Ring-Shear and Slide-Hold-Slide Test Measurements for Soda-Lime Glassbeads of 300-400µm diameter used at the Helmholtz Laboratory for Tectonic Modelling - HelTec, GFZ Potsdam, Germany https://doi.org/10.5880/GFZ.4.1.2021.002

Michael Rudolf[1]*, Matthias Rosenau[1], Onno Oncken[1]

1. *Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Potsdam, Germany*

* *Corresponding author: michael.rudolf@gfz-potsdam.de*

1. Licence

2. Citation

When using the data please cite:

Rudolf, Michael; Rosenau, Matthias; Oncken, Onno; (2021): Ring-Shear and Slide-Hold-Slide Test Measurements for Soda-Lime Glassbeads of 300-400µm diameter used at the Helmholtz Laboratory for Tectonic Modelling, Potsdam, Germany. GFZ Data Services. https://doi.org/10.5880/GFZ.4.1.2021.002.

The data are supplementary material to:

Rudolf, M., Rosenau, M., & Oncken, O. (2021). The spectrum of slip behaviours of a granular fault gouge analogue governed by rate and state friction. Geochemistry, Geophysics, Geosystems. https://doi.org/10.1029/2021gc009825

Table of contents

1. Licence 1
2. Citation 1
Table of contents 1
3. Data Description 2
3.1. Machine Setup 2
3.1.1. Sample Preparation and Recording 3
3.1.2. Main Series Procedure 3
3.1.3. SHS Series Procedure 3
3.2. Data Analysis 3
3.2.1. Main Series Analysis 4
3.2.2. SHS Series Analysis 5
4. File Description 6
4.1. Data Files 6
4.2. Processing Parameters 7
4.3. Intermediate Results 7
5. References 8

3. Data Description

This data set provides two series of experiments from ring-shear tests (RST) on glass beads that are in use at the Helmholtz Laboratory for Tectonic Modelling (HelTec) at the GFZ German Research Centre for Geosciences in Potsdam. The main experimental series contains shear experiments to analyse the slip behaviour of the granular material under analogue experiment conditions. Additionally, a series of slide-hold-slide (SHS) tests was used to determine the rate and state friction properties. A basic characterisation and average friction coefficients of the glass beads are found in Pohlenz et al. (2020).

The glass beads show a slip behaviour that is depending on loading rate, normal stress and apparatus stiffness which were varied systematically for this study. The apparatus was modified with springs resulting in 4 different stiffnesses. For each stiffness a set of 4 experiments with different normal stresses (5, 10, 15 and 20 kPa) were performed. During each experiment loading rate was decreased from 0.02 to 0.0008 mm/s resulting in 9 subsets of constant velocity for each experiment. We observe a large variety of slip modes that ranges from pure stick-slip to steady state creep. The main characteristics of these slip modes are the slip velocity and the ratio of slip event duration compared to no slip phases. We find that high loading rates promote stable slip, while low loading rates lead to stick-slip cycles. Lowering the normal stress leads to a larger amount of creep which changes the overall shape of a stick-slip curve and extends the time between slip events. Changing stiffness leads to an overall change in slip behaviour switching from simple stick-slip to more complex patterns of slip modes including oscillations and bimodal slip events with large and small events.

The SHS tests were done at maximum stiffness and higher loading rates (>0.05 mm/s) but at the same normal stress intervals as the main series. Using various techniques, we estimate the rate-and-state constitutive parameters. The peak stress after a certain amount of holding increases with a healing rate of b=0.0057±0.0005. From the increase in peak stress compared to the loading rate in slide-hold-slide tests we compute a direct effect a=-0.0076±0.0005 which leads to (a-b)=-0.0130±0.0006. Using a specific subset of the SHS tests, which have an equal ratio of hold time to reloading rate, we estimate (a-b)=-0.0087±0.0029. Both approaches show that the material is velocity weakening with a reduction in friction of ca. 1 % (0.87%-1.3%) per e-fold increase in loading rate. Additionally, the critical slip distance D_c is estimated to be in the range of 200 µm. With these parameters the theoretical critical stiffness k_c is estimated and applied to the slip modes found in the main series. We find that the changes in slip mode are in good agreement with the estimated critical stiffness and thus confirm the findings from the SHS tests.

