A Risk Analysis Subsidence Approach for the Design of Coal Refuse Impoundments Overlying Mine Workings

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ABSTRACT: Coal refuse impoundments constructed in the steep valleys of the Appalachian coal producing states of the Eastern USA can be easily and economically used to confine large volumes of slurry material. In this paper, a "risk analysis" approach was utilized to evaluate the potential impacts of room-and-pillar mine workings on a specific coal refuse impoundment site. Under this methodology, a "worst case" scenario of total pillar collapse was assumed and the resulting surface ground movements were calculated using the Surface Deformation Prediction System (SDPS), a ground movement prediction technology accepted by industry and regulatory authorities in Appalachia. Potential impacts on the impoundment were assessed using established and accepted damage criteria. The ground movement predictions were subsequently utilized by the design engineers in developing the final specifications and tolerances for this impoundment.

1 INTRODUCTION

Appalachian coal recovered during mining frequently contains diluting material such as shale, clays, bone, and sulfur streaks originating from the immediate roof and floor. This waste must be removed in order to produce a marketable product. This is compounded by the fact that current coal production in the Appalachian region is concentrated in thin seams. In addition, the economics of underground room-and-pillar or longwall coal production do not allow for the separation of waste during coal recovery as is commonly done in surface mining. Since the majority of underground coal must be cleaned through a processing facility, the generation of coarse and fine coal refuse is an inherent part of Appalachian underground coal mining (Newman 2003).

Storage of coal processing waste is limited to above ground slurry impoundments, slurry cells, or, in a very few cases, underground in abandoned mines. Slurry impoundments permit the settlement, dewatering, consolidation, and compaction of fine wastes behind an engineered embankment.

To be economically efficient, a preparation plant must be located close to the mine portal so that the run-of-mine coal can be delivered to the plant by conveyor belt. Similarly, the slurry impoundment must be located close to the preparation plant to minimize material handling costs (Newman 2003).

When impoundments are constructed in close proximity to active or abandoned underground coal mines, the impact of past and present mining on the long-term stability of the structure must be evaluated. Such an analysis requires the ability to predict potential surface ground movements, both vertical (i.e., subsidence) and horizontal (i.e., displacement/strain).

In the case under investigation, the mine is an underground operation that underlies a portion of an impoundment in West Virginia, USA. The impoundment overlies a section of the mine workings and, therefore, long term stability of the mine workings is of concern, as the impoundment reaches the maximum crest at an elevation of 2,240 ft (683 m). The corresponding maximum pool elevation is 2,218 ft (676 m).

In order to address long-term mine stability, a number of detailed studies have been conducted by consulting companies engaged in this project. These investigations have addressed the stability of the pillars, roof, floor and overburden of the mined area, by considering both individual pillars as well as "global" sections. In addition, these studies have addressed the potential impact of mine subsidence on the impoundment, using a comprehensive finite element analysis (Newman, 2003).

In this paper, a "risk analysis" approach was utilized to evaluate the potential impacts of room-andpillar mine workings on the impoundment site. Under this methodology, a "worst case" scenario of total pillar collapse was assumed and the resulting surface ground movements were calculated using the Surface Deformation Prediction System (SDPS). This ground movement prediction technology is widely accepted by industry and regulatory authorities in the Appalachia coal producing states. Potential impacts on the impoundment were assessed using established and accepted damage criteria. The predicted ground movement values were utilized by the design engineers in developing the final design specifications and tolerances for this impoundment.

In order to perform this investigation, the following tasks were completed:

- Evaluation of the mining and geological conditions
- Review of background literature information and reports submitted by consultants
- Development of site-specific ground prediction techniques
- Prediction of expected ground movements in the study area
- Assessment of possible mining impacts on the impoundment

2 DEFORMATION PARAMETERS AS RELATED TO POTENTIAL DAMAGE

Damage to surface structures, especially buildings, is mainly caused by tilt, angular distortion (as related to differential settlement), bending (differential tilting) and horizontal strain, or a combination of these effects (Singh, 1992). Surface movements caused by underground mining are usually described by a number of characteristic indices, including: vertical displacement or subsidence, horizontal displacement or lateral movement, slope or tilt, horizontal strain, ground strain, and vertical curvature (Agioutantis and Karmis, 1998).

