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

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

GFZ Helmholtz Centre Potsdam

EGU2011-1277

Study on ground subsidence development during and after underground coal gasification

Tian, H.[1], Kempka, T.[2], Feinendegen, M.[1], Ziegler, M.[1]

[1]RWTH Aachen University, Department of Geotechnical Engineering, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany

[2]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Problem statement and objectives

Underground coal gasification (UCG) is currently being revived worldwide. As one of the main environmental risks, ground subsidence has to be studied in detail. Due to pyrolysis and oxidation/reduction processes, the temperature in the reactor can be up to 1200°C. Furthermore, the strength and deformation characteristics of rocks under high temperatures are quite different from those at room temperature. Therefore, a coupled thermo-mechanical (TM) model is essential for the corresponding analysis of UCG, such as roof deformation and ground subsidence.

The aims of the authors are to establish a TM model reflecting the effects of high temperatures on rocks, implement it in a Finite Element Software Package (*Abaqus*) to simulate the UCG process, and compare the results with those under conventional conditions.

Methodology

The methodology applied is shown in Fig. 1. The TM model is a modified Mohr-Coulomb (MC) model, including the temperature effects on the mechanical parameters of rocks. Comparison between elasto-plastic and strain softening behaviors has also to be considered. Besides, the plastic potential is assumed to be identical to that in *Abaqus 6.7*.

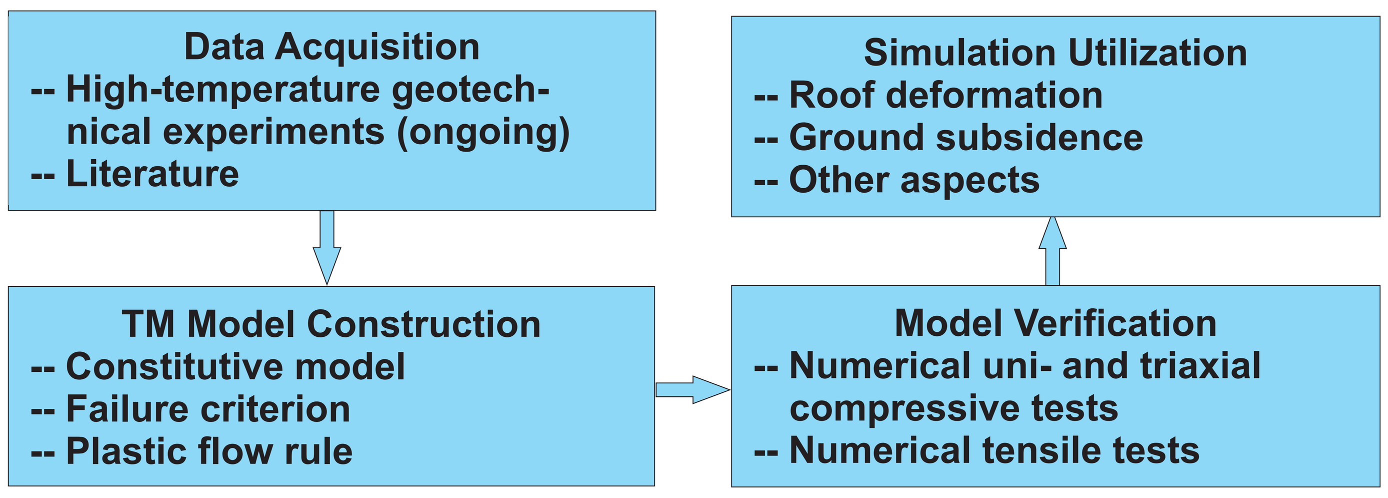

Fig. 1 Research workflow

Thermo-mechanical model construction

The effects of high temperatures on the elastic modulus *E* and strength of several rocks are shown in Fig. 2. The tests were performed at high temperatures (solid lines) and after high temperature treatment (dashed lines). In both cases, *E* and strength decrease with increasing temperature, but after high temperature treatment these parameters are of higher quality compared to those determined at high temperatures.