3.1. Machine Setup

The machine used to generate the data is a SCHULZE RST-01.pc (Schulze, 1994, 2003, 2008) which is based at HelTec - GFZ Potsdam. It is an annular shear cell apparatus designed to measure shear stresses within loose granular (bulk) materials at confining stresses from 0.1 to 20kPa and loading rates ranging from 10^{-4} to 10^{0}mm/s. The material is filled into a shear cell (cell ID: Scherzelle 1) with high bottom friction and sheared at constant normal stress and loading rate while shear stress and lid displacement are measured at the lid with a high friction interface which is placed on top of the cell. More details on the working principle are found in Klinkmüller et al. (2016) and Ritter et al. (2016). In addition to the standard change in loading rate and normal stress we also modified the apparatus stiffness for this study. The overall machine stiffness is 1354 kN/mm which is measured without bulk material inside and mainly defined by the stiffness of the force transducers. This stiffness is lowered using springs of variable stiffness which are attached between force transducers and the attachment points of the lid with modified tie rods. Table 1 lists all relevant parameters used for the experiments.

Table 1: Experimental parameters for both series of experiments.

TYPE	STIFFNESS (N/MM)	NORMAL STRESSES (KPA)	LOADING VELOCITIES (MM/S)
MAIN SERIES	3.3, 19.6, 82.6, 1354.0	5, 10, 15, 20	0.0008 – 0.02
STRESSED SHS TESTS	1354.0	5, 10, 15, 20	0.05, 0.16, 0.52
UNSTRESSED SHS TEST	1354.0	5, 10, 15, 20	0.16

3.1.1. Sample Preparation and Recording

For sample preparation we follow the standard protocol as described in Pohlenz et al. (2020). The material is carefully sieved from 30 cm height into the shear cell and scraped to the height of the shear cell. Afterwards the cell is transferred into the machine and the lid is lowered onto the sample. The normal stress is applied and shearing can commence. To be able to record high-frequency stick-slip cycles the main series experiments are recorded with a "BMCM PCI Base 50" PCI-ADC-converter card at 12.5kHz per channel and averaged down to 625 Hz. For the SHS-Tests the sampling frequency was 50kHz per channel with a "NI CompactRIO C Series ADC Module NI-9219" which was averaged to 1kHz. The glass beads were dried for 24 hours at 150°C prior to testing and then stored at laboratory conditions to cool down. The laboratory conditions are kept constant for all experiments at a temperature of 23°C and a humidity of 45% by an air condition.

3.1.2. Main Series Procedure

After preparing the sample and applying normal stress the sample is pre-sheared by 10mm at 0.5mm/s. This leads to a fully developed shear zone which then is characterized during the experiment. A main series experiment is carried out at constant normal stress but at decreasing velocities. After 1mm of displacement the velocity is decreased by 1/5 order of magnitude to get logarithmically spaced changes in loading rate. As a result of the 1mm displacement the temporal length of the loading intervals also increases logarithmically which produces similar amount of slip events.

3.1.3. SHS Series Procedure

Similar to the main series, the SHS tests were also conducted with pre-sheared samples (10mm shear displacement at 0.5mm/s). Each experiment was done at constant normal stress and with constant loading velocity. After 5mm of displacement at the given loading rate, the shearing was stopped and the sample held at rest for a specific amount of time. Then shearing is resumed at the loading velocity which leads to a peak in shear stress before the sample starts moving again. Each SHS-cycle is repeated three times to be able to calculate a standard deviation from the results. The hold time ranges between 10^0 and 10^3s with two steps per decade (1/2 order of magnitude change per interval). During a stressed SHS test the normal stress is applied throughout the whole experiment, while for an unstressed SHS test the normal stress is released during a hold. Due to the slow adjustment the hold intervals were only changed from 10^2 to 10^3s.

3.2. Data Analysis

The data analysis of all experiments is done through a series of Python scripts "rst-stick-slipy" that are available from https://git.gfz-potsdam.de/analab-code/rst-stick-slipy and also included in this data publication.