These ground movements have been utilized in a number of damage classification systems to develop damage criteria as a function of structure type. The National Coal Board (NCB, 1975) proposed one of the earliest and most widely used damage-scale classification systems. A study to develop established damage-limit values that correspond to various types of movements for different building categories was reported by Bhattacharya and Singh (1985). This classification scheme was based on extensive information collected in a number of countries. The results of this study were tabulated (Singh 1992) according to building categories, movement types and ranges of damage-limits. In addition, Karmis et al., (1995) reported a comparison of damage classification schemes utilizing horizontal strain and angular distortion.

When considering the impacts of ground movements on surface impoundment, the most comprehensive analyses of damage criteria and threshold values are derived from case studies documented mainly in Britain and Australia. These case studies have suggested that, when undermining bodies of water, tensile strain values in the range of 5 to 15 mm/m (or 5 to15 x 10^{-3}) can be used as potential ground movement limits. The National Coal Board (NCB, 1975), for example, has recommended a threshold damage value of 10 mm/m for the United Kingdom. Whittaker and Reddish (1989) have provided further discussion in support of the 10 mm/m limit. This threshold value was also recommended by Babcock and Hooker (1977) in Bureau of Mines Information Circular 8741, a document generally accepted as the "best practice" guide in the USA.

3 THE SDPS SOFTWARE

The Surface Deformation Prediction Software (SDPS) is a package that can address both surface deformations due to underground mining, as well as mine stability issues. One of the programs in this package implements the influence function method as described by Karmis *et al.* (1990a). This program can calculate a number of surface deformation indices given a digitized mine plan and digitized surface topography and appropriate subsidence parameters (see sections 3.1 and 3.2). Calculations are based on several empirical relationships, developed through the statistical analysis of data from a number of case studies (VPI&SU 1987, Karmis *et al.* 1992), which include:

- A correlation of the maximum subsidence factor with the width-to-depth ratio of a panel and the percent hardrock (%HR) in the overburden.
- The percent hardrock in the overburden is defined as the sum of the thickness of the strong rocks expressed as a percentage of the total overburden thickness. In the original work (VPI&SU, 1987) a minimum thickness for hardrock layers of 2 feet was assumed. In this case, a more conservative approach, assuming 5 feet as the minimum thickness in the hardrock calculations was used.
- A correlation of the distance of the inflection point from the rib of the panel, with respect to the width-to-depth ratio of the panel
- A regional value for the tangent of the influence angle (tanb) and the radius of influence
- A regional value for the horizontal strain coefficient (Bs)

In effect, this implementation of the influence function method can model very complex mine layouts under variable surface terrain, and can calculate a number of deformation indices, including: subsidence, slope, horizontal strain and surface curvature, at any point on the surface or at any other elevation above the extracted seam (Karmis *et al.*, 1990b). Finally, it should be emphasized that the SDPS software has been tested extensively and has given excellent correlation between predicted and actual measured subsidence and horizontal strain values, for a number of case studies (VPI&SU, 1987; Karmis *et al.*, 1989; Newman *et al.*, 2001).



Figure 1: Partial view of the study area where the impoundment foundation and slurry contour (thick line) are superimposed on mine workings.

3.1 Typical Analysis Steps

When investigating ground movements due to underground mining, the following analysis steps should be performed:

- Digitization of the mine plan and the surface topography
- Importing the mine plan and surface topography into SDPS
- Evaluation of geologic and overburden properties (mainly from drillers' logs)
- Calibration of SDPS with regional parameters
- Adjustment of extraction geometries based on panel characteristics
- Calculation of the pertinent deformation indices
- Contouring of results and superposition on the mine and topography map
- Evaluation of the results

3.2 Typical Parameters used in the Analysis

Parameters that are typically utilized in such analyses include:

- Geometry of the mine layout (panels, pillars, etc.) in 3-D space
- Extraction characteristics of each panel
- Mining height of each panel
- Location of prediction points in 3-D space
- Values of regional parameters as determined through the calibration procedure (influence angle, strain coefficient, edge effect)

4 CASE ANALYSIS

4.1 Case Description

A room-and-pillar mine was developed in the Eagle seam in West Virginia, USA. In 1996, nine panels were driven off a set of mains and terminated beneath the valley floor. At the time of mining the coal refuse impoundment used by the company was downstream of the mining and posed no conflict with the underground works. As adjacent reserves were acquired, the footprint of the impoundment moved upstream. In the proposed final stage of the impoundment (at 2,240 ft (683 m)) the embankment and pool are located above the panels in the now idled mine. The location of the mine workings relative to the embankment and slurry pool is shown in Figure 1 (Newman, 2003).

