Geotechnik im Bauwesen
Geotechnical Engineering
Univ.-Prof. Dr.-Ing. Martin Ziegler

RWTH RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Forschungsprojekt

Evolution of shear zones in layered sand-clay sequences

Scherfugenentwicklung in Sand-Ton-Wechselfolgen

Faults in Miri, Malaysia

Gefördert von der Deutschen Forschungsgemeinschaft (DFG)
Gemeinschaftsprojekt mit Geologie – Endogene Dynamik (GED)

Problem definition

The aim of the study, which is going to be done within an interdisciplinary research project in cooperation with the Geological Institute of the RWTH Aachen University, is to analyse the shearing of layered sand-clay sequences due to tectonic processes.

The material performance of the cohesive layer is of special importance. Due to the relative displacement of the wall rock, which can reach a multiple of the layer thickness, the clay is drawn into the shear zone which can lead to a sealing of the fault.

As a result of the horizontal layering and the low permeability of the cohesive layer there is an interruption of vertical flow in the underground. In addition to the blockage of the vertical flow the clay, which is drawn into the fault causes a sealing in horizontal direction. This can lead to a complete separation of an existing aquifer.

The authentic prognosis of the fault sealing process is of special interest for the exploration of groundwater and oil. The analysis of how and under which condition the clay is drawn into a shear zone with increasing displacement in layered sequences is the main objective of this study.

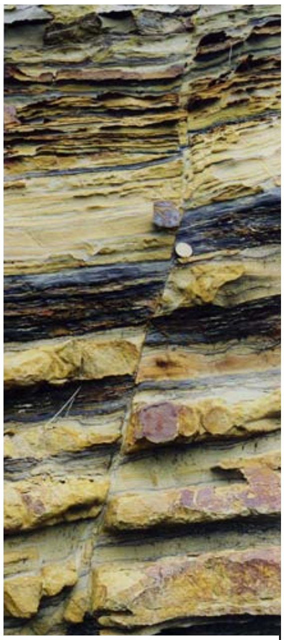

Figure 1: natural fault in layered sequences

State of the art

Clay Smear
The term “clay smear” includes all processes which somehow transform clay in the wall rock into clay in the fault. For applied studies of fault seal evolution, a number of semi-empirical tools were developed to analyse the process of clay smearing (“clay smear potential”, “shale smear factor” and “shale gouge ratio”, Bouvier et al. 1989, Lindsay et al. 1993, Yielding et al. 1997, Fristad et al. 1997, Yielding 2002, van der Zee et al. 2003, Doughty 2003, Faerseth 2006).
The majority of these methods are based on the assumption that the shear zone is an equivalent to the wall rock without any addition or removal of material. None of these methods are based on detailed models of fault evolution and therefore imply a high level of uncertainties. Other authors suggest that clay smearing results in more clay in the fault than can be expected from the clay-sand ratio in the wall rock sequence (Lehner & Pilaar 1997).

Analogue Sandbox modeling
Scaled Sandbox experiments emerged as effective means for simulation of deformation processes in fault zones (Cloos 1930, McClay & Ellis 1987, Dahlen & Suppe 1988, Huqui et al. 1992, Gutscher et al. 1996, McClay 1996, Wang & Davis 1996, Koyi 1997, Kukowski et al. 2002, Lohmann 2003, Maser et al. 2006, Wolf 2005).
The use of “Particle Image Velocimetry Analysis” (PIV) as a medium for evaluation and interpretation of the Sandbox experiment allows digital image documentation to visualize displacement vector fields of granular materials. These digital images are the basis for

authentic calculation of deformation and distension fields. The “Benchmark Group” is currently analysing the reproducibility of the analogue Sandbox experiment.

