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PREDICTION OF SURFACE SUBSIDENCE DUE TO INCLINED VERY SHALLOW COAL SEAM MINING USING FDM

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ABSTRACT: Surface subsidence as an inevitable consequence of underground mining can cause problems for the environment and surface structures. Subsidence due to mining two shallow panels from an inclined coal seam C_1 of the Parvadeh (Tabas) coalfield, located in the eastern part of Iran, was predicted by finite difference method (FDM) using FLAC^{3D} software. The predicted subsidence profiles were compared favourably with both the measured values as well as the profile functions method. Using the parametric analysis, the position of maximum subsidence area was predicted over the panel rise side, which was completely in contrast with deep coal seam mining. The range of critical width to depth ratio (W/H) for both panels was determined between 1.0 and 1.4.

INTRODUCTION

Longwall mining of coal seams causes the formation of subsidence troughs which lead to a range of damages to the environment and surface structures. In order to protect the environment and structures from these damages, relatively accurate subsidence prediction is essential. The shape of subsidence trough due to horizontal coal seam mining is symmetric, whereas it is asymmetric for inclined ones. Most of the research on this subject has been validated for deep panels, while subsidence prediction for shallow and very shallow coal seams has not been given adequate attention. The position of maximum possible subsidence point (S_{max}) due to inclined deep seam mining shifts toward the panel dip side as illustrated in Figure 1 (Peng, 1992; Whittaker and Reddish, 1989).

Surface subsidence can be final (static), dynamic (progressive) and creep (delay or time-dependent). The final subsidence trough is that which exists long after the mining has been completed and its magnitude and shape are quite different from the dynamic subsidence trough formed during the face moving. For longwall coal mining, creep subsidence in fairly short time (4 to 12 months) will be completed and its magnitude is between three to five per cent of maximum subsidence. This period becomes even shorter with decreasing depth (Peng, 1992). In this study, creep subsidence will be neglected with a good approximation due to very shallow depth of objective panels (below 50 m).

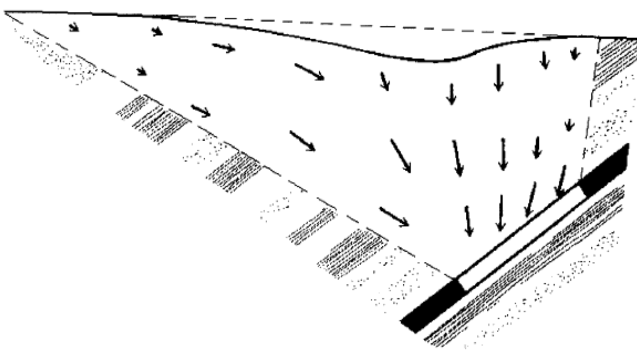

Figure 1 - Strata movements in inclined deep seam mining (Whittaker and Reddish, 1989)

There are three types of subsidence trough, ie; subcritical, critical and supercritical, depending on the width to depth ratio (W/H) of the opening. In subcritical conditions, subsidence does not reach to full development or maximum possible subsidence (S_{max}). When both the width and length of the opening have increased to critical conditions, subsidence reaches the maximum possible value. Thereafter, though both the width and length of the opening continue to increase, the maximum possible subsidence (S_{max}) does not increase, but spreads laterally into an area (Peng, 1992; Whittaker and Reddish, 1989).

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In this paper, a 3D numerical model of the panel No 28 located at Madanjou coal mine is developed using FLAC^{3D} code (Itasca, 2002) which is based on finite difference method (FDM). Then subsidence due to inclined shallow coal seam mining is predicted and compared to profile function developed by Asadi, Shahriar and Goshtasbi (2004) for this coalfield. The proposed numerical model is validated in another coal mine of Parvadeh coalfield (Negin coal mine).

SUBSIDENCE PREDICTION METHODS

Controlling measures in surface subsidence can be considered in three stages including prediction, prevention and protection. The accuracy of subsidence prediction greatly influences the effectiveness of preventative and protective measures (Afsari Nejad, 1999).

