Numerical Modelling of Ground Subsidence at an Underground Coal Gasification Site

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ABSTRACT: A detailed numerical modelling study was carried out to represent geotechnical aspects of the Wieczorek underground coal gasification (UCG) site in Poland. A coupled thermos-mechanical numerical model was created to represent a single coal burning panel. The coal burning process was simulated by modifying the energy balance equation with an additional term related to the calorific value of coal as a source. Temperature dependent material properties were assigned to the coupled thermal-mechanical model according to published data. In the model, the burning zone spread about 7.5m laterally after 20 days of burning. Results from the coupled model were used to gauge a worst-case scenario in terms of the potential size of a formed cavity. This data was used within a less computationally expensive mechanical-only numerical model in order to evaluate the ground subsidence caused by the worst-case scenario for single and multiple UCG burning panels. The single panel burning resulted in 23mm of ground subsidence at the top of the model after long term coal burning. The ground subsidence measured at the top of the model, at the center point of the gasification arrangement, was approximately 72mm when five panels were burnt with an edge to edge panel distance of 5m; this was increased to 85mm for seven panels. The numerical modelling results have implications to the industrial application of UCG.

KEYWORDS: Numerical model, Underground coal gasification, Calorific value, Subsidence.

1. INTRODUCTION

Underground coal gasification (UCG) offers a significant potential contribution to future energy demand. The process allows obtaining energy in the form of syngas from a thin coal seam that cannot be extracted by conventional methods. According to Bhutto et al. (2013), UCG is a combination of mining, exploitation and gasification that eliminates the need for conventional mining techniques including human involvement and can be used in deep or steeply dipping, un-mineable coal seams.

Though UCG was first tried as early as 1868 by the German scientist Sir William Siemens, it was not industrialized as very few detailed research studies had been carried out on UCG. In 1909, Anson G. Betts obtained the patent for UCG. The first UCG field test program was carried out by Ramsey in England in 1912 (Bhutto et al. 2013) with more extensive trials in North Derbyshire in the late 1950’s (National Coal Board 1964).

The UCG process not only offers a more environmentally friendly energy source compared to traditional coal mining energy but also provides a sub-surface cavity that could potentially be used for the storage of CO_2 (Sarhosisa et al. 2013). Also, as the coal is gasified in-situ, generation of mining related waste is minimized compared to traditional mining (Naghouni 2013; Imran et al. 2014; Shirsat 1989).

The industrial application of UCG is carried out with several parallel burning panels, as illustrated in Figure 1, which enhances the gas production considerably compared to a single panel. One of the major concerns of parallel burning is the induced ground subsidence. The selection of distance between parallel burning panels should be made after a thorough study of the effect of the coal burning process on ground subsidence.

A UCG field study carried out at the Wieczorek mine, Poland, in 2014 was used as the basis of the numerical analyses described in this paper. The numerical analyses were conducted in two stages. The stage 1 numerical model included a section near the UCG panel which was assigned a coupled thermal-mechanical constitutive relationship. This model can capture various important features of the UCG process, including the geotechnical situation during in-situ coal burning, the variation of temperature in the cavity, a gradually decaying energy emission, either forward or backward movement of the burning head, and temperature dependent material properties (Ekneligoda et al. 2015). Stage 2 involved a similar but more computationally efficient mechanical-only numerical model that incorporated results of maximum cavity size from stage 1 in order to evaluate the worst-case scenario of ground movements from single and multiple UCG panels.