3.2.1. Main Series Analysis

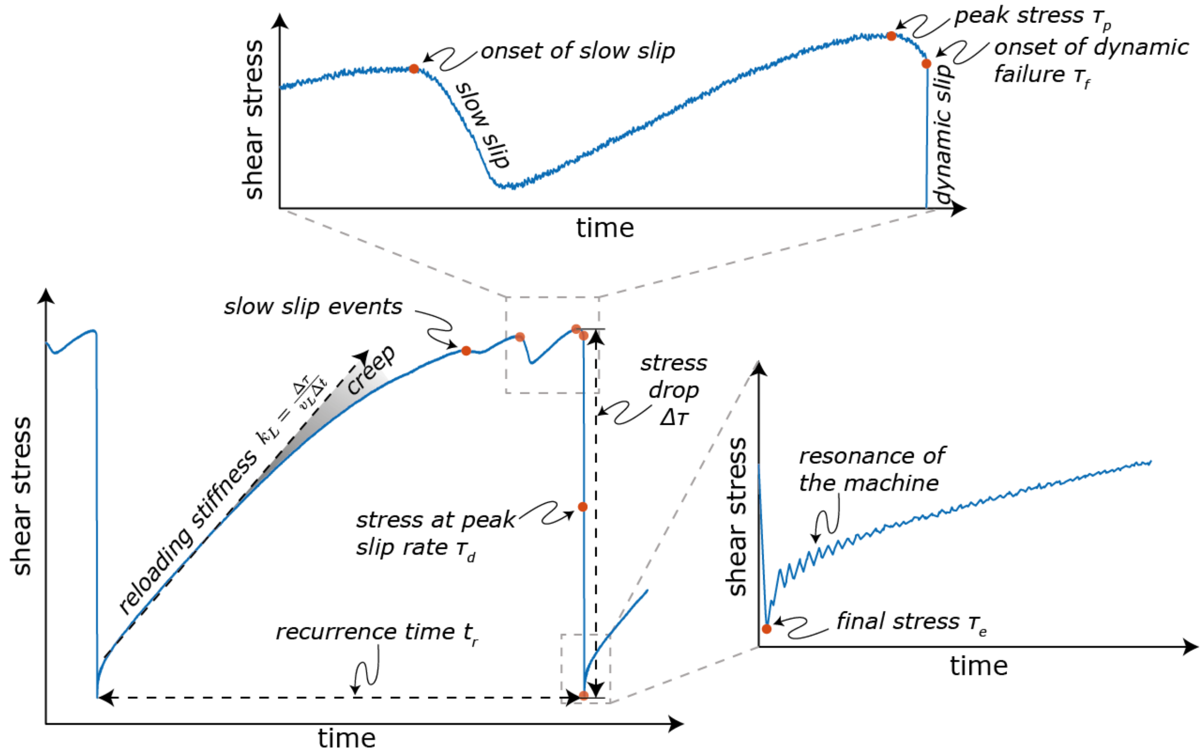

Figure 1 - Peak detection convention and other points of interest for the algorithm implemented in rststickslipy.

The main series is analysed by running rst-stick-slipy->main.py. The user is then prompted to open a directory where data files are located. The software then uses the parameters read from the configuration files for each experiment file in the data folder to pick slip events in the data set. In the following text, parameters and settings found in the *.ini file are highlighted in italics (e.g. *params->min_stress_drop*). The intermediate results are saved into the folder “eqs” which is created in the data folder. Additionally, a plot is saved as *.png file for manual inspection whether the parameters in the configuration file are correct.

The first step is to detect slip events in the time series. This is facilitated with a peak search algorithm based on a Matlab script by E. Billauer. It finds the local maxima and minima based on a local difference in stress between two points. The difference is given in the configuration file as the *params->min_stress_drop*. The minimum stress drop has to be adjusted for each series to be able to capture all types of events which can be quite different from experiment to experiment which can also be done interactively by setting the appropriate option “interactive = True” in “rststickslipy.modules.processing.py”. To improve the performance of peak detection the picking happens on a low-pass filtered time series. The default is using a Butterworth filter with *params->filter_order=10* and a frequency cutoff *params->filter_cutoff=60* Hz. This means that all oscillations above 60 Hz are filtered out. After detection it is assured that the first entry is a maximum and the last entry is a minimum which ensures that only complete events are present.