Subsidence prediction methods can be categorised into empirical methods (SEH graphical method, profile and influence functions), physical models and numerical methods (National Coal Board, 1975; Alejano, Ramirez-Orangemen and Taboada, 1999; Whittaker and Reddish, 1989).

Empirical methods are designed based on a large number of field measurements. Profile functions are based on a curve fitting procedure that uses a mathematical function to match the measured subsidence profile. When this mathematical function is established by use of actual field data then it can be used for the future prediction of surface subsidence in the mining area (Peng, 1992; Whittaker and Reddish, 1989). Asadi, Shahriar and Goshtasbi (2004) and Asadi et al (2005) developed some profile functions for Parvadeh coalfield (Table 1) which will be compared with numerical method obtained in this paper. Influence functions are based on superposition principle and are suitable only for supercritical conditions (Peng, 1992; Whittaker and Reddish, 1989).

Physical models are helpful for understanding the subsidence mechanism, but are not a good tool for estimating displacements (Alejano, Ramirez-Oyanguren and Taboada, 1999). Numerical methods are different from the other methods in that both the geological and geotechnical aspects of the mine working can be taken into account. Among numerical techniques, FDM is the most suitable method for solving highly nonlinear and large strain problems like subsidence phenomena. Therefore the code FLAC^{3D} which is based on FDM and explicit solution technique was chosen for simulating the subsidence in this study.

The application of numerical methods to real cases has to be accompanied by three processes: calibration of real data, validation and sensitivity analysis (Alvarez Fernandez et al, 2005).

MADANJOU COAL MINE

Madanjou coal mine is a part of Parvadeh 3 coalfield which is located at the south of Tabas city, Yazd province, Iran. Panel No 28 of Madanjou coal mine is selected in order to simulate the subsidence. Geometry and characteristics of this panel are shown at Table 2. Geological column and geomechanical properties of coal seam and surrounding strata are presented in Figure 2 and Table 3 respectively.

SUBSIDENCE SIMULATION

Modelling was carried out with FLAC^{3D} code (Itasca, 2002) which is based on finite difference method and it was performed in following five steps:

1. Determination of boundaries, material behaviour model and material properties.
2. Formation of the model geometry and meshing.
3. Determination of the boundary and initial conditions; Initial running of the program and monitoring of the model response.
4. Re-evaluation of the model and necessary modifications.
5. Interpretation of the results.

In order to avoid disturbance at boundaries and considering the face length of 60 m according to Table 2, a block with dimensions of x=350 m, y= 200 m and z= 160 m was selected as the initial geometry (Figure 3).

Table 1 - Profile functions developed for Parvadeh coalfields by Asadi, Shahriar and Goshtasbi (2004) and Asadi et al (2005)

Location	Developed profile function
Madanjou coal mine	$S(x) = -0.798\left[ce^{-1.9\left[\frac{-x}{19.15}\right]^{2.1}} + de^{-1.75\left[\frac{x}{31.6}\right]^{2.2}}\right]$
Negin coal mine	$S(x) = -0.7457\left[ce^{-8.8\left[\frac{-x}{60}\right]^{2.17}} + de^{-7.4\left[\frac{x}{100}\right]^{2.11}}\right]$

Table 2 - Geometry of panel No 28 in Madanjou coal mine

face length	60 m
dip angle of coal seam	20 º
dip side depth	28 m
rise side depth	7 m
average depth	17-18 m
extracted C_1 seam height	1 m
mining method	unmechanised shortwall mining with caving
direction of mining	along the strike

It has been found that the elasto-plastic constitutive models are the most suitable ones for the simulation of surface subsidence (Peng, 1992; Whittaker and Reddish, 1989; Alejano, Ramirez-Oyanguren and Taboada, 1999; Afsari Nejad, 1999). The elastic models underestimate the maximum subsidence (S_{max}) and mislead the position of maximum subsidence point. Therefore, the elasto-plastic Mohr-Coloumb behaviour model was chosen for simulating the surface subsidence. It is pointed out that the correct determination of S_{max} position is very important in inclined seams. In flat seams, the position of S_{max} locates over the panel center but in inclined deep seams, this point shifts toward dip side of the working (Whittaker and Reddish, 1989).

