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Modelling surface subsidence during underground coal gasification

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Abstract

Underground coal gasification (UCG) is an alternative method of extracting energy from coal whereby the coal is burnt within an in situ UCG reactor. The method has been established for almost a century, but it has not been widely used despite its advantages, which include the circumvention of underground human presence and the possibility to work with low quality coal that is deep underground. One of the main difficulties associated with the implementation of UCG on an industrial scale is the prediction of surface subsidence, which is required to assess potential damage to surface infrastructure, UCG equipment, and boreholes.

This work considers the numerical modelling of surface subsidence during UCG. For this, the finite difference numerical modelling software FLAC3D by Itasca is utilized. Historically, this tool has been used for modelling surface settlement caused by traditional coal mining activities. The mechanism of surface subsidence during conventional coal mining and UCG are almost identical; however, the UCG reactor has some distinguishing features, for example, thermal strains and the resulting altered mechanical properties of the soil-rock. In this work, firstly, a thermal analysis is run to impose the thermal fields. Secondly, the engineering properties relationship with temperature is implemented in the model. Finally, model results are compared with field observations and discussed. The conclusion is drawn that updating the mechanical properties, i.e. elastic stiffness, friction angle and cohesion, in correlation with the elevated temperatures improves the surface subsidence predictions.

Keywords: *Underground Coal Gasification, Surface Subsidence, Numerical Modelling, Thermal Analysis, FLAC3D*

Introduction

UCG as an advanced method of extracting energy from coal has been known for a century. Some attempts have been undertaken to model surface subsidence after UCG. For example, Ekneligoda et al. (2017) and Otto (2017) modelled surface subsidence at the Wieczorek UCG site in Poland. Yang et al. (2014) simulated surface subsidence for the possible UCG site in Bulgaria. Tian (2013) modelled soil-rock displacements for a potential site for UCG in the Münsterland Basin (North of North-Rhine Westphalia) in Germany. Vorobiev et al. (2008) compared the modelling results with the analytical solutions showing good correlations. Much earlier, Sutherland and Hommert (1984) modelled surface subsidence for two UCG projects, i.e. TONO and Hoe Creek III in the USA, without consideration of the thermal effect.

Distinctively, this research includes the thermal analysis and influence of high temperatures on properties of soil-rock. Besides, this work compares the modelled results with the measurements at a UCG project of relatively long duration. In the considered UCG station, the combustion lasted for 36 months. At the end of combustion, surface subsidence was measured. The model simulated the surface subsidence at the UCG station in the Moscow basin. The field data was obtained from the work of Turchaninov and Sazonov (1958) to compare with the modelling results. The old but accurate data is unique due to limited industrial implementation of UCG. To model surface subsidence after UCG, the commercial software FLAC3D was used. This 3D tool was chosen to model a 2D problem because once the 3D tool could correctly solve the 2D problem, the solution could be extended to 3D. At the beginning of the work, the model was run without thermal analysis to simulate the collapse of a conventional mine. Then to model a collapse of the UCG reactor, the research dealt with the distribution of high temperatures in the overburden and the influence of the high temperatures on the mechanical properties of the rock-soil.

Methodology

Description of the Model

The settings of the domain and boundary conditions of the FLAC3D model were typical for the analogical models in FLAC2D, which were developed, for example, by Yavuz (2002) or by Alejano and Alonso (1999). To model the 2D problem, the domain of the FLAC3D model was fixed in the out-of-plane direction. The symmetry of the problem was used to cut the domain along the centre of the reactor and to reduce the domain twice. The size of the domain was of 60m height, 100m length and 0.5m in the out-of-plane direction. The domain consisted of equally distributed cube-shaped zones of 0.5m. Therefore, there was one zone in the out-of-plane direction. The line of symmetry was placed on the left side of the model. The roller boundary conditions were imposed on this right end as well as on the bottom and the left end of the domain as shown in Figure 1.