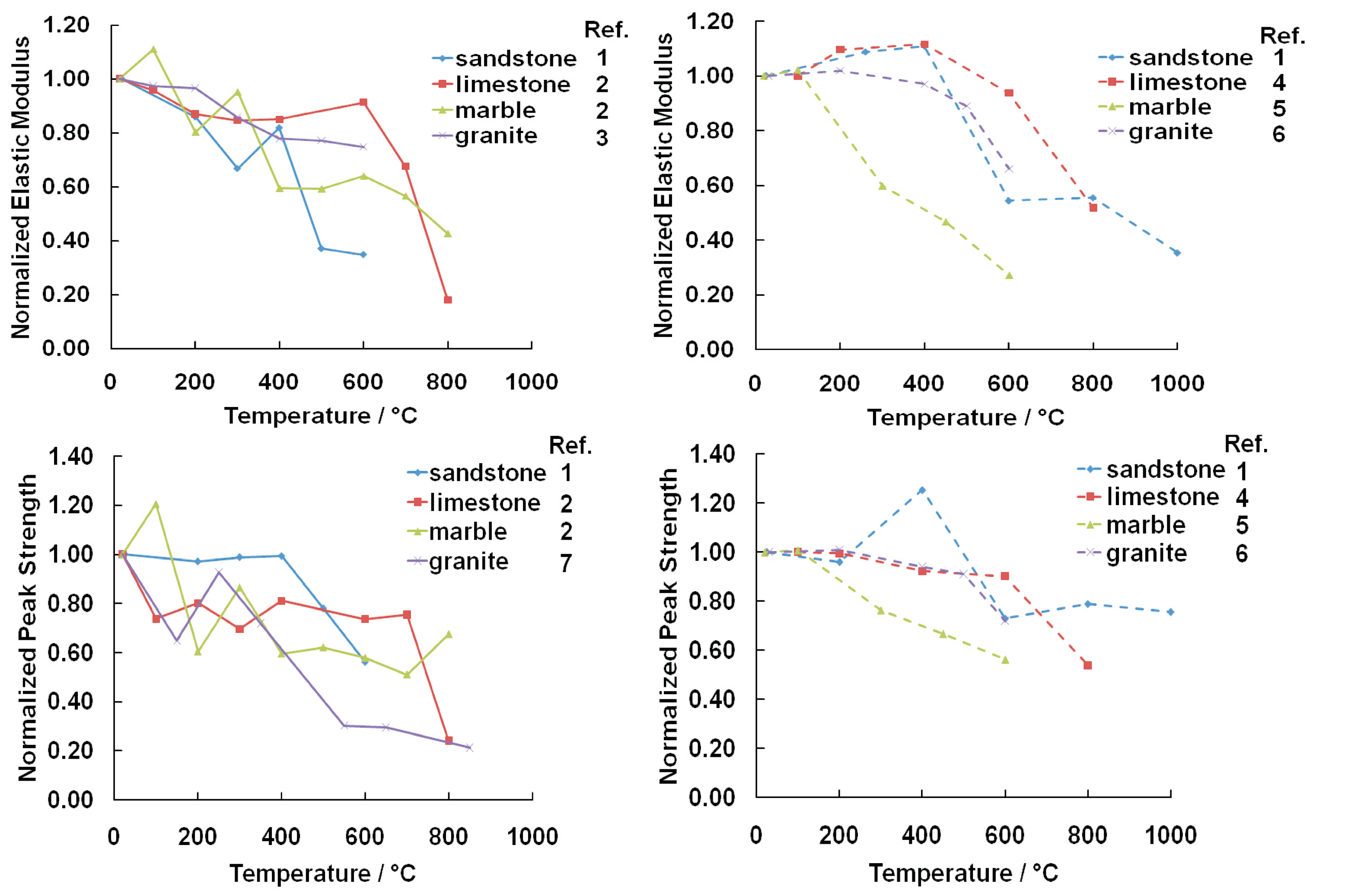

Fig. 2 Normalized elastic modulus and peak strength vs. temperature for different rocks. The solid lines represent the results at high temperatures, and the dashed lines those after high temperature treatment.

The TM MC model is constructed based on the reduction in cohesion as follows:

$$F(\sigma, T) = (\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3)\cdot \sin\phi - 2c(T)\cdot \cos\phi$$

where *T* is the temperature in °C, *c(T)* the rock type dependent cohesion function, and ϕ the friction angle.