Additional points are then searched from the initial event database. Several points of interest are defined in Table 2.

Table 2: Points of interest calculated by rst-stick-slipy.

EQI	Onset of a slip event
EQE	End of a slip event
EQD	Onset of a dynamic event where slip rate > *params->cvel*
EQF	End of a dynamic event
EQM	Point of maximum slip rate
LINEAR	Deviation from linear loading between events
K_REL	Slope of the linear loading
SLIP_DEFICIT	Deficit of slip extrapolated from linear loading at the failure point *eqi*
OVERSHOOT/ OVERSHOOT_ERR	Difference of stress between end point *eqe* and the value interpolated from linear loading and estimated error.
CREEP_RATE/ X_CREEP	Creep rate during the interevent period estimated from the linear trend defined by *k_rel* and associated x-coordinates for plotting.
STRESS_DEFICIT	Deficit of stress extrapolated from linear loading at failure point *eqi*

These points of interest are then saved into an intermediate results file and are processed using the scripts found under "rststickslipy.scripts.paper_plots" or in the "Scripts" folder of this data publication.

3.2.2. SHS Series Analysis

The points of interest for a slide hold slide test are different from the main series points. The most important feature is the reloading peak which occurs due to healing during the hold (Figure 2). The reloading peak becomes greater the longer the holding time which is termed $\Delta\mu_p$ in Figure 2. This change is normalized by the average shear strength during shear measured during all slide phases.

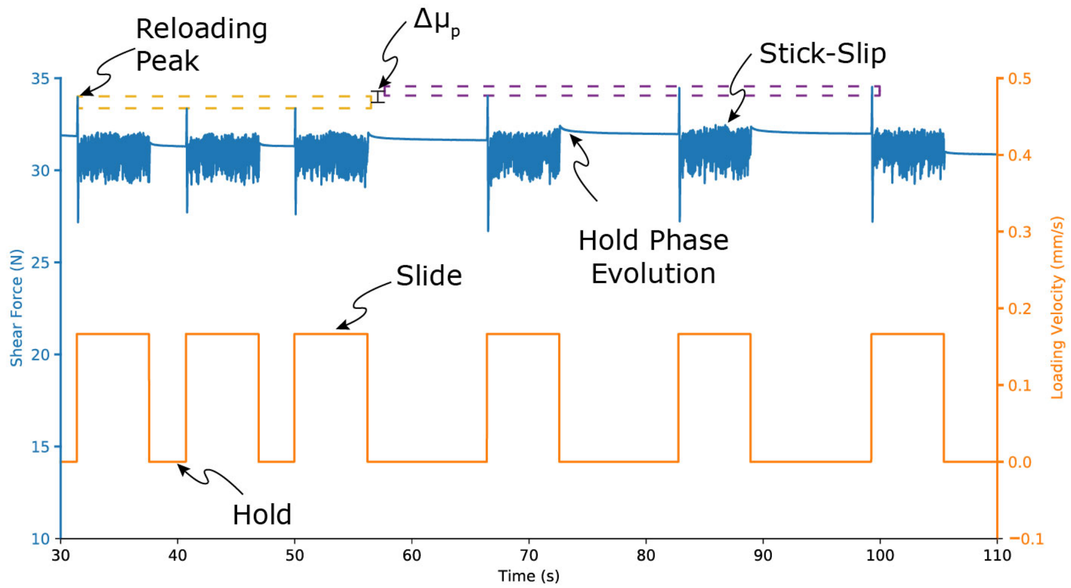

Figure 2 - Points of interest and typical shear stress curve for a SHS Test. $\Delta\mu_p$ indicates how this quantity is measured. It is not derived from shear force but from the frictional strength of the material that is $\mu = \frac{\tau}{\sigma_N}$.

In addition to the change in peak strength the evolution during hold is analysed. In most cases it shows an exponential decay indicating slow slip in the first few seconds of hold. The script "rststick-slipy.scripts.shs_analysis.py" detects all of these quantities and points and saves them into an intermediate results file in the form of a *.json file. The scripts in "rststickslipy.scripts.paper_plots" then use these results to create the plots for the publication and to calculate all relevant parameters.

