CHAPTER 8:

SUBSIDENCE

PREDICTION METHODS

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DEQ Exhibit 20

8.1 OVERVIEW OF SUBSIDENCE PREDICTION METHODS

There are several methods developed for predicting the final subsidence and the subsidence profiles. The methods to predict subsidence can be divided into various methods:

- Graphical Methods - Profile Function Methods
- Influence Function Methods
- Numerical Modeling Methods
- Empirical Methods

The models based on theoretical and numerical methods usually require extensive information about the properties of the overburden to be properly calibrated for a particular field site. The models based on the empirical methods require an extensive set of field data.

8.2 GRAPHICAL METHODS

8.2.1 PROFILE FUNCTION METHODS

The Profile Function Method is essentially a curve-fitting method against the measured subsidence profiles in a particular region. There are many profile functions developed empirically for nearly all major coalfields in the world. These include for the United Kingdom, the National Coal Board - Subsidence Engineer's Handbook of 1975 and for the United States, Peng and Chen, 1981 and Karmis et al, 1984.

These are generally only applicable to single panels, since they assume the profiles to be symmetrical and fail to recognize the way in which subsidence shapes are modified over adjacent and previously mined areas.

For the SDPS software program, the following equation is used for the profile function calculation (these equations vary by method):

$$S(x) = \frac{1}{2} S_{max} \left\{1 - \tan\left[\frac{cx}{B}\right]\right\}$$

S(x) = Subsidence at x
x = distance from the inflection point
S_{max} = maximum subsidence of the profile
B = distance from the inflection point to point of S_{max}
c = constant
Note: This function was developed using statistical evaluation of data from the Eastern U.S. coalfields.

8.3 INFLUENCE FUNCTION METHODS

The Influence Function Method was first proposed by Bals in 1931. It was further developed by Knothe (1957), Liu and Liao (1965), Brauner (1973), and Marr (1975). This method is now widely used in the world, and can be applied to a wide range of mining geometries, but are more difficult to calibrate than profile function methods.

For the SDPS software, the influence function utilized is the bell-shaped Gaussian function. This method progresses and can simplify to the following formula for calculating subsidence at any given point P:

$$S(x,s) = \frac{1}{r}\int_{-x}^{+x} S_o(x)exp\left[-\pi\frac{(x-s)^2}{r^2}\right]dx$$

m = extraction thickness
a = roof convergence (or subsidence) factor
$S_o(x) = S_{max}$ = maximum subsidence of the profile (if constant m & a)
x_1 and x_2 are the limits of the excavation
r = the radius of principal influence = $\frac{h}{\tan\beta}$
h = overburden depth
β = angle of principal influence

8.4 NUMERICAL MODELING METHODS

Finite element has been used in difficult and complex situations. This is a numerical method and it can simulate nearly every conceivable material property, inhomogeneity, bedding planes, anistropy, and various boundary conditions. It needs skilled personnel and more information which makes this model costly and time consuming and less attractive. While these tools are useful for investigating strata mechanisms and hydrological impacts, they have not yet been found to produce sufficiently accurate predictions of mine subsidence parameters.

8.5 EMPIRICAL METHODS

Empirical methods can be developed for the prediction of subsidence parameters whenever a large database of measured subsidence parameters is available. These methods can be advantageously employed over a wide range of mining geometries, taking into account local variations in strata lithology. Further information on these types of methods can be found in Kratzsch (1983) and Whittaker and Reddish (1989).

8.6 SOFTWARE PROGRAMS

Various models have been used in the US over the past decades, but we will briefly discuss the following:

1) Subsidence Deformation Prediction System (SDPS – VPI & SU)
2) LaModel (WVU)
3) Comprehensive and Integrated Subsidence Prediction Model (CISPM – WVU)
4) NIOSH Ground Control Software

8.7.1 SUBSIDENCE DEFORMATION PREDICTION SYSTEM (SDPS - VT)

SDPS can be obtained through OSMRE's TIPS program for all SMCRA programs – contact your TIPS Service Manager for the program (for industry customers, purchase can be done through Carlson Software). It was developed by Dr. Karmis and Dr.

Agioutantis through Virginia Tech, and is updated periodically by Dr. Agioutantis.

SDPS can predict the vertical subsidence, horizontal displacement, tensile and compressive strains, slope and curvature. It is a computer friendly, easy to use and predicts within reasonable accuracy. The output can be in text, table, graph or CAD-compatible format. The current installation package for SDPS also includes copies of the NIOSH Ground Control Software, see section 4.7.4.