Numerical Modeling
The simulation of fault location claims special requirements on the numerical model. In general there are two possible and well defined approaches: The numerical solution using the discrete particle method or the solution using the finite element method.
Using the discrete particles based on Cundall and Strack (1997) it is possible to observe typical shearband phenomenons such as dilatancy and particle rotation (Giese et al. 2006). The mechanical behavior of granular material is simulated by rigid plates and balls. However, this method is highly limited by the required processing power. The sand and especially the clay particles in the model can not be represented in realistic dimensions.
There are various studies about finite element simulations which point out the difficulties of fault zone development, like increased stress and displacement gradients and the dependency of the shear zone location on the finite element mesh (Herle & Feda 2001, Hügel 1995). To receive a shearband width which is independent of discretisation, it is possible to take advantage of several regularisation methods like the “Cosserat Kontinuum” (Mühlhaus 1986, Tejchmann 1995, Tejchmann 1997, Ehlers & Volk 1999), the “Gradient Method” (Mindlin 1965), the “Not-local Method” (Eringen 1972, Bažant & Pijauder-Cabot 1087) and the “Fracture-Energy Approach” (Crook et al. 2003, Crook et al. 2006).
Karcher (2003) achieved good results with his numerical simulation of the evolution of the “Niederrhein”-delta. However, the simulation of large relative displacements as that appear in fault zones is still challenging. The Modeling of clay smearing processes in fault zones has also achieved good results and has even shown the coherency of the vertical thickness of the clay layer and the fault throw. But nevertheless, these numerical calculations are also only valid for a small scale scenario. Crook et al. (2006) show that this scaling problem can be solved by the use of adaptive remeshing.

Method of resolution

The interdisciplinary collaboration of engineers and geologists includes three main topics: outcrop studies, Sandbox experiments and numerical modeling.