Table 3 - Laboratory properties of coal seam and surrounding rocks in Madanjou coal mine

Formation	Density (kg/m^3)	Poisson's ratio	Cohesion (MPa)	Internal friction angle (degree)	Modulus of elasticity (GPa)
coal seam	1500	0.26	0.4	22	0.7
roof sandstone	2700	0.32	5.1	38	4
roof siltstone	2700	0.31	2.1	30	2.2
floor sandstone	2700	0.31	3	35	3.6
floor siltstone	2700	0.31	1.2	28	1.6
floor shale	2000	0.26	0.5	25	0.8

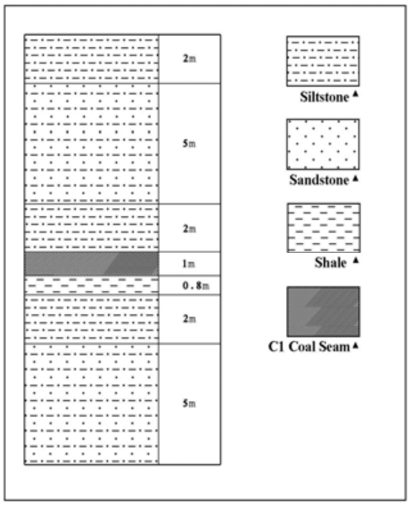

Figure 2 - Geological column at Madanjou coal mine

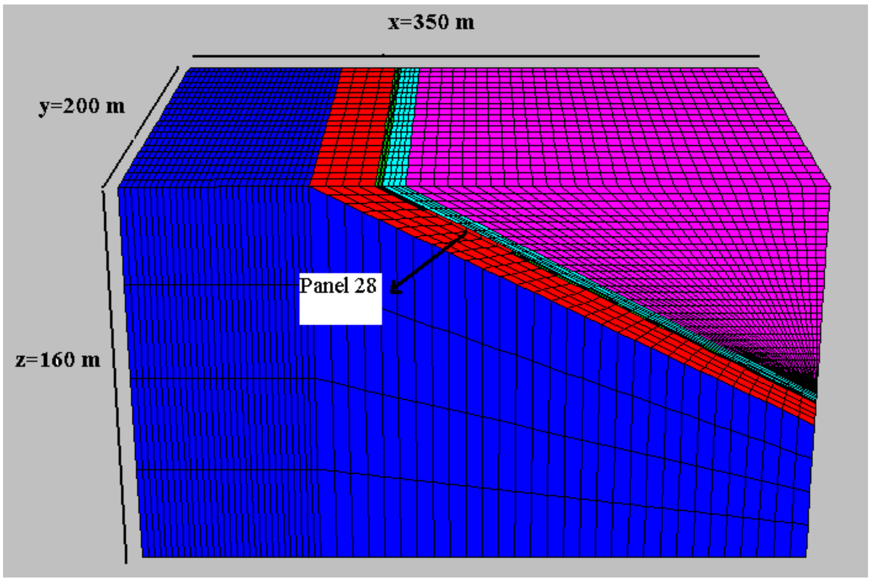

Figure 3 - Model boundaries

Assessment of input parameters

The results of numerical modelling are very sensitive to input parameters. Different methodologies are available in order to achieve them. The concept of reduction factor (RF) has been used successfully by several researchers especially in subsidence problems (Peng, 1992; Alejano, Ramirez-Oyanguren and Taboada, 1999 ; Afsari Nejad, 1999).

Different models are based on different assumptions and may account for different factors, so that rules for deriving parameters for one model may not be valid for another model. For example, one model may be purely elastic and use a Young's modulus that best reflects the rock failure that may occur. The rule to obtain this value from measurements would not be valid in a model that did account for rock failure. Thus, parameter selection for a model requires significant calibration work and experience with that model before there can be confidence in its prediction (Kelly, Luo and Craig, 2002).

