Developing A Subsidence Management Plan

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Abstract: Mining-induced subsidence is a very complex issue. Prediction of the magnitude and impact of subsidence requires a systematic approach integrating a wide range of disciplines including geology, hydrogeology, and geotechnical, environmental, mining and civil engineering. A subsidence management plan may be used as the interface to integrate all the disciplines and to assist the coal mining industry in dealing with the conflicting demand for maximum recovery and minimum impact at the ground surface. This paper discusses the important steps in developing such a subsidence management plan. Essential to the proposed plan is that subsidence occurrences must be planned for in advance in the mine design stage, and controlled during the production phase to limit the subsidence occurrences to within the proposed design limits. By planning for the anticipated subsidence and its possible impact on the ground surface, coal mining companies can be prepared to avoid surprises or confrontations between the mine and its neighbours.

Key Words: Subsidence, Planning, Control, Surface Impact, Coal Mining

Introduction

In today’s coal mining environment, the objective to maximise coal recovery is not always compatible with environmental legislation and an increasing public awareness or perception of subsidence effects. Coal mining companies often have to deal with constraints such as railways, roads, reservoirs and dams, rivers and lakes, and numerous types of surface improvements. Thus, one of the significant challenges faced by the coal industry is the conflicting objectives of maximum recovery and minimum impact on the ground surface.

Through Coffey’s 20 year involvement with the assessment of mine-related subsidence, and especially from our experience gained from a number of recent case studies, we believe that a subsidence management plan can assist the coal mining industry in making management decisions to optimise mine design. The following list of the recent projects involving studies on impact of subsidence illustrates the range of problems which can arise:

- assessment of subsidence effects due to longwall mining beneath a reservoir;
- investigation of damage to a river due to longwall mining;
- assessment of impact on surface drainage pattern and groundwater changes due to
longwall mining in a rural area;
- assessment of subsidence effects due to mining adjacent to a main railway and beneath surface improvements;
- design and assessment of longwall layout against four different subsidence criteria;
- development of a strata management plan for longwall mining approximately 40m above old workings (a combination of first working, pillar extraction and longwalling);
- impact assessment for civil structures above old mine workings.

This paper presents some initial considerations on the development of such management plans in an attempt to initiate a discussion or debate on the need of such a program.

**Approach to Subsidence Management**

Good practice dictates that a subsidence management plan incorporates planning for subsidence occurrences (Luxbacher, 1992) in advance in the mine design stage, and provides for control during the production phase to limit the subsidence within the design limits. With such planning and control measures, coal mining companies can be prepared to avoid surprises or confrontations between the mine and its neighbours. However, mining-induced subsidence is a very complex issue involving geology, hydrogeology, geotechnical, environmental, mining and civil engineering, as well as a wide range of social aspects. From a geotechnical engineering perspective, the following list of aspects is selected to illustrate the difficulties and complexities in predicting or dealing with mining-induced subsidence:

- the effects on reducing vertical subsidence due to the spanning of massive strata, for example, those found in Newcastle Coalfield;
- the development of localised strain concentrations due to structural features, or locally collapsed spanning strata;
- time-dependant subsidence occurrences relating to pillar settlement into claystone floors;
- subsidence due to pillar failures (bord and pillar operation). In certain areas, these pillars were designed with adequate factor of safety considering coal strength, but failed because the stresses applied to the floor exceeded the bearing capacity of thin, weak layers in the floor strata.

These complexities result in significant technical challenge and uncertainty in development of a subsidence management program and mine planning. Because of the complexities as discussed above, subsidence occurrences must be managed with a systematic approach integrating disciplines such as geology, hydrogeology and geotechnical, environmental, mining and civil engineering, not just considering subsidence prediction based on principles of mechanics/mathematics or statistical analyses.

**Objectives of a Subsidence Management Plan**

At present, the objectives of developing a subsidence management plan are considered to
be:

- to assist the mine management in making decisions regarding subsidence issues;
- to optimise the mine design that maximises coal recovery and minimises the impact at the ground surface;
- to predict possible impact to the surface and to plan protective or remedial measures;
- to control subsidence occurrences within the design limits by implementing risk management and monitoring programs;
- to define key areas or aspects for the development of a subsidence policy.

**Managing Subsidence**

The following sections outline the steps that may be contained in a subsidence management plan.

**Data Collection**

At various stages of geological and geotechnical exploration for a coal mine, a wide range of data is collected. Most data required for subsidence assessment can be obtained from the exploration programs. Experience has shown that a database specifically designed and developed for subsidence assessment is essential.