4. File Description

4.1. Data Files

All raw data and a few intermediate processing results are stored in the Hierarchical Data Format (HDF5, *.h5). This is an open binary file format where datasets can be stored in container structures called "groups". There is a large amount of officially supported APIs for this data format. It can also contain compressed data which makes it very efficient for data storage while still maintaining high performance for data access. The measurement systems do not support the export of data into HDF5 so they are converted from their respective formats into HDF5 using the "h5py" module for Python. The original data from the main series experiments were stored in a proprietary binary format (*.lfx) by BMCM which were converted using the vendor-supplied ActiveX component "LIBADX" to ASCII delimited text with a VisualBasic program and then converted to HDF5 with Python. The data from the NI-CompactRIO were saved in the NI-TDMS file format (*.tdms) which is open and has a similar structure to HDF5 files. Although NI-TDMS is open the data still has been converted using the Python module "nptdms" in order to improve performance and to unify the file types for this data publication. An overview of all files of the data set is given in the **List of Files.**

The scripts in rst-stick-slipy allow to pick slip events from the raw data. These picks are also stored in the form of HDF5 files with the same name as the subset and the suffix "_eqs", usually into a separate folder named "eqs" for each set of experiments. Furthermore, the original files were split into subsets of equal loading velocity and normal stress for better processing with rst-stick-slipy.

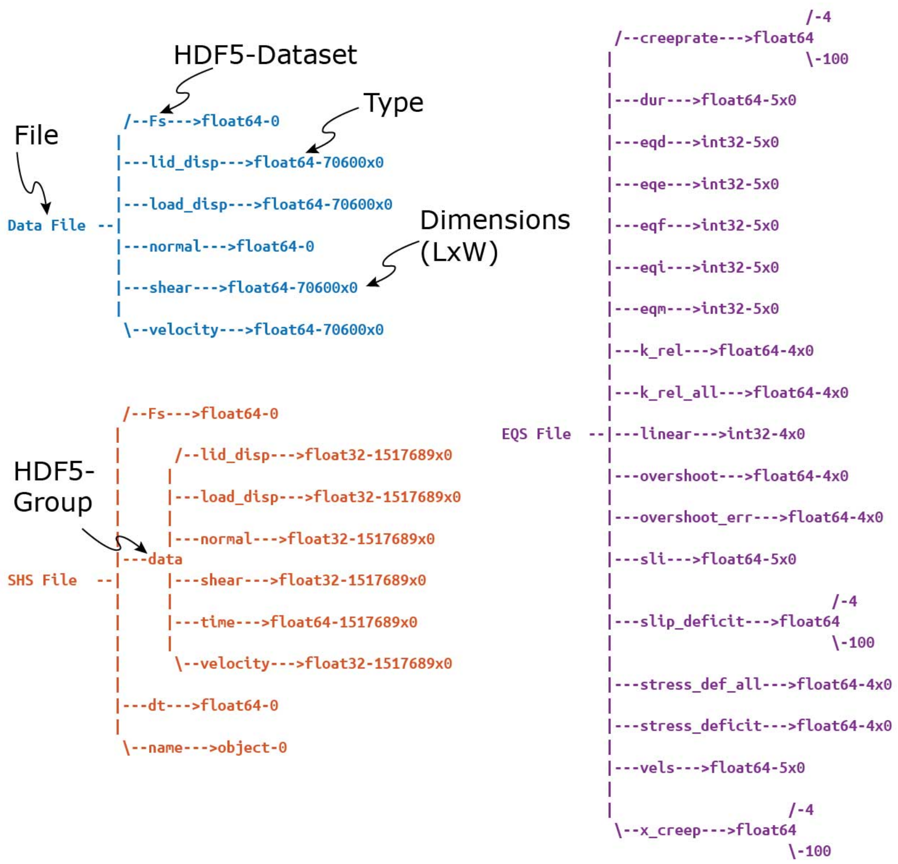

Figure 3 - Contents of the HDF5 Files represented as file trees.