Input parameters are classified into stiffness (deformability) and strength parameters. Deformability parameters consist of modulus of deformation (E) and Poisson's ratio. Experiences have shown that Poisson's ratio is little affected by size and does not change appreciably with rock mass scale effects. Therefore in this study, in situ magnitudes of this parameter are approximated equivalent to laboratory ones.

Research has revealed that shape and magnitude of the subsidence trough are strongly dependent on both Young's (E) and shear (G) moduli. Thus, in this analysis, characterisation is performed in two steps. The first one, based upon empirical relationships, allows one to estimate the values of parameters roughly. The second one requires a benchmarking numeric procedure to estimate the final values.

There are some common empirical formulae for estimating the rock mass deformation modulus (E_{RM}) from rock mass rating (RMR) and intact rock deformation modulus (E_i) which are shown in Table 4 (Alejano, Ramirez-Oyanguren and Taboada, 1999 ; Afsari Nejad, 1999; Sonmez et al, 2006).

Starting from an intact rock Young's modulus of 2.2 GPa up to 4 GPa for the immediate and main roof (Table 3), and having RMR=30, then Ramamurthy equations have better agreement in comparison with others. Alejano, Ramirez-Oyanguren and Taboada (1999) used these formulae successfully. Ramamurthy equations result in reduction factors of one-fifth and one-fifty second for horizontal and inclined stratification, respectively. Therefore the range of one-fifth up to one-fifty second is selected as the initial reduction factor of Young's modulus. After back analysis and benchmarking, reduction factor of one-twentieth is considered in order to achieve the *in situ* pre-failure Young's module; ie according to Table 3, E_{RM} = 0.1 GPa up to 0.2 GPa.

According to different studies, the shear modulus of a stratified rock mass must be a small value. For instance, Afsari Nejad (1999) used G=E/15, Alejano, Ramirez-Oyanguren and Taboada (1999) used G=E/24 and Yao, Reddish and Whittaker (1993) used a value somewhat smaller. In this study, G was measured E/50 after running several models and using back analysis.

The Mohr-Coloumb behaviour model is isotropic, while in fact coal measures are anisotropic bodies. Furthermore, due to bedding planes in the coal measures, the post failure values of shear modulus (G) decrease more than the modulus of elasticity and consequently, the bulk modulus (K). Obviously a unique reduction to shear and bulk modulus for derivation of post failure properties can not explain the anisotropic behaviour of rock materials (Lloyd, Mohammad and Reddish, 1997). Thus, two different reduction factors were applied to bulk and shear modulus. After running several models, reduction factors of one-tenth for bulk modulus and one-fiftieth for shear modulus gave the best results.

Initial stresses

From the information held on the world stress map project it can be concluded that the principal horizontal stress direction is likely to be in a north east-south west (NE-SW) direction at Tabas coalfield. No information was available on the magnitude of in situ stresses except that K (ratio of horizontal stresses to vertical stresses) is larger than one. Therefore sensitivity analysis was carried out in order to approximate the horizontal to vertical stress ratio $(K = \frac{\sigma_H}{\sigma_V})$ for this region.

It is found that K=1.5 and K=2 have similar trend with each other while for K=2.5, S_{max} reduces significantly and its position shifts to the panel center, besides uplift of surface becomes abnormal. Therefore K is considered 1.5 with a good approximation in model (Figure 4).

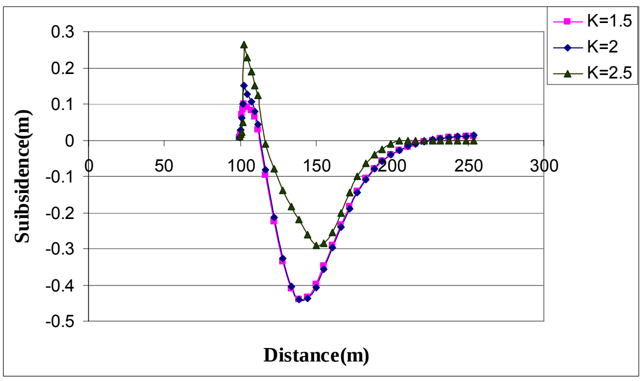

Figure 4 - Sensitivity analysis to initial stress

The similar results between K=1.5 and K=2 might be due to horizontal stresses in practice being anisotropic and maximum horizontal stresses are nearly 1.4 times the minimum horizontal stresses, but this issue is not considered in the model because of data deficiency.

