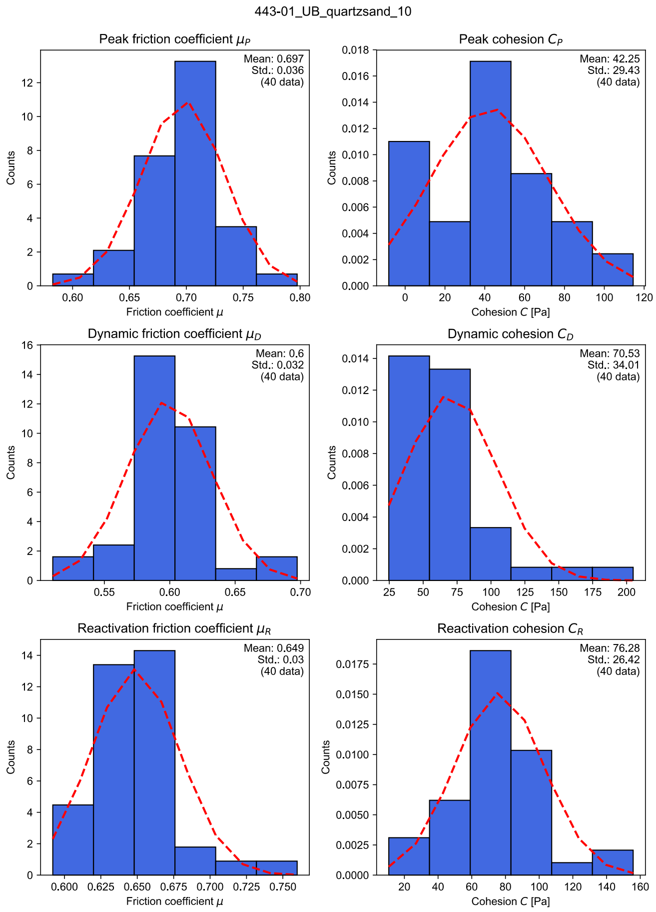

Figure 3: Histogram plots (443-01). *Histograms of mutual two-point regression results for slope (friction coefficient µ) and y-axis intercept (cohesion C). Red curves are synthetic normal distributions with the same mean and standard deviation (std.) as the data set for comparison (UB = University of Bern).*

3.3.2. Python-based analysis and visualization

Python scripts are provided along with this data set allowing analysis and visualization of the data. Python is an open-source, interpreted programming language. A complete Python-distribution is, for instance, provided by the "Anaconda"-platform, which can be downloaded from: https://www.anaconda.com/download/.

For conducting the RST analysis, the "RSTanalysis_2Repetitions.py"- file has to be opened and executed, respectively, in the "Spyder"-editor (Note: make sure that folders "Data files" and "Script" are stored in the same directory.)

3.3.3. Matlab-based analysis and visualization

A Matlab script is provided along with this data set allowing analysis and visualization of the correlation between density variations due to varying sieving height and its effect on friction coefficients and cohesion values.

For conducting the correlation analysis, the "correlation_3_heights.m" – file has to be opened and executed in Matlab (Note: Default directory is set to Mac computer indicated by "1" in line 33. For Windows computer it must be set to 0). Folders "Data files" and "Script" must be stored in the same directory) . Required µ and C values are obtained from the pdf files "File name_hist.pdf"

4. File description

For the RST measurement, there exist the following files in the folder “Data files”:

(i) RST shear curve data (“File name_ts.txt”; example Table 2)
(ii) RST shear curve plot (“Filename_ts.pdf”; example Figure 1)
(iii) RST friction data (“File name_peak.txt”, “File name_dynamic.txt”, “File name_reactivation.txt”; example Table 3)
(iv) RST friction plot (“File name_linregr.pdf”; example Figure 2)
(v) RST histogram of friction data (“File name_hist.pdf”; example Figure 3)
(vi) RST correlation data (“File name_cor.txt”; example Table 4)
(vii) RST correlation plot (“File name_cor.png”; example Figure 4)

Furthermore, the Python-script “RSTanalysis_2Repetitions.py” as well as the Matlab-script “RSTcor_3_heights.m” can be found in the folder “Scripts”. An overview of all files of the data set is given in the **List of Files.**

4.1. RST shear curve data

Shear curve data are given as (i) time series (ts) data in .txt-format (“File name_ts.txt”, Table 2) and visualized as (ii) shear stress τ versus shear displacement d plots (“Filename_ts.pdf”) (e.g. Figure 1).