The corresponding constitutive model can be both perfect elasto-plastic and strain softening, where $E = E(T)$.

Benchmark setup

To study the TM MC model in detail, four scenarios of a simplified model, whose boundary and load conditions are depicted in Fig. 3, were applied to realize the case studies shown in Table 1.

Table 1 Description of the four scenarios

Scenarios	Calculation Procedure	T-effected Parameters
CASE 1	Conventional model (M)	-
CASE 2	Partial TM	*E(T)*
CASE 3	Partial TM	*c(T)*
CASE 4	Complete TM	*E(T) + c(T)*

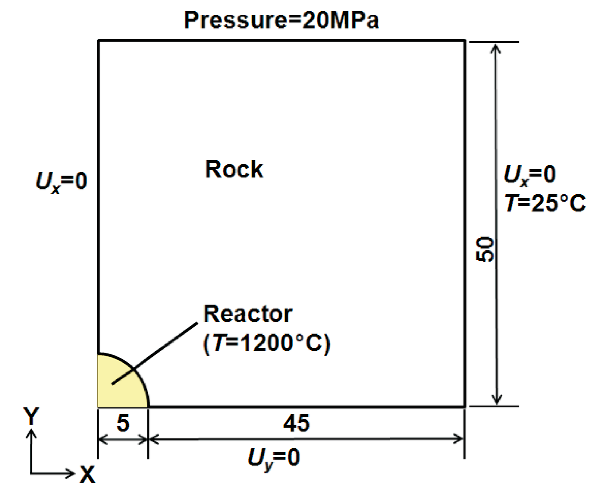

Fig. 3 The benchmark model (units: m)

Parameterization

The functions *E(T)* and *c(T)*, modified from the sandstone data at high temperatures in Fig. 2, are shown in Fig. 4, where E_0 and c_0 represent the values of *E* and *c* at room temperature. The dashed parts were assumed by the authors due to a lack of data. The geotechnical parameters used here are shown in Table 2.

Table 2 Geotechnical parameters

Density kg/m³	E_0 GPa	Poisson's ratio	C_0 MPa	ϕ °	Expansion k^{-1}	Conductivity J/kg·k	Specific heat W/m·k
2500	5.0	0.3	2.0	30	10^{-5}	2.0	800

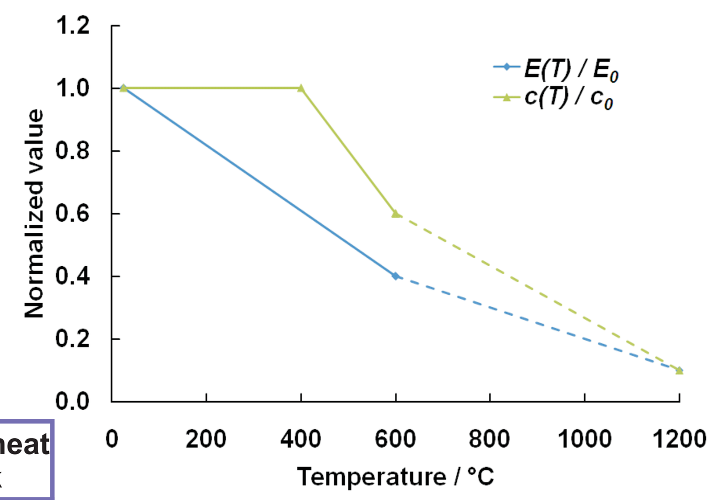

Fig. 4 *E(T)* and c(T) for sandstone (the dashed lines are assumed)

Results

Since the thermal parameters in all the scenarios are identical and temperature independent, the temperature field based on steady heat transfer for all the cases is shown in Fig. 5.

The yield zones increase progressively from CASE 1 to CASE 4, as shown in Fig. 6.

Table 3 lists the horizontal displacement of point A (U_{Ax}), the vertical displacement of point B (U_{By}), and the thickness of the yield zone (*H*) (Fig. 7). These values are higher under TM conditions compared to the conventional mechanical model (CASE1).

In the TM MC model (CASE 4), maximum displacements in the reactor and the yield zone are about 7.4 and 2.4 times higher compared to the conventional model (CASE 1), respectively.