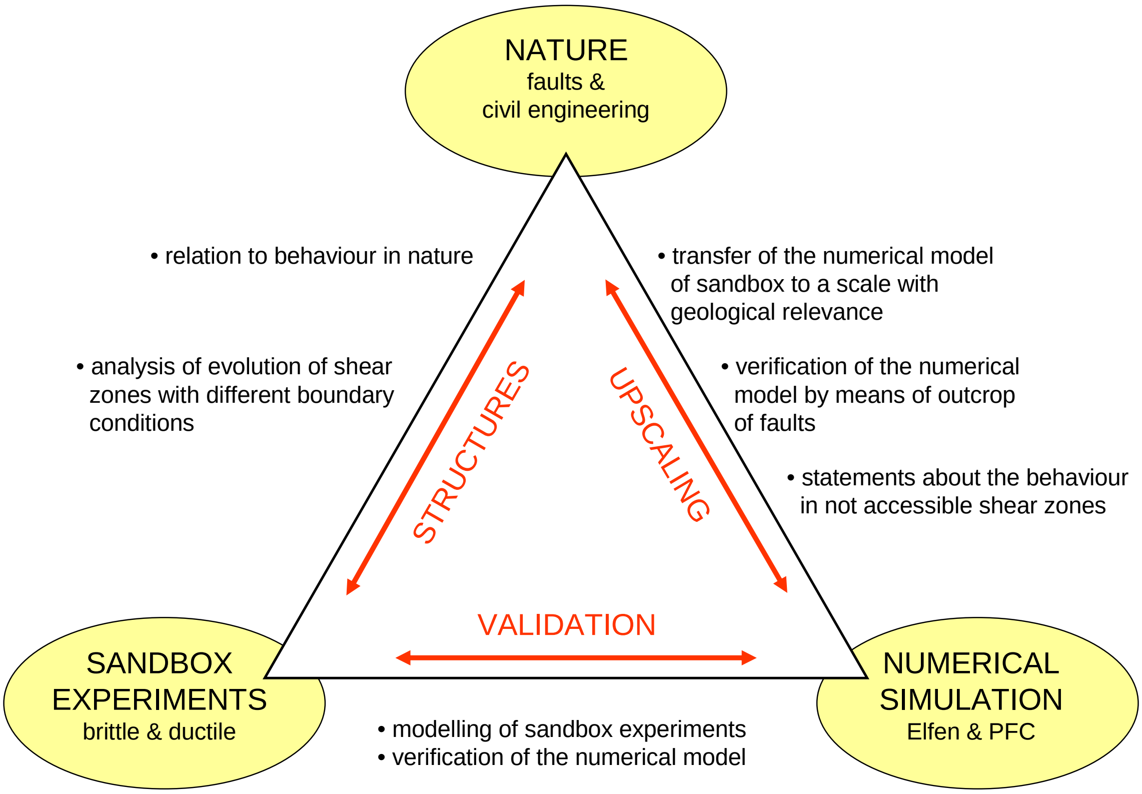

Figure 2: Overview and indication of interaction between different parts oft he project

The outcrop studies imply the examination of shear zones in layered sequences and the extraction of material samples which can be analysed in the geotechnical laboratory to determine material parameters for the numerical model.

Figure 3: Sandbox

The Geological Institute of the RWTH University is running a sandbox experiment where the sandbox is especially developed for this purpose. It allows the simulation of typical shear processes in natural faults under controlled boundary conditions. Based on the results of these sandbox experiments the Geotechnical Institute of the RWTH University develops a numerical model to transfer not only the sandbox experiments but also the fault evolution into geological structures.

The numerical model is done using the program ELFEN by Rockfield® software. Because of adaptive remeshing, this program allows the simulation of large relative displacements.

To express not only the small scale stress-/strain conditions at low overburden load in the sandbox experiment but also the large scale, natural stress-/strain conditions, it is necessary to use an adequate constitutive equation.

Present findings

As a result of the Sandbox model in homogenous Sand material with varied predefined basement fault dips it appears that a smooth dip causes a V-shaped fault and a steep dip causes one single fault.

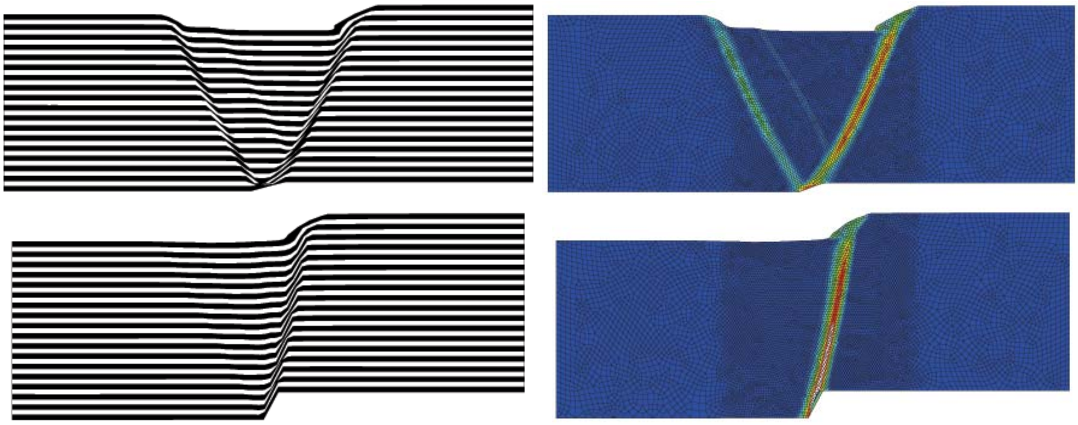

Figure 4: Results (material grid stripes and effective plastic strain) of a numerical model of an analogue sandbox experiment with homogeneous sand properties and a basement fault dip of 20° (top figures) and 70° (bottom figures).

The Sandbox model in layered sequences shows how the material in the clay layer (soft or rigid) influences the fault evolution.