Interpretation of the results

The program was run up to obtaining the final results which is shown in Figure 5. It is observed that the predicted limit angle by FDM over the rise side has a good agreement with measured limit angle (nearly 40°) while at the dip side, FDM predicts wider subsidence trough in comparison with measured one ie 57° vs 49° which is illustrated in Figure 6.

Table 4- Empirical equations suggested for estimating the rock mass modulus of deformation (Sonmez et al, 2006; Alejano, Ramirez-Oyanguren and Taboada, 1999)

Originator(s)	Required parameters	Limitations	Equation
Bieniawski(1978)	RMR	$RMR > 50$	$E_{RM} = 2RMR - 100\ (GPa)$
Serafim and Pereira(1983)	RMR	$RMR \leq 50$	$E_{RM} = 10^{(\frac{RMR-10}{40})}\ (GPa)$
Ramamurthy(1986)	E_i, RMR	horizontal stratification inclined stratification	$E_{RM} = E_i e^{(0.0217RMR-2.17)}$ $E_{RM} = E_i e^{(0.0564RMR-5.64)}$
Nicholson and Bieniwaski(1990)	E_i, RMR	-----------	$E_{RM} = E_i\left[0.0028\ RMR^2 + 0.9\exp(\frac{RMR}{22.82}\right]$
Mitri et al(1994)	E_i, RMR	-----------	$E_{RM} = E_i\left[0.5(1-(\cos(\frac{\pi.RMR}{100})))\right]$
Sonmez et al(2006)	E_i, RMR	-----------	$E_{RM} = E_i \times 10^{\left[\frac{(RMR-100)(100-RMR)}{400\exp(\frac{-RMR}{100})}\right]}$

Figure 7 compares predicted subsidence profiles by FDM, surveying and profile function method. The position of predicted S_{max} by FDM completely coincides with surveying and profile function method. Therefore in shallow workings like this case (average depth=17.5 m), the position of S_{max} shifts to rise side (shallower part) of the panel. This phenomenon is totally in contrast with deep seams in which point of S_{max} shifts toward dip side of the panel. From this point of view, Parvadeh (Tabas) coalfields are exceptional.

Furthermore, predicted S_{max} by FDM is nearly three per cent less than the predicted S_{max} by surveying and profile function. Actually FDM neglects residual subsidence so it underestimates S_{max} while the profile function predicts final subsidence basin.

Residual or time-dependent subsidence in this mine is roughly three per cent of maximum subsidence. On account of low depth, ground movements reach to the surface sooner than usual. Generally in longwall mining with caving, especially in shallow mines, the residual subsidence is almost negligible; vice versa in room and pillar method it has an outstanding role in creating the final subsidence profile (Peng, 1992).

Some uplift or upsidence (less than 10 cm) is created over the rise side and panel floor. It can be due to sequences of sandstone strata that behave like a beam in which one similar case has been reported in one of the Columbia's mines (Donnelly et al, 2001). In addition, due to very low depth of panel, cover load pressure may not be high enough for reconsolidation of gob material and accordingly uplift results. One of the advantages of FDM in comparison with profile function is its ability to figure the uplift at the surface or panel floor. No uplift is observed in measured profile provided by Asadi, Shahriar and Goshtasbi (2004) and Asadi et al (2005) because of their efforts were just focused on measuring downwards subsidence.