There are four separate modules within SDPS:

1) Profile Function
    a. Easiest to apply
    b. Minimum input needed: panel width, overburden depth, seam thickness, and percent hardrock in the overburden
    c. Location of prediction points automatically established along the transverse axis of the panel
    d. Empirical parameters are already built into the profile function equation
2) Influence Function
    a. More inputs required for the influence function, with the following steps usually followed:
        i. Establish the mine plan
        ii. Establish the location of the prediction points
        iii. Develop empirical parameters pertaining to each case study
        iv. Time parameter
3) Pillar Stability Analysis Module – to be discussed in the Pillar Design chapter
4) Graphing Module – for display of results

UPDATE from Agioutantis et al, 2014: Original programming for SDPS was done using mainly Appalachian coalfield data. Due to this “bias” in the software, some of the other areas of the country were not satisfied with the results of the analysis performed using SDPS. In 2007, OSMRE funded further software development to take into account data from the Illinois coal basin. Illinois coal bearing strata creates unique and challenging mining conditions and unique subsidence conditions. The immediate floor is often a weak clay-rich rock (underclay or fireclay) and of a highly variable thickness. Pillar punching and floor heave can be highly variable and unpredictable. A paper is available in your reference material describing the modifications to the software that were done for this region.

8.7.2 LAMODEL (WVU)

LaModel has been developed by Dr. Keith Heasley with West Virginia University (WVU) since 1994, and is available here: http://web.cemr.wvu.edu/~kheasley/LaModelDownloads/. This is a numerical modeling software package, and is usually used in more complex mining situations, such as multiple seam mining, complex mine geometries, yielding pillars and variable topography. The use of this program is more complex than SDPS, but support is available from NIOSH, WVU and OSMRE.

8.3.3 COMPREHENSIVE AND INTEGRATED SUBSIDENCE PREDICTION MODEL (CISPM - WVU)

Developed by West Virginia University, available here:
http://web.cemr.wvu.edu/~yluo/CISPM.htm

A computer program package for predicting surface subsidence induced by underground mining operations. The development of the prediction package is based on the influence function method that is widely adopted in the major mining countries including US coal mining industry. The findings from our researches in the last 15 years on mining subsidence have been incorporated into this package. The prediction model has been validated by a large amount of field data. It has been successfully employed in numerous cases of assessing the subsidence influences on as well as designing and implementing mitigation measures for various surface structures.

8.7.4 NIOSH GROUND CONTROL SOFTWARE

Suite of software programs developed by NIOSH and distributed via:
http://www.cdc.gov/niosh/mining/researchprogram/groundcontrol.html. The ones in bold are the ones we will discuss in class. For more information, please see the NIOSH website.

- **Analysis of Longwall Pillar Stability (ALPS)**
- **Analysis of Retreat Mining Pillar Stability (ARMPS)**
- Coal Mine Roof Rating (CMRR)
- Analysis of Roof Bolt Systems (ARBS)
- Analysis of Horizontal Stress Effects in Mining (AHSM)
- Analysis of Multiple Seam Stability (AMSS)
- **Analysis of Retreat Mining Pillar Stability - Highwall Mining (ARMPS-HWM)**

8.7.3.1 ANALYSIS OF LONGWALL PILLAR STABILITY (ALPS)

Required by MSHA for permitting of underground coal mines, used for designing pillars for longwall mines. Estimates the load and load-bearing capacity within the mine, and calculates a stability factor (SF) from the calculations.

8.7.3.2 ANALYSIS OF RETREAT MINING PILLAR STABILITY (ARMPS)

Required by MSHA for permitting of underground coal mines, used for designing pillars for room-and-pillar retreat mining. Calculates the stability factor (SF) from estimated pillar loads and load-bearing capacity within a given design.

8.7.3.3 ANALYSIS OF RETREAT MINING PILLAR STABILITY (ARMPS - HWM)

Not currently required by MSHA for permitting of highwall coal mines. However, the program is being used in permit applications for highwall mines in the US. Calculates a stability factor (SF) for the web and barrier pillars associated with a highwall mine plan.

References, Chapter 8

Agioutantis, Z., Barkley, D., Karmis, M. and Elrick, S. 2014. *Development of an Enhanced Methodology for Ground Movement Predictions Due to Longwall Mining in the Illinois Basin.* Proceedings of the 33rd International Conference on Ground Control in Mining. Morgantown, WV.

CISPM website: http://www2.cemr.wvu.edu/~yluo/CISPM.htm

Keith Heasley's website: http://www2.statler.wvu.edu/~kheasley/

Mine Subsidence Engineering Consultants. 2007. *General Discussion on Systematic and Non-Systematic Mine Subsidence Ground Movements.*

National Coal Board. 1975. *Subsidence Engineers' Handbook.* London: National Coal Board, Mining Department.

NIOSH Ground Control website: http://www.cdc.gov/niosh/mining/topics/GroundControlOverview.html

SDPS Help file

Whittaker, B.N. and Reddish, D.J. 1989. *Subsidence: Occurrence, Prediction and Control.* Department of Mining Engineering, The University of Nottingham, United Kingdom.