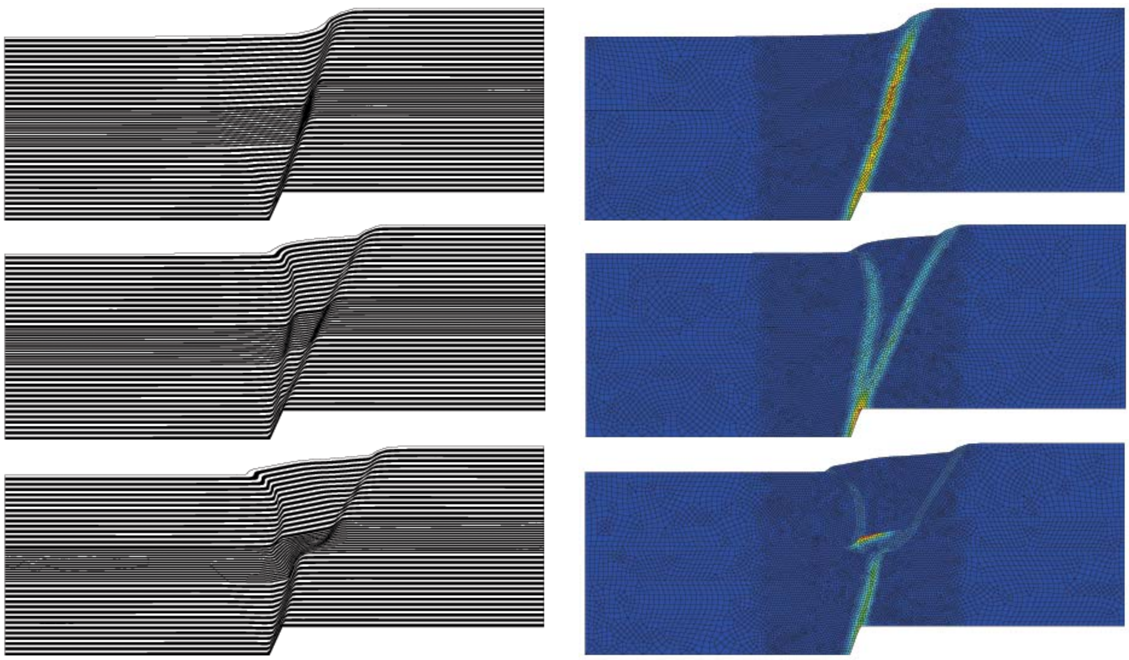

Figure 5: Results (material grid stripes and effective plastic strain) of an analogue sandbox experiment with three different clay layers (strong, soft and very soft) with basement fault dip of 70°.

Further experiments show how one fault develops in homogenous material irrespective of the basement fault dip. For these reasons a model is developed where the collateral boundaries are pulled apart. In the center of the model there is a so called “soft” element located, with very soft material parameters which is supposed to assure the origin auf fault development in the center of the model. The intention is to create one single fault and not a fault pattern. In this model the influence of the material parameters can be analysed with almost no influence by external boundary conditions.