Table 2: Shear curve time series data (443-01). *First line is header. First column is time (in s). Columns 2-11 are shear forces (in N) for corresponding normal stresses as specified in the header of the respective columns (5 stress levels from 250 to 2000 Pa, two repetitions each stress level).*

Time [s]	Normal stress [Pa]: 250	500	1000	…
0.0	-0.030682	-0.014321	0.947399	…
0.1	…	…	…	…
…	…	…	…	…

4.2. RST friction data

Friction data are given as (iii) data pairs (normal stress σ_N and shear strength τ^*; Table 3) for peak, dynamic and reactivation friction in txt format (“File name_peak.txt”, “File name_dynamic.txt”, “File name_reactivation.txt”). They are visualized by (iv) plotting into Mohr Space (normal stress σ_N vs. shear stress τ) including a linear regression (File name_linregr.pdf”; e.g. Figure 2). The results of the regression analysis (see 2.3) are plotted in (v) histograms for friction coefficients μ and cohesions C (“File name_hist.pdf”; e.g. Figure 3).

Table 3: Friction data (443-01, peak). *First line is header. First column is normal stress σ_N (in Pa). Second column is shear strength τ^*(in Pa).*

Normal stress [Pa]	Shear strength [Pa]
250.0	223.95
500.0	413.33
…	…

4.3. Correlation data

Correlation data are given as (vi) friction coefficient μ, cohesion C and density values with correlating standard deviation in dependency of sieving heights (Table 4) in txt format ("File name_cor"). They are analyzed individually and visualized in (vii) subplots of a summary plot ("File name_cor.png"; Figure 4).

Table 4: Correlation data (443). *First line is header. First column is sieving height (in cm). Columns 2-18 are friction coefficients, densities (g/cm^3) and cohesion (Pa) and the corresponding standard deviation in the column to the right as specified in the header of the respective columns Friction coefficients, cohesion and corresponding standard deviations are derived from the file "File name_hist.pdf". Density values and corresponding standard deviations are derived from RST excel file "File name.xls"*

Sieving height	μ peak	std	densities	std	…
10 cm	0.679	0.036	1.512	0.013	…
20 cm	…	…	…	…	…
…	…	…	…	…	…

5. Results

5.1. Overview of friction parameters

Our analysis reveals that the tested material behaves as a Mohr-Coulomb material characterized by a linear failure envelope. Further, the variation of friction coefficients as well as cohesion values due to increasing sieving height is negligible. Values of friction coefficients and cohesions are listed in Table 5. Peak, dynamic and reactivation friction coefficients are μ_P = 0.70, μ_D = 0.60 and μ_R = 0.65 (10 cm sieving height), μ_P = 0.72, μ_D = 0.61 and μ_R = 0.65 (20 cm sieving height) and μ_P = 0.72, μ_D = 0.61 and μ_R = 0.65 (30 cm sieving height), respectively. Cohesions *C* are in the order of 40 – 80 Pa (10 cm sieving height), 50 – 80 Pa (20 cm sieving height) and 48 – 90 Pa (30 cm sieving height), respectively.

Table 5: Summary of RST data.