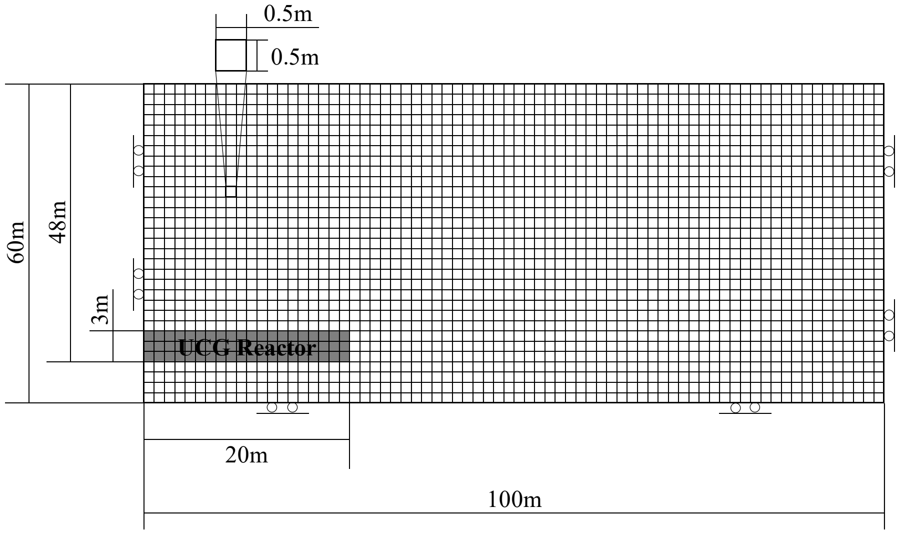

Figure 1. Scheme of the model

Figure 1 shows the 3m high UCG reactor at a depth of 48m. The width of the UCG reactor was 40m. Since the domain was cut along the symmetry line, the half width of the UCG reactor was 20m as shown in Figure 1. The initial hydrostatic stress was imposed on the mesh. A rock density of 2000 kg m^{-3} and a gravitational acceleration of 10m s^{-2} were used throughout the model. The popular Mohr-Coulomb model was implemented. The model was run to equilibrium. Then, prior to the collapse of the UCG reactor, the thermal analysis was carried out for 27 months, the period of the coal combustion at the UCG station in the Moscow basin (Semenenko and Turchaninov, 1957). According to the temperature, the mechanical properties were updated once the temperature field was defined. To simulate the collapse of a reactor, the double-yield constitutive model was implemented at the place of the combustion of the coal seam. There the products of combustion and the material from the collapsed roof formed a so-called goaf. The mechanical properties of the roof were assigned to represent the goaf behaviour. Altering the volumetric properties of the double-yield model, the height of the goaf after the simulation was adjusted to equal 10% of the primary height of the goaf following Derbin et al. (2018).

Thermal Analysis

For the thermal analysis, a temperature in the UCG reactor of 1250°C (Olness, 1981) was fixed in the goaf area of the model. An initial thermal field of the whole domain was the annual average underground temperature in the Moscow basin of 5°C. Three thermal properties were used, namely conductivity, the thermal expansion coefficient, and the specific heat (heat capacity per kilogram), in the thermal conduction model incorporated in FLAC3D.

Thermal conductivity is described by Fourier's law:

$$\lambda = -G/\nabla T \qquad [1]$$

where G [W m^{-2}] is the heat flux density and ∇T [°C m^{-1}] is the temperature gradient.

For the model at hand, a thermal conductivity of 2.097W m^{-1}°C^{-1} was assigned. This value was the average found by Witte (2002) using insitu measurements of a 30m-deep soil profile, which was saturated from a depth of 1m below surface.

The thermal expansion coefficient is determined through the thermal-strain increments as follows (Itasca, 2011)

$$\Delta\epsilon_{ij} = \alpha_t \Delta T \delta_{ij} \qquad [2]$$

where δ_{ij} is the Kronecker delta, and α_t [°C^{-1}] is the coefficient of linear thermal expansion. The thermal expansion coefficient is defined as

$$\alpha_t = \frac{1}{L}\frac{dL}{dT} \qquad [3]$$

where L is a particular length measurement and dL/dT is the rate of change of that linear dimension per unit change in temperature.