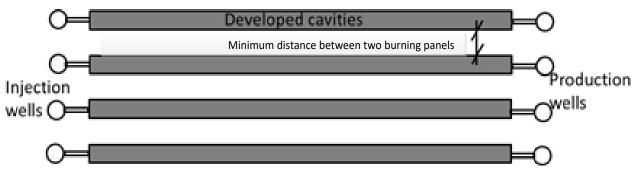


Figure 1 Multi-panel industrial application of UCG

2. NUMERICAL MODELS

A three-dimensional model representing the geological cross section at the Wieczorek site in Poland was created in FLAC-3D (see Figure 2). In the stage 1 analysis, a model extending from a depth of 395m (Z=94m) to 489m (Z=0m) was used, with a section from Z=24.5 to 45m (total height of 20.5m) assigned the coupled thermal-mechanical constitutive relationship (see Figure 2) in order to simulate the coal burning process. This was done by modifying the energy balance equation and adding an additional term as a source that relates to the calorific value of coal. The mesh was fixed horizontally and free vertically along all vertical boundaries (representing planes of symmetry). The bottom boundary was fixed in the vertical direction but free horizontally. A stress boundary condition was assigned to the top of the model to represent the overburden pressure. The geothermal gradient in the Wieczorek area is very low. Therefore, constant temperature was assigned to the model for thermal calculation. For the right-hand side and the bottom of the model, constant temperature (50^{o}C) was set as the boundary conditions. Symmetry (for temperature) was used as the boundary condition for the left-hand side of the model.

It is important to have a such complex modelling approach as the coal burning process is not similar to a mere excavation of a cavity. To account for the fact that the energy release from coal gradually decreases with time, the source term was given as a time decaying function. The mechanical degradation of coal due to burning was carried out by removing the burnt zone from the calculation. The zone was removed after one hour from ignition. The temperature dependent material properties were assigned to the coupled analysis according to the experimental data provided by Ranjith et al. (2012), as given in Table 1.

Table 1 Selected material properties in the present numerical model

Geological layer	Temp. (°C)	Cohesion (MPa)	Friction angle (°)	Tension (MPa)	Elastic modulus (GPa)	Poisson's ratio	Density (kg/m³)
Shale	>100	30	32	10	1.5	0.3	2400
	>400	30.05	33	10.5	1.56	0.3	2450
	>800	30.06	33.5	10.06	1.60	0.3	2450
	>1000	20.98	31.5	9.98	1.48	0.3	2400
Coal	>100	10	30	10	1	0.35	1500
	>400	10.05	33	10.05	1.56	0.3	2450
	>800	10.06	33.5	10.06	1.60	0.3	2450
	>1000	9.98	31.5	9.98	1.48	0.3	2400
Sandstone	>100	10	32	10	1.5	0.3	2350
	>400	10.05	33	10.05	1.56	0.3	2450
	>800	10.06	33.5	10.06	1.60	0.3	2450
	>1000	9.98	31.5	9.98	1.48	0.3	2400

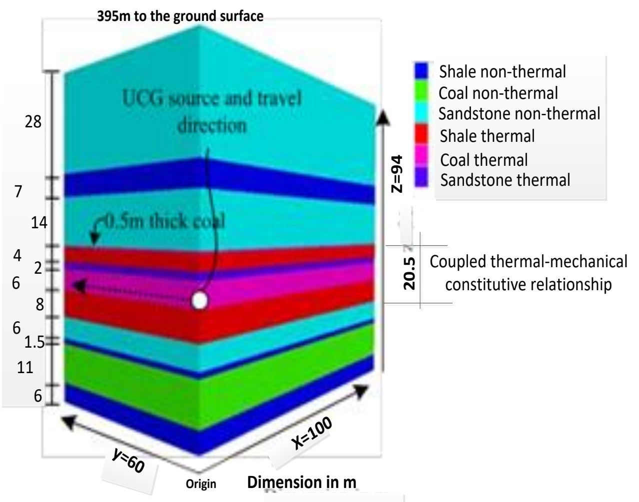


Figure 2 Details of geological profile used in FLAC3D model (Stage 1 dimensions)

The additional stress component due to heat transfer is coupled to the stress calculation. It is important to note that the coupling occurs only in one direction. Therefore, mechanical stress change does not affect the temperature rise, but the temperature rise affects the mechanical stress change. The coupled equation can be presented in simple form as in Eq. (1). Assuming that the thermal expansion/contraction is isotropic, the stress–strain relationship for a non-isothermal material can be presented as;

$$\frac{\partial \sigma_{ij}}{\partial t} = 2G\left[\frac{\partial \varepsilon ij}{\partial t} - \alpha_t \frac{\partial T}{\partial t}\delta_{ij}\right] + \left(K - \frac{2}{3}G\right)\left[\frac{\partial \varepsilon_{kk}}{\partial t} - \frac{\partial T}{\partial t}\right]\delta_{ij} \quad (1)$$

Where $G = E/2(1 + \nu)$, $K = E/3(1 - 2\nu)$ and $\varepsilon_{kk} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$. σ_{ij} is the component of the total stress tensor, ε_{ij} is the component of the total strain tensor, G is shear modulus, K is bulk modulus, E is Young's modulus, ν is Poisson's ratio, δ_{ij} is the Kronecker delta, T the temperature, and α_T is the thermal expansion coefficient.