Sieving height	Parameter	Symbol	Unit	Linear least-squares regression method		Mutual two-point regression method	
				Value	Standard deviation	Value	Standard deviation
10 cm sieving height	Coefficient of peak friction	μ_P	-	0.698	0.007	0.697	0.036
	Peak cohesion	C_P	Pa	42.02	8.09	42.25	29.43
	Coefficient of dynamic friction	μ_D	-	0.594	0.007	0.6	0.032
	Dynamic cohesion	C_D	Pa	65.57	8.73	70.53	34.01
	Coefficient of reactivation friction	μ_R	-	0.643	0.006	0.649	0.03
	Reactivation cohesion	C_R	Pa	75.83	7.90	76.28	26.42
20 cm sieving height	Parameter	Symbol	Unit	Linear least-squares regression method		Mutual two-point regression method	
				Value	Standard deviation	Value	Standard deviation
	Coefficient of peak friction	μ_P	-	0.708	0.006	0.715	0.036
	Peak cohesion	C_P	Pa	52.82	7.46	49.0	30.89
	Coefficient of dynamic friction	μ_D	-	0.598	0.005	0.607	0.036
	Dynamic cohesion	C_D	Pa	63.57	6.48	64.47	22.23
	Coefficient of reactivation friction	μ_R	-	0.641	0.004	0.647	0.029
	Reactivation cohesion	C_R	Pa	78.75	4.97	78.5	17.32
30 cm sieving height	Parameter	Symbol	Unit	Linear least-squares regression method		Mutual two-point regression method	
				Value	Standard deviation	Value	Standard deviation
	Coefficient of peak friction	μ_P	-	0.714	0.005	0.718	0.026
	Peak cohesion	C_P	Pa	47.33	6.63	47.99	25.67
	Coefficient of dynamic friction	μ_D	-	0.599	0.009	0.613	0.059
	Dynamic cohesion	C_D	Pa	62.33	10.87	65.66	38.95
	Coefficient of reactivation friction	μ_R	-	0.636	0.009	0.647	0.049
	Reactivation cohesion	C_R	Pa	84.91	10.63	88.44	38.17

5.2. Effect of sieving height on density, friction coefficient and cohesion

To ensure a proper vertical density gradient in analogue sandbox experiments, a potential way is to control bulk density in different brittle layers by varying the sieving height. The influence of various sieving heights (i.e. 10 cm, 20 cm and 30 cm) on density, friction coefficient and cohesion is systematically analysed and quantified.

For each friction coefficient μ and cohesion value C the variation caused by changing the sieving height is within the range of the standard deviation and is negligible (figure 4). Maximum variations of friction coefficients μ_P, μ_D and μ_R are 0.039, 0.013 and 0.002, respectively. For cohesion maximum variations for C_P, C_D and C_R are in the range of 6.75 Pa, 6.06 Pa and 12.16 Pa, respectively.