The overburden thickness above the mine workings ranges between 760 ft (232 m) near the south abutment of the embankment and 120 ft (37 m) beneath the main portion of the embankment. The overburden thickness under the pool ranges between 240 ft (73 m) in the main valley and 720 ft (219 m) on the valley wall. The hardrock component (sandstones and sandy shales), consistent with the definition given above, is about 60%.

The immediate roof of the mine and the main roof strata consist of sandstones, sandy shales and shales, with minor fireclays and coal.

The impact of underground workings was evaluated for two scenarios:

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Figure 2: Simplified mine plan and yielding conditions around the collapsed panels

- The maximum elevation of the crest of the proposed impoundment to reach 2001 ft (610 m), i.e., up to the ninth development stage
- The maximum elevation of the crest of the proposed impoundment to reach 2240 ft (683 m), i.e., up to the eleventh or final development stage

4.2 Calculation Assumptions

Mining Layout Assumptions

- Mine panels were digitized based on the mine map drawings.
- Panel boundaries were simplified to allow for edge effect calculations. Figure 2 presents the simplified panel boundaries for three areas with uniform extraction characterictics.

Mining and Geological Assumptions

- Average extraction height = 6 ft
- Average extraction ratio = 49.6%
- Percent hard rock %HR = 60%
- Overburden depth was calculated using the appropriate overburden contours.

Subsidence Assumptions

- The global pillar safety factors for each of the digitized mine panels and for both impoundment construction scenarios are shown in Table 1.
- Based on the information in Table 1, all three panels could be considered as totally collapsed to allow for a worst case scenario regarding pillar stability of the mine working under and immediately adjacent to the impoundment and pool area. Thus, for both impoundment construction cases it was assumed that panels were totally collapsed and the pillars became coal rubble partially filling the void.
- Equivalent extraction thickness for full collapse = 2.97 ft (i.e. 6 ft x49.6%)
- Subsidence factor for full collapse = 30.9%

- The average parameters for the eastern Appalachian Coalfields were assumed as:
 - Influence angle = 2.31 (default value)
 - Strain coefficient = 0.35 (default value)
- The edge effect for each panel was adjusted based on the mining characteristics at each rib. In genera:
 - The edge effect, towards the unmined, solid, coal was set to 100 ft (30 m), i.e. it was assumed that the rib does not exhibit any yielding.
 - Barriers have a pillar safety factor well above 2.5, but if adjacent panels are assumed to have collapsed it is reasonable to assume that barriers will exhibit some yielding and support loss at the edges surrounding the pillar core. Hence, the edge effect for these areas was set to 50 ft (15 m) allowing for partial yielding of the rib (50% yielding).

5 SDPS SUBSIDENCE MODELING AND DISCUSSION OF RESULTS

Results of the SDPS calculations included vertical movement (subsidence) as well as maximum horizontal strains for the ground surface under the impoundment. Therefore these values were the same for the two impoundment construction scenarios (Figures 3 & 4). Strain contours include both tensile horizontal strains (positive values) and compressional horizontal strains (negative values).

Figure 3 shows a detail of the calculated subsidence contours superimposed on the mine plan. The "footprint" of the impoundment is also depicted for easy comparison. Subsidence values range from -0.5 ft (0.15 m) to 1 ft (0.30 m).

In a similar manner, the horizontal strain contours over the area of interest, superimposed on the mine plan, are presented in Figure 4. Horizontal strain values range from $-4x10^{-3}$ to $+4 x10^{-3}$ (±4 milli-



Figure 3: Subsidence contours over the area of interest with "footprint" of the impoundment for the final construction stage

strains). High tensile strains are concentrated over the non-yielding portion of the barrier pillars. This is to be expected since there is an abrupt change in the subsidence characteristics over that area.

6 CONCLUSIONS

From the extensive analysis, subsidence and horizontal strain calculations and literature review conducted in this study, it reasonable to conclude that the impoundment under consideration will not be impacted by ground movements, in the unlikely event of a total collapse of the underlain mined panels in the aforementioned mine workings.

The predicted strain calculations are well below the accepted threshold value of 10 mm/m for maximum allowable strain. In fact, the actual calculated horizontal strain magnitudes are below 5 millistrains, in the area underneath the footprint of the impoundment.

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Figure 4: Maximum horizontal strain contours (both compressive and tensile) over the mined and collapsed area. Thick line depicts the "footprint" of the impoundment.

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