For the given model, a thermal expansion coefficient of 3.75e-4°C^{-1} was assigned following the research of Semenenko and Turchaninov (1957). Semenenko and Turchaninov (1957) reported changes of the porosity of clay and sandy clay from 34% to 49% and from 22% to 26% respectively over a range of temperatures of 200°C-600°C at the Moscow basin. Therefore, the thermal expansion coefficients were 3.75e-4°C^{-1} for clay and 1e-4°C^{-1} for sandy clay. Since the UCG reactor was located in the clay, and mostly the clay was heated by the UCG; the thermal expansion coefficient of the clay was chosen for the model domain.

In FLAC3D (Itasca, 2011), the specific heat (Cp) is determined by Equation 4 from the energy-balance:

$$-q_i + q_v = \rho C_p \frac{\partial T}{\partial t} \qquad [4]$$

where q_i [W m^{-2}] is the heat-flux vector, q_v [W m^{-2}] is the volumetric heat-source, ρ [kg m^{-3}] is the mass density, Cp [J kg°C^{-1}] is the specific heat at constant pressure. Waples and Waples (2004) collected and presented the specific heat of different geomaterials in one table. Since the roof and floor of the reactor consisted of clay and were mostly exposed to the heat, a clay specific heat of 860J kg°C^{-1} was taken from the table.

After assigning the thermal properties, the model was run to impose a field of high temperatures. Figure 2 shows the red 'Modelled' curve of the distribution of the temperatures near the UCG reactor.

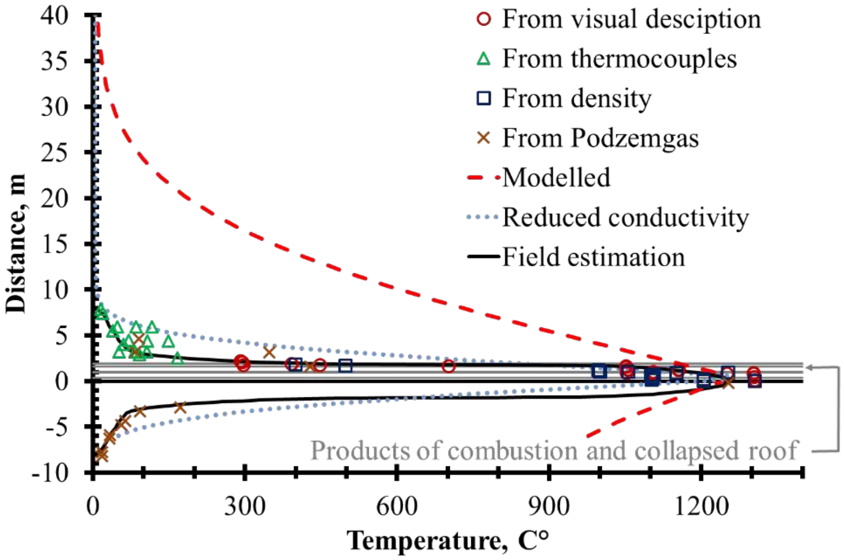

Figure 2: Distribution of Measured (Agroskin and Kazak, 1959 and Kazak and Semenenko, 1960) and Modelled Temperatures