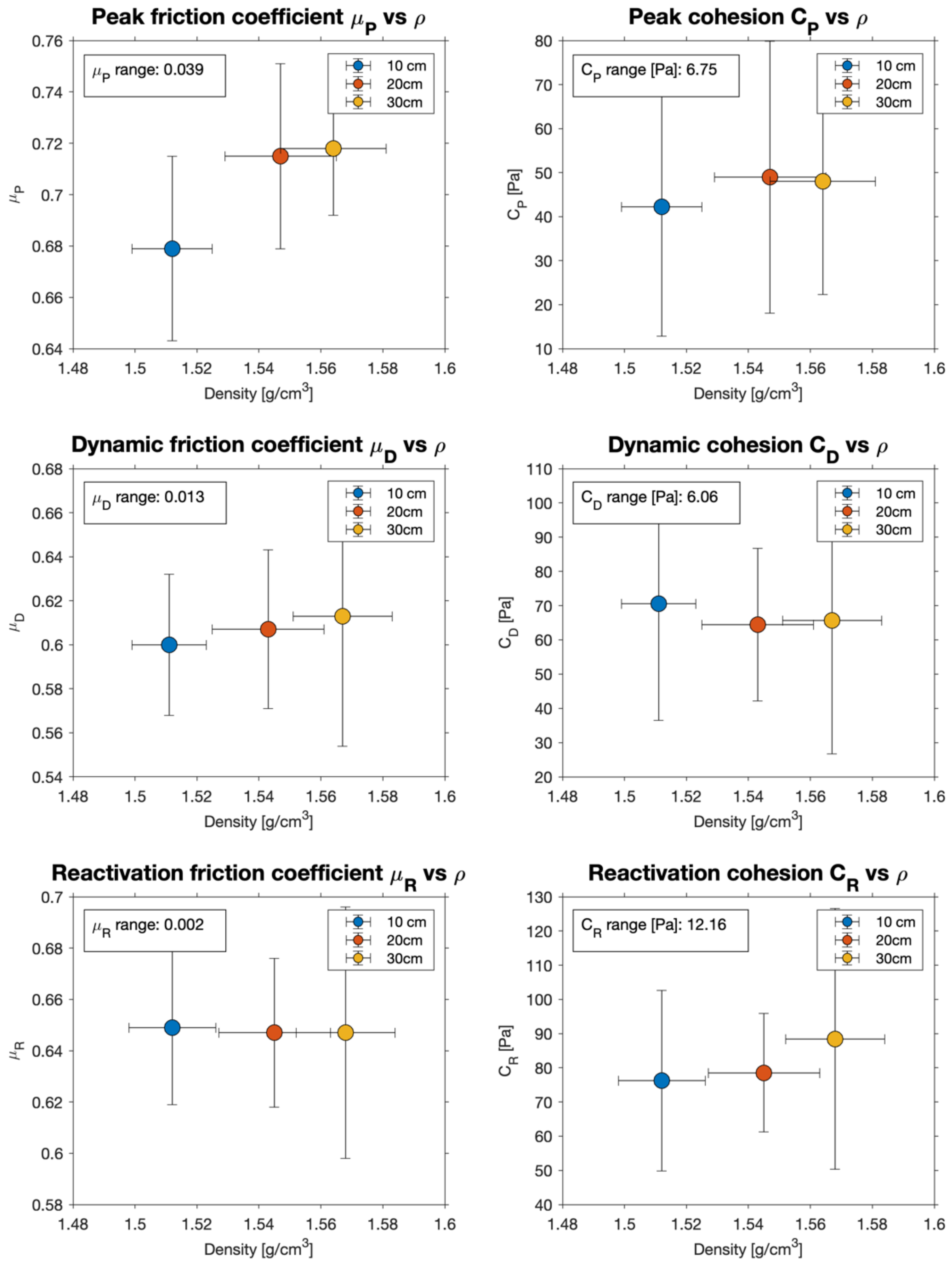

Figure 4: Correlation plots (443). *Peak-, dynamic- and static friction coefficients are plotted against corresponding density values (left). Peak-, dynamic- and static cohesion values are plotted against corresponding density values (right). Vertical error bars indicate standard deviation of friction coefficient and cohesion values, horizontal error bars indicate standard deviation of density values.*

6. References

Klinkmüller, M., Schreurs, G., Rosenau, M. & Kemnitz, H. (2016). Properties of granular analogue materials: A community wide survey, *Tectonophysics,* 684, 23-38, http://doi.org/10.1016/j.tecto.2016.01.017

Ritter, M. C., Leever, K., Rosenau, M. & Oncken, O. (2016). Scaling the sandbox—Mechanical (dis) similarities of granular materials and brittle rock. *Journal of Geophysical Research: Solid Earth*, *121*(9), 6863-6879, http://doi.org/10.1002/2016JB012915

Santimano, T., Rosenau, M., & Oncken, O. (2015). Intrinsic versus extrinsic variability of analogue sand-box experiments – Insights from statistical analysis of repeated accretionary sand wedge experiments. *Journal of Structural Geology*, 75, 80–100. http://doi.org/10.1016/j.jsg.2015.03.008

Schulze, D. (1994). Entwicklung und Anwendung eines neuartigen Ringschergerätes. *Aufbereitungstechnik*, 35 (10), 524-535

Schulze, D. (2003). Time-and Velocity-Dependent Properties of Powders Effecting Slip-Stick Oscillations. *Chemical Engineering & Technology,* 26(10), 1047-1051, http://doi.org/10.1002/ceat.200303112

Schulze, D. (2008). Powders and Bulk Solids - Behavior, Characterization, Storage and Flow, Springer Berlin Heidelberg New York, ISBN 978-3-540-73767-4, 511 pp., URL: https://www.springer.com/de/book/9783540737674

Zwaan, F., Schreurs, G., Naliboff, J. B., & Buiter, S. J. H. (2016). Insights into the effects of oblique extension on continental rift interaction from 3D analogue and numerical models. Tectonophysics, 693, 239-260. URL https://doi.org/10.1016/j.tecto.2016.02.036

Zwaan, F, Schreurs, G., Gentzmann, R., Warsitzka, M. & Rosenau, M. (2018).Ring-shear test data of quartz sand from the Tectonic Modelling Lab of the University of Bern (CH).GFZ Data Services, URL: https://doi.org/10.5880/fidgeo.2018.028