4.2. Processing Parameters

To save processing parameters such as bandpass frequency, picking thresholds and constants the software rst-stick-slipy produces a configuration file (*.ini) with the same name as the data file that is currently processed. These configuration files are written and read by the Python config parser and are ASCII-formatted human readable text files with a specific format to facilitate easier reading. A group name is indicated by a header in square brackets (e.g. *[options]*). This is followed by a list of variables and their assigned value (e.g. *source_parameters = true*). If the user wants to change specific parameters for the data analysis, such as the minimum stress drop for a detected slip event (*params->min_stress_drop*), the user has to change it in these processing files.

```
[options]
source_parameters = true
fft = false
hide_plots = false
developer_mode = false
artificial_mode = false
export = false
folder_mode = false
similarity = false
angles = false
vst = false
save = true
precursory = false
play_sound = false
peakdet = default
preslip = false
interactive_threshold = false
interactive_precursor = false
usefilesettings = true
creep = false
reload_dat = true
ide = false
normalization = false
memory = false
```

```
[params]
min_stress_drop = 10
mr_stress_drop = -.1
mr_steps = 100
mr_win = 5
cvel = 0.001
filter_order = 5
filter_cutoff = 150
size_bins = -7.5:.1:-5
a_fault = 0.022619
l_fault = 0.4712
k_machine = 3300
e_gel = 150000
v_gel = 0.5
```

Figure 4 - Contents of a configuration file. Options determine which parts of the software are activated. Params are constants and properties for the individual dataset.

4.3. Intermediate Results

Intermediate results from the SHS tests and also the qualitatively determined slip modes are stored in JavaScript Object Notation (*.json) which is a simple text based data interchange format. Data is organized into name-value pairs in the form of *"Name": Value*`,` and grouped using brackets. The syntax is similar to the Python dictionary syntax and is easy to read for humans and is fast to parse into Python with the built-in "json" module. The naming of the SHS intermediate results is the same as the original experiment file with a separate extension. The slip modes are stored as a list with the file name as the Name and a numeric value for slip mode (1=stick slip, 2=oscillation, 3=random, 4=bimodal).

a) shs_file.json

```
{
    "end_hold": [ 7383, ... , 1510502],
    "hold_changes": [ -0.0347, ... , -0.0029],
    "hold_friction": [ 0.4323,  ... , 0.4641],
    "hold_times": [ 1.12, ... , 318.64],
    "load_vel": 0.16699999570846558,
    "norm_load": 4866.9,
    "peak_changes": [ 0.0021, ... , 0.0456],
    "post_friction": [ 0.469, ... , 0.5126],
    "pre_friction": [ 0.4596, ... , 0.4698],
    "selected_decay": [ 0, ... , 1],
    "start_hold": [ 6262, ... , 1191867]
}
```

b) modes.json

```
{
    "10_10kPa_0.0002_mm-s_375-3.h5": "4",
    "10_15kPa_0.0001_mm-s_375-6.h5": "1",
    "10_20kPa_0.0001_mm-s_375-1.h5": "1",
    ...
    "9_5kPa_0.0010_mm-s_371-01-27-GB300.h5": "4",
    "9_5kPa_0.0010_mm-s_375-4.h5": "4",
    "9_5kPa_0.0011_mm-s_371-01-21.h5": "1"
}
```

Figure 5 - Contents of the intermediate results in a JSON file. a) Picked SHS intermediate results. b) Qualitatively determined slip mode in the individual file.

5. References

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

Pohlenz, Andre; Rudolf, Michael; Kemnitz, Helga; Rosenau, Matthias (2020): Ring shear test data of glass beads 300-400 µm used for analogue experiments in the Helmholtz Laboratory for Tectonic Modelling (HelTec) at the GFZ German Research Centre for Geosciences in Potsdam. GFZ Data Services. https://doi.org/10.5880/GFZ.4.1.2020.008

Ritter, M., K. Leever, M. Rosenau, and O. Oncken (2016): Scaling the Sand Box - Mechanical (Dis-) Similarities of Granular Materials and Brittle Rock, J. Geophys. Res - Solid Earth, https://doi.org/10.1002/2016JB012915

Rudolf, Michael; Rosenau, Matthias; Oncken, Onno (submitted): The spectrum of slip behaviours of a granular fault gouge analogue governed by rate and state friction.

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.