The equations of equilibrium and the strain–displacement relations can be expressed as

$$\sigma_{ij,j} + f_i = 0 \quad (2)$$

$$\epsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) \quad (3)$$

Where f_i and u_i ($i = x, y, z$) are the components of the net body force and displacement in the i-direction, respectively. A comma followed by subscripts represents the differentiation with respect to spatial coordinates and repeated indices in the same subscript imply summation over the range of the indices (generally 1–3, unless otherwise indicated) (Detournay 1993; Zhang 2008).

In the stage 2 analyses, the lateral dimensions (X and Y) of the model illustrated in Figure 2 were modified in order to ensure boundary effects on measurements of displacements were minimized. For the single panel analysis, the lateral dimensions were increased to X=110m and Y=120m; for the multiple panel analyses they were increased to X=200m and Y=120m. The total height of the model was maintained at 94m for both single and multiple panel analyses. This model used standard mechanical constitutive relationships in order to decrease the computational time required to obtain results. Analyses were conducted to evaluate ground movements for worst-case UCG scenarios for single and multiple panels. This model was deemed to represent the worst-case scenario because it included an estimate of maximum cavity size after long term burning (based on stage 1 results) and also because it does not redistribute stresses gradually with excavation.

3. RESULTS

In this study (stage 1) it was found that maximum temperature within the mesh was always less than 1000°C (Ekneligoda et al. 2015). The numerically measured temperature value well agrees with the field measurement (Butto et al. 2013). Therefore, the same arrangement was used in all the subsequent analysis. The burning zone in the numerical model spread 7.5m perpendicular to the burning direction in the horizontal plane and 5.5m in the vertical direction after 20 days of burning. The numerically predicted cavity after 20 days of burning is illustrated in Figure 3.

In the stage 2 analysis, the worst-case scenario of single cavity development was simulated by removing a region of the coal layer 30x12x6m all at once. The longest dimension of 30m was selected to account for uncertainty associated with the movement of the burning head and to ensure a worst-case scenario was considered. The ground subsidence measured at the top of the model (395m below the real ground level) was 23mm directly above the cavity and 5mm at a distance 100m (in X-direction) offset from the cavity centerline. The far filed effect of the underground coal gasification is implied by the subsidence at 100m away from the gasification site.

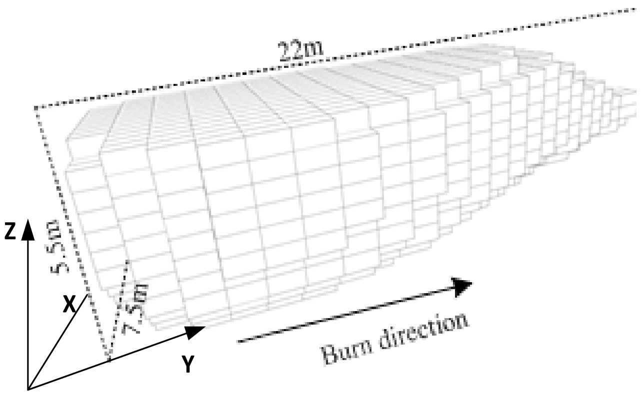
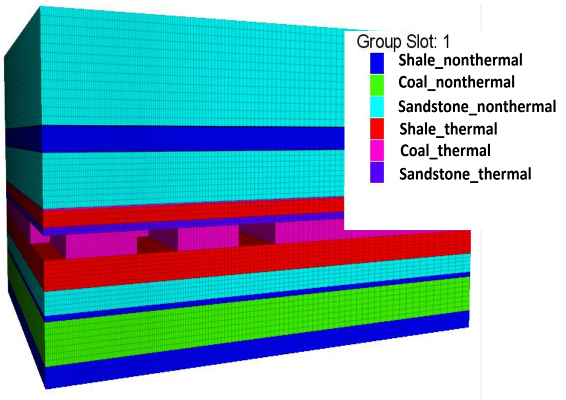
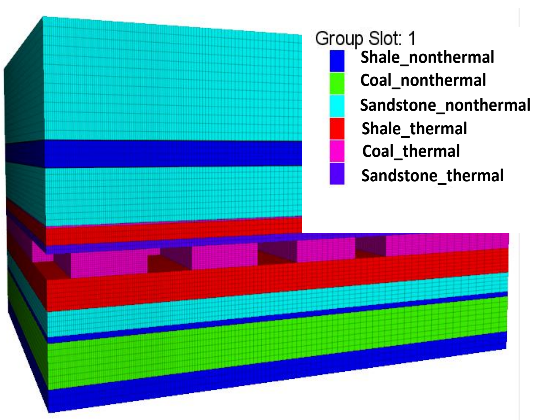