The impacts of *c(T)* on the results are higher than those of *E(T)*.

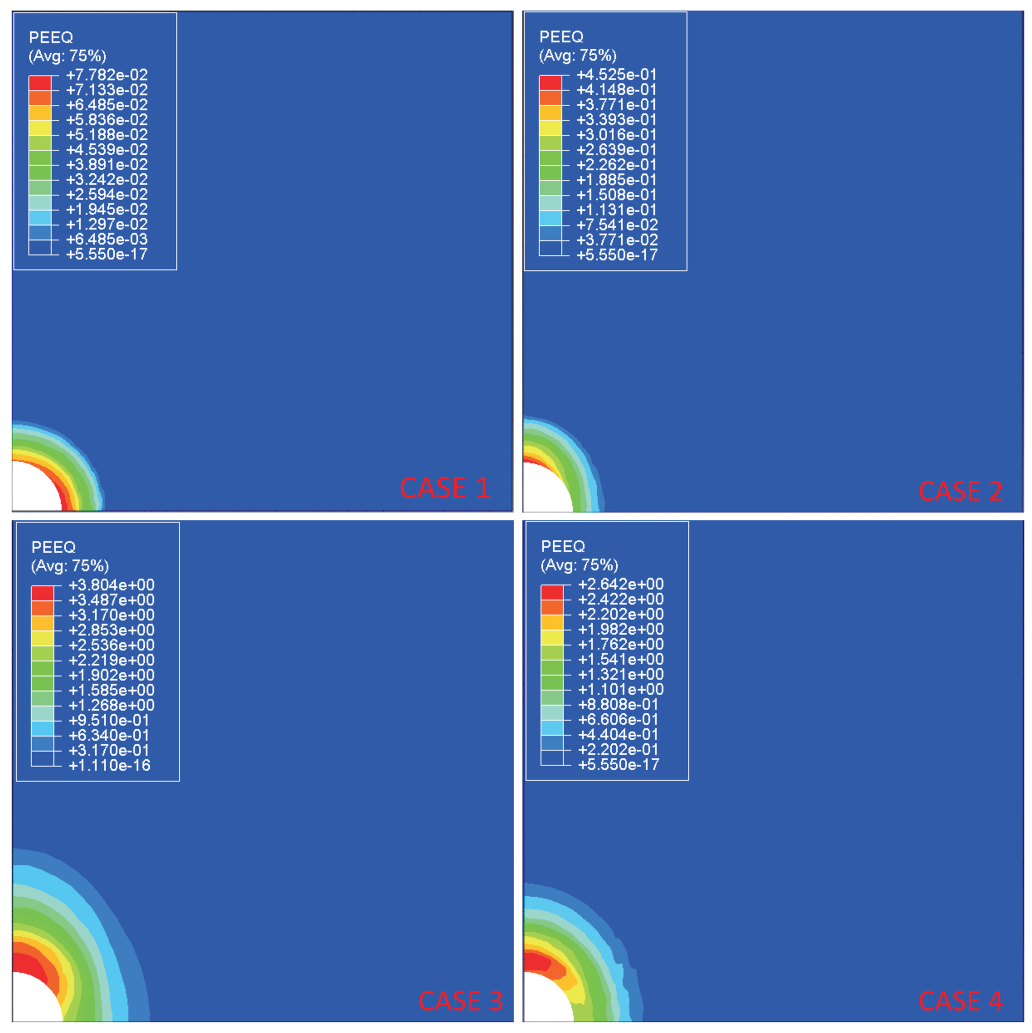

Fig. 6 Yield areas of the four scenarios

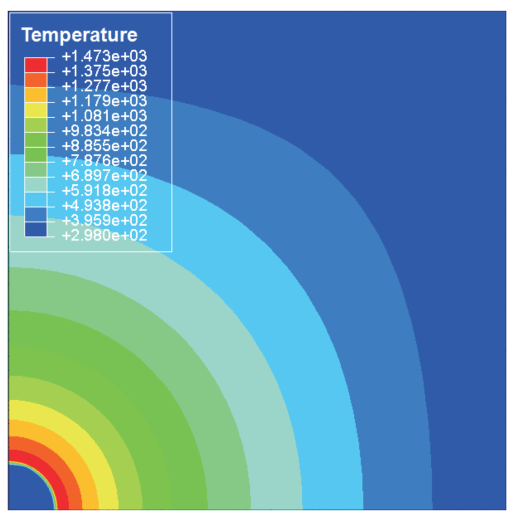

Fig. 5 Temperature field

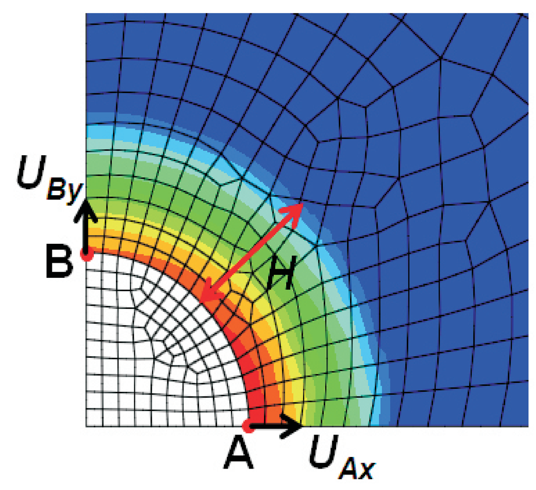

Fig. 7 Key parameters studied

Table 3 Numerical results

	U_{Ax} (m)	U_{By} (m)	*H* (m)
CASE 1	-0.073	-0.072	4.115
CASE 2	-0.283	-0.293	5.011
CASE 3	-0.558	-0.660	13.705
CASE 4	-0.543	-0.585	10.355

Conclusions and further studies

During the UCG process, the reactor temperature is extremely high (up tp 1200°C). Thus, a TM model should be applied, if numerical simulations are carried out to evaluate deformation and ground subsidence. Subsequent to the UCG process, a TM model is also required, since geomechanical rock properties change after its exposure to high temperatures.

Conventional mechanical models have to be modified to remain consistent with the change of rock properties under high temperatures. Even though the TM MC model proposed here is rather simple, it provides an improved description of parameters considering experimental data on rock bahavior under high temperatures.

Four scenarios were calculated to compare the TM MC model with the conventional MC model and study the sensitivity of the geomechanical parameters. Deformation and the yield zones are higher for the TM model, and deformation is more sensitive to cohesion than to the elastic modulus.

Further studies include a) constitutive model comparisons, b) TM model verification, and c) model validation based on data from real UCG sites.