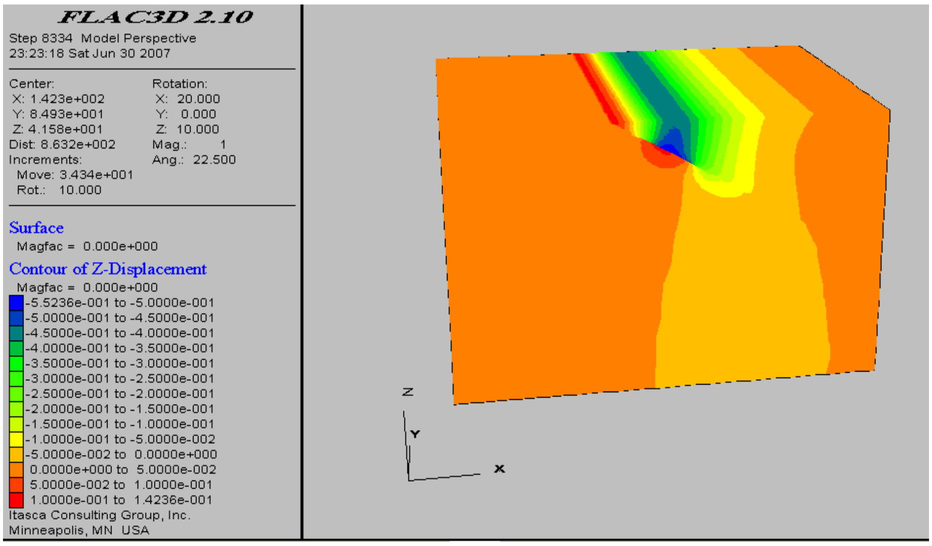

Figure 5 - Ground subsidence over panel No 28

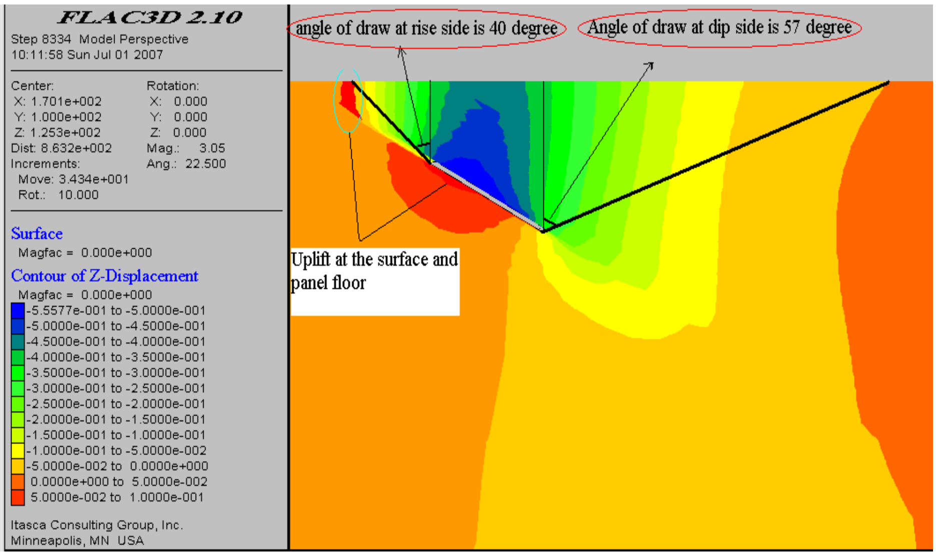

Figure 6 - Angles of draw at the sides of panel No 28 located at Madanjou coal mine

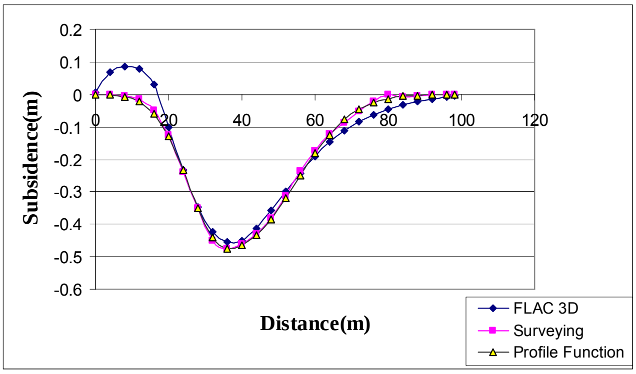

Figure 7 - Predicted subsidence profiles by FDM and profile function vs measured ones by surveying