In Figure 2, the 'Modelled' curve gives an idea that the distribution of high temperatures is wide, i.e. up to a vertical distance of 40m from the reactor. To understand if the modelled temperature field was correctly imposed, the literature was reviewed. The previous research has showed that the high temperature was not observed far from the UCG reactor. According to the model of Otto (2017), in the Polish coal basin, the noticeable (more than 50°C) temperature increase occurred at a maximum distance of 10m after 50 days of combustion, and the significant (more than 200°C) temperature increase of the overburden was limited to a distance of 6m. At the Lisichansk UCG station in the Donetsk basin, the high temperature was not noticed further than 8m from the UCG reactor as the black and dashed black curves indicate in Figure 2. Unfortunately, the surface subsidence measurements are not available at the Lisichansk station. At the Lisichansk UCG station, the temperatures were estimated according to the either the visual descriptions of the sample and density data from the lab, measured insitu using thermocouples by Kazak and Semenenko (1960) or obtained from the company Podzemgas (Agroskin and Kazak, 1959). The literature shows the highest temperature was on the floor of the reactor and in the products of coal combustion. The temperature dramatically reduced until a distance from the reactor of 3m. At 8m, the temperature increase was not noticed. The higher temperatures (more than 300°C) were estimated based on the visual descriptions and densities of the samples. Temperatures of less than 300°C were measured by thermocouples. In Figure 2, the modelled curve shows that the distribution of the modelled temperature occurred over a larger distance from the reactor than the measured distribution at the Lisichansk station. The reason might be that the average thermal conductivity of the rock surrounding the reactor is smaller than those inferred from Witte (2002) because of cracks in the overburden.

The thermal conductivity depends on many factors, for example, a soil-rock type and its state. The proportion of water, solids, and air in the soil-rock also influences the conductivity (Ochsner et al., 2001). According to Richter and Simmons (1974), the thermal conductivity is significantly smaller for the cracked soils-rocks. Following this logic, the model was rerun 10 times each time reducing the model thermal conductivity twice. Figure 2 presents the curve 'Reduced conductivity', which shows the thermal distribution modelled with a conductivity of 20 times less (0.1W m °C^{-1}) than the primary conductivity suggested by Witte (2002). The new obtained curve was slightly smoother than the curve of measurements. This can be explained by groundwater (advection) which cools the host soil at the Lisichansk station. In this case, the distance of the distribution of the high temperatures was identical to the measured distance at the Lisichansk station. Base on this identity, a conductivity of 0.1W/m K was assumed to model surface subsidence.

Mechanical Model

The routine of deriving the mechanical properties for modelling surface subsidence, was programmed in FISH, the embedded programming language in FLAC. The procedure of calculation followed Derbin et al. (2018). Distinctively, in this work the mechanical properties were updated according to the raised temperature after imposing the thermal field. One of the key properties of soil-rock for the calculations of the mechanical parameters of the model is the uniaxial compressive strength. The uniaxial strength depends on the temperature. Based on the experimental results of Semenenko and Turchaninov (1957), this dependence was obtained for the clay of the Moscow basin and is presented in Figure 3.