To develop such a database, it is important that the engineers involved in a particular project understand the critical issues of the mine site, and know the critical factors to be investigated. At Coffey we have found it useful to establish a database established by using conventional geological and geotechnical information, as well as fracture mechanics data for estimating the depth of surface cracks (Li and Moelle, 1993) and soil mechanics information for assessing pillar settlement (Bowles, 1988). In some cases, thin, weak layers in the floor strata were identified through back analyses, as one of the key issues for subsidence control in some mining operations, as mentioned earlier.

It is important to recognise that the prediction of subsidence magnitude is not the ultimate aim of a subsidence management plan. The predicted subsidence leads to the prediction of subsidence impact on the surface or on sub-surface strata. It follows that the database for subsidence investigation should specifically include data relevant to impact assessment for the mine under consideration. For example, if the concerns are related to groundwater changes, information regarding strata caving and hydrogeology would be required, whereas structural information would be essential for an impact assessment on civil structures on the surface.
Development of Geological and Geotechnical Models

The development and implementation of a successful subsidence management plan calls for data processing capabilities, understanding of the controlling geological factors and the establishment of geological and geotechnical models to characterise the prevailing geological and geotechnical conditions. Important tasks of the geological and geotechnical modeling include the identification of vulnerable facilities or natural features which may be present at the surface and the establishment of distribution patterns of the key geological and geotechnical factors over the mine lease.

Two recent case studies illustrate the importance of the geological and geotechnical models.

Case 1: The first example relates to subsidence occurrences over longwall panels, where massive strata exist in the overburden. The critical geological information is the thickness of the massively bedded unit and its location within the overburden. The manifestation of surface subsidence is strongly dependent on nature and thickness of the massive unit and the panel geometry, depth of cover and the above geological information. A geotechnical model to explain this behaviour was established based on the spanning capacity of the massively bedded unit across the underground openings, using the Linear Arch concepts (Brady and Brown, 1985).

Case 2: A second example relates to subsidence occurrences due to partial pillar extraction. A geotechnical model was established and this led to identification of the failure processes that must be avoided to prevent large surface subsidence caused by bord and pillar failures. It also showed that mine design can be optimised by controlling deformation processes including the compression of coal pillars and claystone floors, and the time-dependent pillar settlement into the claystone floor strata. Models developed for the site incorporated the following aspects:

- assessment of time-dependant pillar settlement using the consolidation theory;
- assessment of pillar stability based on coal pillar strength (Galvin et al., 1996), as well as bearing capacities of thin, weak layers in the floor strata;
- evaluation of spanning capacities of massive units to assess bord failures using Linear Arch concepts.

The application of consolidation theory and floor bearing capacity evaluation drew upon classic soil mechanics principals. Back analyses carried out to-date have shown a reasonable agreement between the observations and predictions from there geotechnical models.
Selection of a Subsidence Prediction Methodology

There are many methods available for predicting surface deformation indices at assigned surface points, including numerical, empirical (Holla, 1985, 1987 and 1991a) Profile Function and Influence Function methods. Influence Function methods are commonly used as they provide a practical compromise between the complexity of numerical methods and the simplification of empirical methods. The empirical methods give the maximum values only, whereas the Influence Function methods provide a distribution of surface deformation indices over the area of interest. The Influence Function methods, like the numerical modelling approach, need to be calibrated against subsidence survey data from mines/areas with similar geometry and geology to judge their validity and adequacy. The established prediction model can then be refined with the progression of mining as measured subsidence data for the site become available. Our experience has shown that the Influence Function methods, such as SDPS (VPI&SU, 1987), can provide realistic subsidence prediction values, however, the accuracy and efficiency of the modelling depend largely on the understanding of the influence of overburden geology and mine geometry on the surface subsidence.

Site-specific prediction methods can also be developed. In the second example described above, the model of pillar settlement based on the consolidation theory was incorporated into a subsidence assessment approach addressing a number of geotechnical issues including compression of pillar and floor, floor settlement, deflection of roof beams, and prevention of failures. These examples illustrates that the selection of a subsidence prediction method or a combination of methods for a particular mine should be primarily based on the nature of the problem and the geological and geotechnical conditions.

Establishment of an Impact Assessment Procedure

Concerns with regard to subsidence effects are not restricted to the potential damage to civil structures. In recent years, subsidence impact on areas such as national parks, rivers, lakes, cliffs and graze or agriculture land has become an important issue. Procedures for impact assessment need to be established to address case by case requirements and in some cases may require a significant degree of further research. What is important for mine planning is that the mine management should be advised on the range of issues they may likely be dealing with and especially, what could go wrong. In particular, the following questions should to be asked:

- What are the social consequences and costs for subsidence prevention, damage repairing or compensation as compared with coal recovery?