VALIDATION

In order to ensure the reliability of the proposed numerical model, it has to be validated somewhere else in Parvadeh coalfield. For this purpose, Negin coal mine which is located north of Parvade 2 coalfield is selected. Geometry and characteristics of the simulated panel is shown in Table 5. Figure 8 shows the angles of draw at panel sides as well as flat bottom of subsidence trough due to supercritical dimensions of opening.
Figure 9 compares predicted subsidence profiles by FDM, surveying and profile function method. It is observed that similar to Madanjou coal mine, the predicted angle of draw at rise side has a good agreement with survey and profile function method. Conversely FDM predicts wider profile at the dip side. Furthermore FDM shows again some uplift at the surface which does not appear in surveying and profile function method. The position of S_{max} predicted by FDM has been shifted a little toward the rise side and does not coincide exactly with profile function method. It seems that for steeper coal seams the model has to be calibrated.

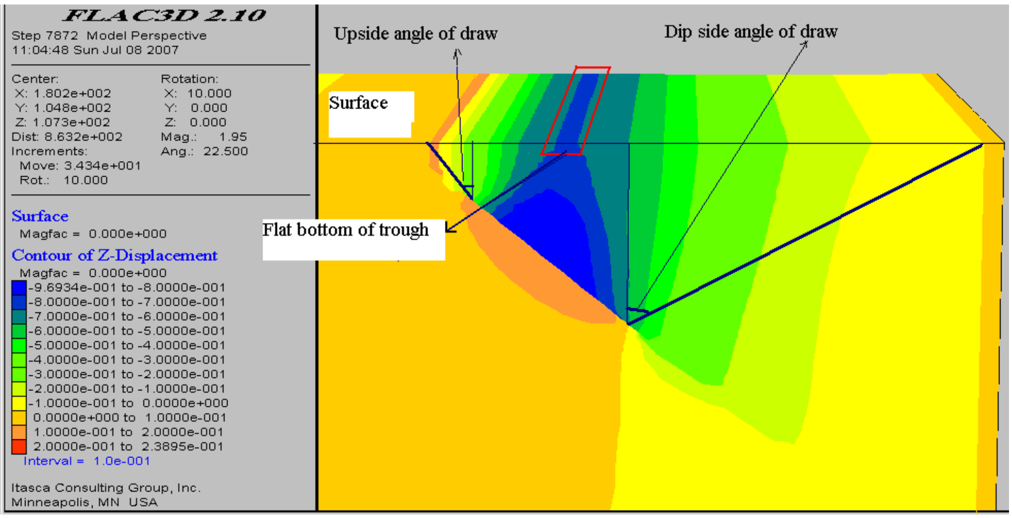

Figure 8 - Angles of draw at the sides of panel

SENSITIVITY ANALYSIS

In order to apply numerical models to real cases, in addition to calibration and validation, sensitivity analysis must be carried out on the parameters affecting the shape and magnitude of the subsidence trough (Alvarez Fernandez et al, 2005).

Sensitivity analysis to panel width

According to Figure 10, when the panel width is 8.5 m (W/H= 0.85), subsidence is about 200 mm and as the panel width increases to 17 m (W/H=1.47) subsidence reaches to 440 mm. By increasing the width to 25.5 m (W/H=1.96) it does not cause any increase in the S_{max} and just subsidence profile spreads laterally. It is concluded that critical width to depth ratio (W/H) is between 0.8 and 1.4. Furthermore increasing the panel width causes subsidence profile to be widen.

Sensitivity analysis to seam depth

Sensitivity analysis was done for three depths of 17 m (W/H=2.91), 50 m (W/H= 1) and 64 m (W/H=0.77) which is shown in Figure 11. It is observed that by increasing the depth, the ground surface uplift is reduced, and the subsidence profile becomes wider due to widening the area of influence. In addition, it is obvious that the critical width to depth ratio (W/H) is larger than one. Therefore according to results obtained from sensitivity analysis on depth and width of the panel, critical width to depth ratio range is between 1.0 and 1.4. According to Figures 10 and 12, subsidence due to mining of panels with similar W/H is equal.