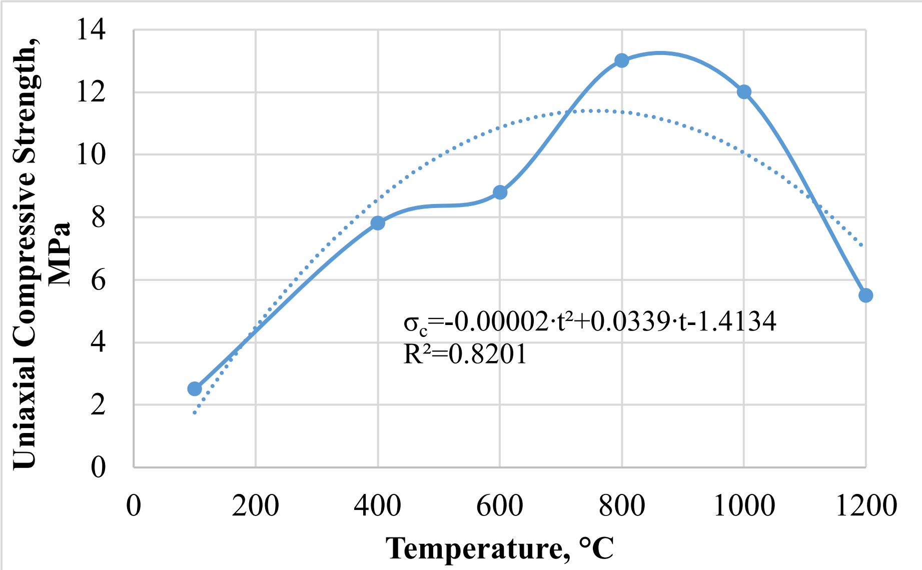

Figure 3. Uniaxial Compressive Strength of Clay under Different Temperatures

The uniaxial compressive strength of the clay under different temperatures has a parabolic-dependence with the vertex at 700°C. The clay got noticeably a little bit stronger at a temperature of 100°C. Figure 3 illustrates that the uniaxial compressive strength of the clay increased from 2.5MPa to 13MPa as the temperature increased from 100°C to 750°C, and then the strength reduced. At a temperature of 1200°C, the clay was two times stronger than the clay at room temperature. Figure 2 also presents a trend line of dependence between uniaxial compressive strength of the clay and temperature with a determination coefficient (R^2) of 0.8201. The equation of the trend line was used in the model to update the uniaxial compressive strength:

$$\sigma_c = -0.00002^{-5} \cdot t^2 + 0.0399 \cdot t - 1.4134 \qquad [5]$$

where t (°C) is the temperature.

Results and Discussion

The model was run for three cases, i.e. without thermal analysis, with thermal analysis, and with thermal analysis including the influence of high temperatures on the mechanical properties of the soil-rock. Figure 4 presents the measured surface subsidence profile and these three results from modelling.

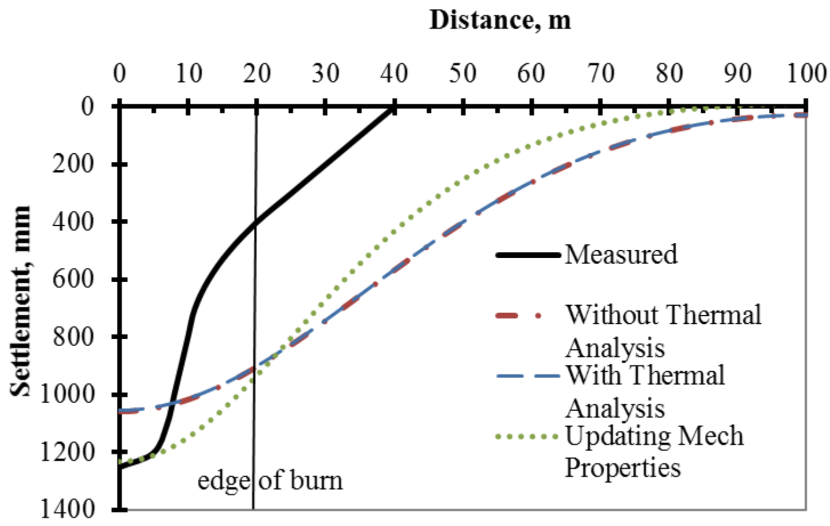

Figure 4. Surface Subsidence Half-Profiles

Figure 4 illustrates that the curves, which are half-subsidence profiles. Two of them are results of modelling with and without thermal analyses. In this research, these two curves are almost identical; however, earlier Derbin (2017) showed that the model with thermal analyses predicted a better subsidence trough. The difference in the earlier and present modelling results were in using different constitutive models. Previously, the modified Cam-clay model was implemented, whereas in this research, the Mohr-Coulomb model was chosen. The modified Cam-clay model requires input of the preconsolidation pressure, which was altered by the thermal stress. This gives the idea that the choice of the constitutive model is vital for accurately predicting the surface subsidence profile. The surface subsidence half-profile obtained with updating the mechanical properties, i.e. elastic stiffness, friction angle and cohesion, according to the temperature, results in an improved prediction of surface subsidence profile to the measurements as shown in Figure 4.

Conclusions

In this work, surface subsidence during UCG was modelled by including a thermal analysis into FLAC3D's finite difference analysis and updating the mechanical properties of the soil-rock, i.e. elastic stiffness, friction angle and cohesion, according to the elevated temperature. During the thermal analysis, it was noticed that the measured thermal field was smaller than the modelled field. This could be caused by cracks in the overburden, which decreases heat conductivity of the soil. Therefore, the conductivity of the soil-rock should be decreased to set the thermal field close to the theoretical prediction. The updating of the mechanical properties of the soil-rock according to the increasing temperature improved the prediction of the surface subsidence.