- Can we establish a damage limit, in terms of strains, vertical subsidence or other types of deformation indices, for different areas or structures within the mining lease?
Level of Confidence in the Predicted Subsidence

Before the prediction results can be used in a mine design process, geotechnical consultants often have to answer such questions as: how much confidence do we have in the predicted subsidence or how conservative should the mine design be? Addressing such concerns is an important part of a subsidence management plan.

The level of confidence can be affected by the following factors:

- geological and geotechnical complexities and variabilities of the site;
- the social consequences and costs as mentioned above, and
- the accuracy of the selected subsidence prediction method and the parameters employed in the prediction method.

Naturally, a geotechnical engineer feels much less confident when he or she has to deal with any social or costing issues than with geology even it is complicated. This is another area where integration of knowledge from the relevant disciplines is required.

Establishing a good database, identifying deviations from the geotechnical models and back-analysis are some of the means that help to achieve a better understanding of mining-related geotechnical issues in a complex geological environment. In a sensitive area, Coffey used information from a specially designed program to calibrate a prediction method through back-analysis, before the area was extracted. This program involved drilling, geological, geotechnical and geophysical logging, mechanical testing, underground test pitting and in particular, subsidence monitoring in designated areas. In another similar case, monitoring data including surface subsidence/strains, groundwater in the overburden, pillar stresses and sub-surface strains were analysed to check the subsidence prediction method before the next block was mined.

If resources are not available to check the prediction method, or subsidence data from cases with similar overburden geology/mine geometry are limited, conservatism or worst case analysis may be required for sensitive cases.

The authors find that a comment made by Holla in his 1991 publication (Holla, 1991b) is particularly relevant in this context:

“The definition of successful prediction, therefore, depends upon the consequences of predicting incorrectly. When the possible cost of failure is small, the name of the game is accuracy of prediction, and skating close to the edge may be justified. When the cost is large, then there is no game; safety and conservatism are paramount”.
Mine Design

From a subsidence management perspective, the authors suggest that the mine design phase have two important tasks.

The first is to optimise the mine layout to gain the highest possible coal recovery while limiting the surface impacts. Important input data to this process may include a factor of safety obtained especially by considering the level of confidence discussed in the proceeding section, and the results from an iterative comparison process between the subsidence predicted based on the mine layout being assessed and the design criteria or damage limits appropriate to the surface structures or sub-surface strata.

The second task is to provide subsidence data for planning purposes, and especially the subsidence levels that must be controlled during the production phase. The following is a list of the suggested outcomes from the mine design phase:

- the maximum values and distributions of the anticipated surface deformation indices over the mining areas, as the design limits for controlling subsidence;
- the anticipated surface impact over the mining areas;
- the division of the mining areas into different zones requiring different mining methods, priorities, or protective/remedial measures;
- the definition of key areas or aspects for the development of a subsidence policy.

By planning for the anticipated subsidence and its possible impact on the surface, coal mining companies can be prepared before the start of mining operation, and avoid surprises or confrontations later on between the mine and its neighbours.

Risk Management to Control Subsidence

A risk management plan is an essential component of a subsidence management plan. It is required during the production phase to control the occurrences of subsidence within the design limits as specified during the mine design. For the priority or sensitive areas, this program may be used to plan for the worst cases to minimise the surface impacts.

The risk management program requires the identification of significant deviations from the established geological and geotechnical models, as well as areas where maximum surface protection is required. During a study on partial pillar extraction, where the coal seam is sandwiched between the claystone floor and massive conglomerate roof, risks of "anomalous" surface subsidence were found to be related to floor deterioration as a result of faulting, and thinning of the conglomerate unit in the roof. The risks of anomalous surface subsidence were not significant on roadway development but were higher on extraction. This fact allowed the development of procedures to monitor the ground conditions during the development stage.
In general, a risk management plan may comprise the following:

- identifying hazards or deviations from the established geological or geotechnical models;
- checking ground conditions during development;
- monitoring surface deformation, and
- reviewing the subsidence management plan and making appropriate modifications.

Conclusions

Mining-induced subsidence is a very complex issue requiring a systematic approach integrating a wide range of disciplines such as geology, hydrogeology, and geotechnical, environmental, mining and civil engineering. A subsidence management plan may be used as the interface to integrate all the disciplines and to assist the coal mining industry in dealing with the conflicting demand for maximum recovery and minimum impact on the surface. This paper discusses the important steps in developing such a subsidence management plan. It is essential that subsidence occurrences must be planned for in advance in the mine design stage, and controlled during the production phase to limit the subsidence occurrences within the proposed design limits. By planning for the anticipated subsidence and its possible impact on the surface, coal mining companies can be prepared to avoid surprises or confrontations between the mine and its neighbours.

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