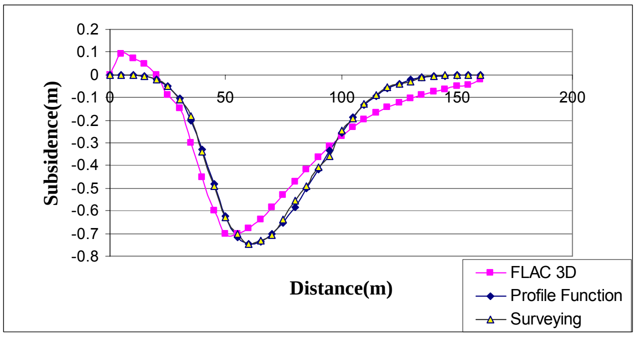

Figure 9 - Predicted subsidence profiles by FDM and profile function method vs surveying

Table 5 - Geometry and characteristics of the first panel of Negin coal mine

face length	90 m
dip angle of coal seam	30 °
dip side depth	62 m
rise side depth	17 m
average depth	40 m
extracted C_1 seam height	1.7 m
mining method	unmechanised shortwall mining with caving
direction of mining	along the strike

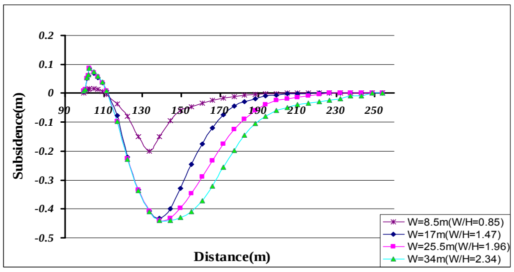

Figure 10 - Sensitivity analysis on panel width

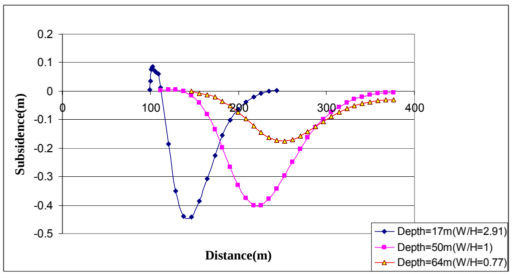

Figure 11 - Sensitivity analysis on seam depth

CONCLUSIONS

In this study, surface subsidence due to inclined very shallow coal seam mining of two underground coal mines in Parvadeh (Tabas) coalfield was simulated by $FLAC^{3D}$ code which is based on finite difference method (FDM). FDM results were compared with measured profile and profile function method. FDM underestimated S_{max} up to three per cent in comparison with surveying and profile function. The reason is that the residual subsidence is neglected in this research but the profile function method predicts final subsidence trough. Furthermore in both cases, FDM in contrast with measured profiles obtained by surveying and profile function method, predicted uplift over the panels rise side at the surface in which was confirmed by local observations. The reason that no uplift was observed in measured profile provided by Asadi, Shahriar and Goshtasbi (2004) and Asadi et al (2005) was due to their efforts just have been focused on measuring downwards subsidence.

The Position of S_{max} in shallow coal seams shifted towards panel rise side which was totally in contrast with deep seam mining. Sensitivity analysis showed that by increasing the depth, this point gradually shifts toward the panel dip side. It was also found that critical width to depth ratio range is between 1.0 and 1.4 for both panels. This range is a little lower than the range of critical W/H ratio which has been found by National Coal Board of UK (1975). This might be related to very low depth situation of both panels.

Numerical methods can illustrate subsidence mechanism better than profile function due to taking into account the geomechanical material properties. Accordingly profile function results can hardly be extrapolated from one coal mining area to another, and even sometimes from panel to panel. Empirical methods have their own advantageous because of their simple and inexpensive applications.

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