Figure 3 Stage 1 analysis results: cavity development after 20 days

Additional stage 2 analyses were conducted in which 5 and 7 burning panels were removed instantaneously from the model (Figure 4). The ground subsidence was evaluated for different distances between panels, ranging from 5m to 20m (edge to edge distance) in steps of 5m. It is also understood from the stage 1 results that by increasing the distance more than 20m between panels would not be economical as most of the coal between the panels will be left unburnt. Therefore, the simulations were not carried out beyond 20m. The subsidence above the center point of the gasification panels was 72mm and 88mm for the 5 and 7 parallel burning models, respectively, for a spacing distance of 5m (Figure 5). Gradually deceasing ground subsidence was observed at the center point of the gasification panel's arrangement by increasing the distance between the burning coal panels.

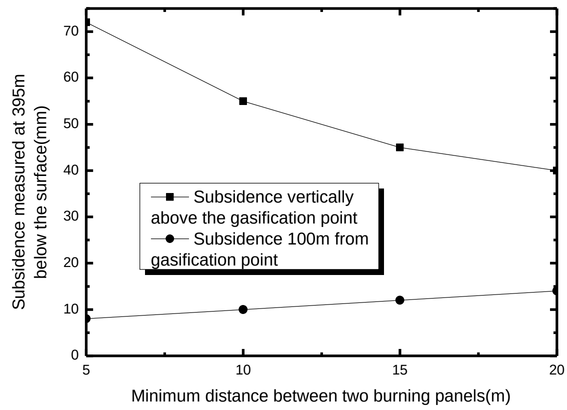


(a) Five burning panels



(b) Seven burning panels

Figure 4 Arrangement of burning panels



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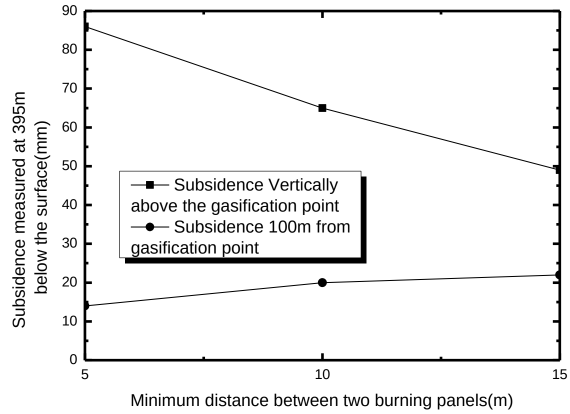

(b) Seven burning panels

Figure 5 Variation of subsidence with panel spacing

4. CONCLUSIONS

A numerical model was presented considering several features that take place in the underground coal gasification process. The maximum temperature during the gasification process was estimated to rise to 1000^{o}C inside the cavity. The maximum dimension of the cavity was 22m in the burning direction, 7.5m perpendicular to the burning direction (lateral direction) and 5.5m in the vertical direction after 20 days of gasification. A worst-case scenario study showed that the maximum displacement directly above the gasification point at the top of the mesh (at a depth of 395) was 23mm and reduced to 5mm at a distance 100m away from the panel.

The ground induced subsidence at the top of the numerical model (a depth of 395m) varied from 72mm to 42mm directly above the gasification point (at the center point of the gasification arrangement) when the minimum distance between panels was varied from 5m to 20m for the 5 burning panel model; the equivalent maximum ground subsidence ranged from 85mm to 50mm for the 7 burning panel model. The outcome of our study is important for developing guidelines during both the pre-gasification stage and the gasification period to optimize the process involved in underground coal gasification.

5. ACKNOWLEDGEMENT

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