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References

Agroskin, A. and Kazak, V., 1959, Heating a coal seam and overburden during underground coal gasification. Underground coal gasification, 2, pp. 10-15.

Alejano, L. R. & Alonso, E., 1999, Subsidence prediction with FLAC. The International FLAC Symposium on Numerical Modeling in Geomechanics, pp. 225-232.

Derbin Y., 2017, Numerical modelling of surface subsidence induced by underground coal gasification. PhD thesis, University of Nottingham Ningbo China

Derbin, Y., Walker, J., Wanatowski, D., and Marshall, A., 2018, Numerical Simulation of Surface Subsidence After the Collapse of a Mine. Civil Infrastructures Confronting Severe Weathers and Climate Changes Conference, Springer, pp. 80-97.

Ekneligoda, T., Yang, L., Wanatowski, D., Marshall, A. & Stace, L., 2017, Numerical modelling of ground subsidence at an underground coal gasification site. Geotechnical Engineering, 48, pp. 151-154.

Itasca, 2011, Fast Lagrangian analysis of continua in 3 dimensions, user's guide. Itasca Consulting Group, Minneapolis, Minnesota.

Kazak, V. and Semenenko, D., 1960, Study of geological factors determining the underground coal gasification process. Management of the seam roof under underground coal gasification. Scientific Work of All-Soviet Research Institute of Underground Coal Gasification, 1, pp. 72-83.

Ochsner, T. E., Horton, R. & Ren, T., 2001, A new perspective on soil thermal properties. Soil science society of America Journal, 65, pp. 1641-1647.

Olness, D. U., 1981, The Podmoskovnaya Underground Coal Gasification Station, Lawrence Livermore Laboratory, University of California.

Otto, C., 2017, Numerical analysis of thermal, hydraulic and mechanical processes in the near- and far-field of underground coal gasification reactors. PhD Thesis. GFZ

Richter, D. & Simmons, G., 1974, Thermal expansion behavior of igneous rocks. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, Elsevier, pp. 403-411.

Semenenko, D. K. & Turchaninov, I. A., 1957, Rock performance under underground coal gasification. Underground coal gasification. Underground coal gasification, 3, 8.

Sutherland, H. J. & Hommert, P. J., 1984, Subsidence Prediction for Two UCG Projects. In Situ, 8(4), 347-367.

Tian, H. 2013. Development of a thermo-mechanical model for rocks exposed to high temperatures

during underground coal gasication. PhD thesis, RWTH Aachen University.

Turchaninov, I. and Sazonov, V., 1958, Some features of coal seam gasification and movements of the overburden during UCG at the Shatsk station. Underground coal gasification, 3, pp. 11-16.

Vorobiev, O., Morris, J., Antoun, T. & Friedmann, S., 2008, Geomechanical simulations related to UCG activities. International Pittsburgh Coal Conference, Pittsburgh, PA.

Waples, D. W. & Waples, J. S., 2004, A review and evaluation of specific heat capacities of rocks, minerals, and subsurface fluids. Part 1: Minerals and nonporous rocks. Natural resources research, 13, pp. 97-122.

Witte, H. J., Van Gelder, G. J. & Spitier, J. D., 2002, In situ measurement of ground thermal conductivity: a Dutch perspective. Ashrae Transactions, 108, 263.

Yang, D., Sarhosis, V. & Sheng, Y., 2014, Thermal–mechanical modelling around the cavities of underground coal gasification. Journal of the Energy Institute, 87, pp. 321-329.

Yavuz, H., 2004, An estimation method for cover pressure re-establishment distance and pressure distribution in the goaf of longwall coal mines. International Journal of Rock Mechanics and Mining Sciences, 41, pp. 193-205.