Figure 6: Localization after a movement of the boundaries of 3mm

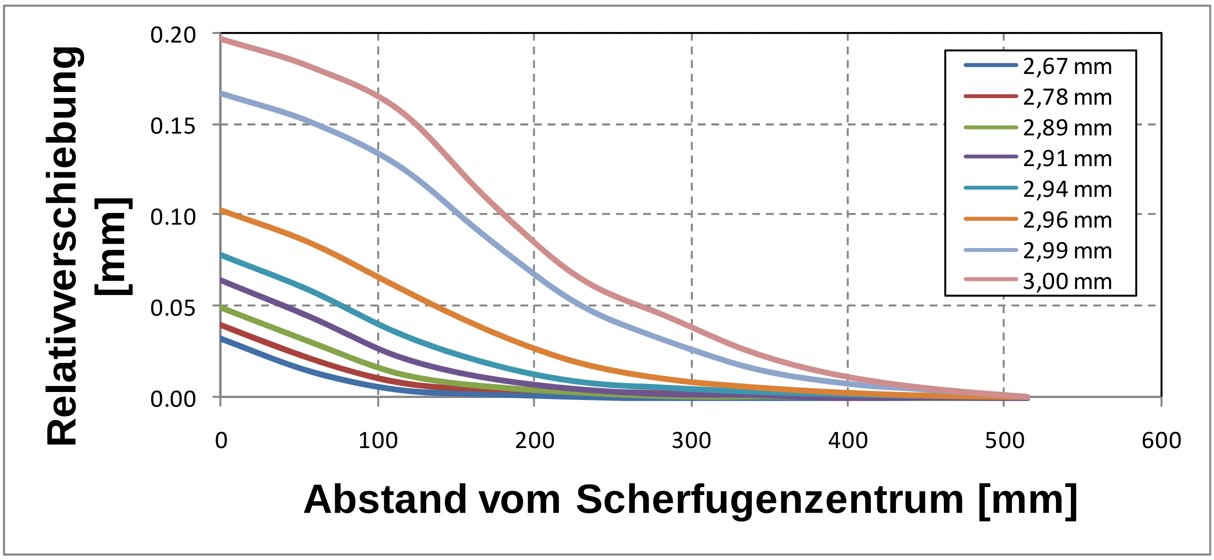

Figure 7 Progress of the relative displacements along the fault during the fault's evolution

Future prospects

After verifying displacement and stress fields of the numerical and analogue model, the numerical models are to be extended to geological relevant scale and boundary conditions.

This is going to be done considering a direct comparison of the numerical model and the results of the outcrop studies.

Literatur

Adam J. J. L. Urai B. Wieneke O. Oncken K. Pfeiffer N. Kukowski J. Lohrmann S. Hoth, W. van der Zee and J. Schmatz (2005) Shear localisation and strain distribution during tectonic faulting – new insights from granular-flow experiments and high-resolution optical image correlation techniques. Journal of Structural Geology, 27:283-301.

Bažant & Pijauder-Cabot 1987: Nonlocal continuum model with local strain. In: D. Owen, E. Hinton, E. Onate (eds.), International Conference of Computational Plasticity, Barcelona, pp. 1757-1780.

Benchmark 2008: URL: http://www.geodynamics.no/benchmarks/index.html

Bouvier et al. 1989: Three-dimensional seismic interpretation and fault sealing investigations, Nun river field, Nigeria. Bulletin of the American Association of Petrolium Geologists, 73(11), 1298-1414

Cloos 1930: Zur experimentellen Tektonik: Methodik und Beispiele. Die Naturwissenschaften, 34, 741-747.

Crook, A. J. L., Willson, S. M., Yu, J. G. & D.R.J., O. 2003: Computational modeling of the localized deformation associated with borehole breakout in quasi-brittle materials, Journal of Petroleum Science and Engineering 38, 177-186

Crook, A. J. L., Willson, S. M., Yu, J. G. & D.R.J., O. 2006. Predictive modelling of structure evolution in sandbox experiments. Journal of Structural Geology 28, 729-744.

Cundall und Strack 1979: A discrete numerical model for granular assemblies. Géotechnique 29, no. 1, 47-65.

Doughty 2003: Clay smear seals and fault sealing potential of an exhumed growth fault, Rio Grande Rift, New Mexico: American Association of Petroleum Geologists Bulletin v. 87 pp. 427-444.

Ehlers und Volk 1999

Eringen 1972: Nonlocal polar elastic continua. International Journal of Engineering Science 10, no. 1, pp. 1-16.

Faerseth 2006: Shale smear along large faults: continuity of smear and the fault seal capacity Journal of the Geological Society 163:741-751.

Fristad, T., Groth, A., Yielding, G. & Freeman, B. 1997: Quantitative fault seal prediction: a case study from Oseberg Syd. In: Hydrocarbon seals: importance for exploration and production (edited by Moller-Pedersen, P. & Koestler, A.G.). NPF Special Publication 7, 107-124.

Giese, S., Kirsch, A., Ziegler, M., 2006. Numerische Untersuchung von Schervorgängen mit der Diskrete-Partikel-Methode. In: Bauingenieur, Band 81, Heft 5, pp. 232-239.