Acknowledgement

The first author appreciates her funding provided by the China Scholarship Council.

References

[1] Wu Zh., Qin B.D., Chen, L.J., Luo Y.J. Sandstone of the upper plank of coal bed under high temperature. Chinese Journal of Rock Mechanics and Engineering. 2005, 24: 1863-7
[2] Zhang L.Y., Mao X.B., Lu A.H. Experimental study on the mechanical properties of rocks at high temperature. Sci China Ser E-Tech Sci. 2009, 52(3): 641-6
[3] Wan Zh.J. et al. Experimental study on mechanical characteristics of granite under high temperatures and triaxial stresses. Chinese Journal of Rock Mechanics and Engineering. 2008, 27: 72-7
[4] Wu G., Teng N.G., Wang Y. Physical and mechanical characteristics of limestone after high temperature. Chinese Journal of Geotechnical Engineering. 2011, 33: 259-264
[5] Jiang Zh.J. Mechanical characteristics and mesotesting investigation of heated marble (thesis). 2007.
[6] Homand-etienne F., Houpert R. Thermally induced microcracking in granites: characterization and analysis. Int. J. Rock Mech. Min. Sci. & Geomech. 1989, 26(2): 125-134
[7] Jiang H.K., Zhang L., Zhou Y.Sh. Characteristics of AE temporal sequences in the process of deformation and failure of granite at high pressure and different temperatures. Earthquake. 2000, 20(3):87-94

Contact
M.Sc. Hong Tian
tian@geotechnik.rwth-aachen.de
Phone: +49 / (0)241 / 80-24172
Fax: +49 / (0)241 / 80-22384
Mies-van-der-Rohe-Str. 1
52074 Aachen, Germany