Gudehus und Karcher 2006: Hypoplastic simulation of normal faults without and with clay smears. Journal of Structural Geology(2006), doi:10.1016/j.jsg.2006.09.011

Herle und Feda 2001: Interaction of spread footings with sandy subsoil. Part 1: State of the art. Engineering Mechanics 8, no. 2, pp. 137-148.

Hügel 1995: Prognose von Bodenverformungen. Veröffentlichungen des Institutes für Bodenmechanik und Felsmechanik der Universität Fridericiana in Karlsruhe, Heft 136.

Karcher 2003: Tagebaubedingte Deformationen im Lockergestein. Veröffentlichungen des Institutes für Bodenmechanik und Felsmechanik der Universität Fridericiana in Karlsruhe, Heft 160.

Koyi 1997: Analogue modeling; from a qualitative to a quantitative technique; a historical outline. Journal of Petroleum Geology 20(2), 223-238.

Kukowski, N., Lallemand, S. E., Malavieille, J., Gutscher, M.-A., Reston, T. J. 2002. Mechanical decoupling and basal duplex formation observed in sandbox experiments with application to the Western Mediterranean Ridge accretionary complex. Marine Geology 186, 29-42.

Lehner & Pilaar 1997: The emplacement of clay smears in synsedimentary normal faults: inferences from field observations near Frechen, Germany. In: Hydrocarbon seals: importance for exploration and production (edited by Moller-Pedersen, P. & Koestler, A.G.). NPF Special Publication 7, 39-50.

Lindsay, N.G., Murphy, F.C., Walsh, J.J., Watterson, J., 1993. Outcrop studies of shale smears on fault surfaces. Spec. Publs Int. Ass. Sediment, 15, 113-123.

Lohrmann, J., Kukowski, N., Adam, J., Oncken, O., 2003. The impact of analogue material properties on the geometry, kinematics, and dynamics of convergent sand wedges. Journal of Structural Geology, 25(10), pp. 1691-1711.Maser et al. 2006

McClay, K. R. 1996. Recent advances in analogue modeling: uses in section interpretation and validation. In: Modern Developments in Structural Interpretation, Validation and Modeling (edited by Buchanan, P. G., Nieuwland, D. A.) 99. Geological Society Special Publication, pp. 201-225.

Mindlin, R., 1965. Second gradient of strain and surface-tension in linear elasticity. International Journal for Solids Structures 1, pp. 417-438.

Mühlhaus, H.-B., 1986. Scherfugenanalyse bei granularem Material im Rahmen der Cosserat-Theorie. Ingenieur-Archiv 56, pp. 389-399.Schreurs et al. 2006:

Tejchman, J., 1995. Grain size effect in bearing capacity of a strip foundation on sand. In: G.N. Pande, S. Pietruszczak (eds.), Numerical models in geomechanics, NUMOG V, Davos, pp. 571-576.

Tejchman, J., 1997: Modelling of shear localisation and autogeneous dynamic effects in granular bodies. Veröffentlichungen des Institutes für Bodenmechanik und Felsmechanik der Universität Fridericiana in Karlsruhe, Heft 140.

van der Zee, W., Urai, J.L., Richard, P.D., 2003. Lateral clay injection into normal faults. GeoArabia 8(3), 501-522.Wang & Davis 1996:

Wolf, H., 2005. Zur Scherfugenbänderung granularer Materialien unter Extensionsbeanspruchung. Veröffentlichung des Institutes für Grundbau und Bodenmechanik der Ruhr-Universität Bochum, Heft 37.

Yielding, G. Freeman, B. & Needham, D.T. 1997. Quantitative fault seal prediction. AAPG Bulletin 81 (6), 897-917.

Yielding, G., 2002. Shale Gouge Ratio - Calibration by geohistory. In: A.G. Koestler, R. Hunsdale (eds.), Hydrocarbon Seal Quantification, NPF Special Publication 11, Elsevier Science B.V. Amsterdam, pp. 1-15.