Proceedings of the 23rd Annual British Columbia Mine Reclamation Symposium in Kamloops, BC, 1999.
The Technical and Research Committee on Reclamation

MANAGING MINE SUBSIDENCE RISKS AT THE THREE SISTERS RESORTS DEVELOPMENT IN CANMORE, ALBERTA

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ABSTRACT

This paper will discuss investigation methods, risk-based evaluation techniques, and remediation strategies that are employed to manage the hazards associated with shallow room and pillar coal mines. Key issues are the size of the development and its proximity to extensive mine workings, as well as the mitigation strategies that have been employed to remediate the mine workings for a wide range of ground conditions and land use objectives. Prior to development, areas are assessed using a risk matrix which correlates the proposed land use with the type of mining hazard that is present beneath the area in order to evaluate the necessity and extent of mitigation that is required. This provides a consistent framework that guides development for the property, and also provides a means with which to convey risk to the developer, investors, regulators, and the general public.

1.0 INTRODUCTION

Three Sisters Resorts Inc. has been progressively developing a large parcel of land 2,035 acres (824 ha), in the Bow Valley Corridor adjacent to existing development within the Town of Canmore. Approximately 50% of the land, which previously belonged to Canmore Mines Ltd., is underlain by abandoned coal mine workings. The long-term development plan incorporates residential accommodations for 10,000 people in the form of 4,200 houses and 600 timeshare units, 1,600 hotel rooms in four hotels, three world-class golf courses and all associated roads and utilities.

Norwest Resource Consultants Ltd is the mining consultant for the Three Sisters project. Our involvement over the past 10 years has been focused on evaluating and mitigating the risk posed by the abandoned mine workings. Hazards from previous mining activity generally fall into three categories:

- **Surface Stability due to Undermining beneath developable areas** - Surface stability is assessed on the basis of potential for surface movements and the impact to the proposed development.

- **Public safety due to near surface collapse of mine workings** - Subsidence features are numerous where the depth of workings is less then 10m to 15m or four to five times the thickness of coal extracted. The evaluation and mitigation of these features is carried out on a progressive manner as development takes place.

- **Gas emissions** - In areas where coal seams are mined in the vicinity of residential housing, especially designed methane collection systems are required to be installed. Testing to date of the vent pipes from these systems has not revealed the presence of methane gas. The systems will continue to be installed where required.

There is no established engineering practice in the area of mitigating mine subsidence over room and pillar mining in steep seams. Nor is there any applicable theory to predict the amount of subsidence which could be expected in these situations. A semi-empirical, semi-qualitative risk-based method has been developed to guide the development of these lands in the Rocky Mountains. This risk analysis method is based on site specific data, engineering judgment and relevant experience from other parts of the world.

2.0 GEOLOGY AND MINING

The Three Sisters Property is situated in the northwesterly trending Cascade Coal Basin, which extends for approximately 80 km within the Front Ranges of the Canadian Rocky Mountains. The Canmore area, and specifically the Three Sisters Resorts Property, is in the northern part of the basin along the Bow River Valley. Lower Cretaceous Age strata of the Kootenay Group form the Bow River Valley floor and outcrops along northwest-trending ridges and depressions.

The coal-bearing formation within the Kootenay Group is named the Mist Mountain Formation and consists of approximately 400 metres of fine-graîned faciès including siltstone, fine sandstones, shales and coal seams. The physical properties of the lithologies are summarized in **Table 1.**

It should be noted that sandstone and siltstone typically comprise 40% to 80% of the coal bearing strata, and that the mud rocks, in general, are non swelling and slake only when subjected to aggressive wetting and drying conditions.

Table 1 : Typical Ranges of Physical Properties for Rocky Mountain Coal Measures Strata

Lithology	Intact Uniaxial Compressive Strength		RQD
	MPa	psi	
Sandstone	50 - 120	7000 - 17000	70 - 100
Siltstone	20 - 90	3000 - 13000	50 - 80
Mudstone/Shale	10 - 40	1500 - 6000	<50
Coal	<7	<1000	0

Though surrounded by rocks of high strength such as sandstones and siltstones, the coal seams themselves are extremely friable, and the coal is very gassy. During the operation of the Wilson Mine gas emission rates of $70m^3$ of methane per tonne of coal mined were normal, the highest level of gas emission the authors have ever encountered.

The Cascade coalfield is characterized by severe faulting and folding of the coal measures. The geology of the coal measures is dominated by asymmetrical anticlinal/synclinal pairs with one moderately steep limb in which dips of 10° to 35° are common and one very steep limb in which the coal seams dip between 60° to 90° and are occasionally overturned. Numerous smaller parasitic folds run parallel to the axis of the main structures and are commonly intersected by a dense pattern of reverse and normal faulting.

Coal mining near Canmore began in 1886 when the first portals of the No. I Mine were opened in the outcrop of an exposed coal seam in the Canmore Creek Valley. Mining was carried out continuously until 1979 when the last mine was closed down. During the 90 years of operation eight mines were operated by room and pillar methods, seven of which impact the Three Sisters Resorts development. Several of these mines operated in more than one seam using horizontal tunnels to connect adjacent seams. Many of the steeply dipping coal seams were rained by methods which more closely resemble caving methods that are used in underground hard rock mining than conventional room and pillar techniques.

For eighty years all the coal was produced from underground mines with minimal mechanization. Room and pillar extraction was used exclusively. The soft coal and steep gradients allowed coal to be blasted safely and effectively. Broken coal was transported by chutes to the haulage level where it was loaded into 1^1A or 2 tonne mine cars which were hauled to the surface by compressed air locomotives and rope haulages.

In the mid 60's continuous miners and cable reel shuttle cars were introduced in the Wilson Mine. This effort to mechanize was reasonably successful though, seam gradients of over 15° caused severe problems and 25° was found to be the limit for operation of this equipment. Subsequently, slusher hoists were installed and were found to be very suitable for the variable conditions, particularly during pillar extraction.

In 1979, when coal production ceased the area owned by the Canmore Mines showed surprisingly little impact after 90 years of coal extraction and processing. The main and most obvious impact was at the tipple site where the coal preparation plant, coal storage areas and various buildings were located. Other active portal sites were hidden by coal refuse and rock piles and approximately six open pit sites had been partially reclaimed. A very large number of old portal sites along the outcrops could still be located, though many of those over 20 years old had been hidden by second growth timber.

Subcrop limits to the mines were common where the coal seams approach existing ground surface. It is along these zones that much of the current investigative work is concentrated, as void migration from the very shallow abandoned workings and through the surficial materials to the surface is evident on the Three Sisters Property.

The only evidence of underground coal extraction other than the surface access roads and waste piles was in areas where mining had taken place at depths of less than 10m to 15m or four to five times the thickness of coal extracted. In areas such as these, over 300 subsidence features have been identified. The most impressive of these features are formed when vertical seams were mined to the subcrop resulting in subsidence trenches which in some instances are over 600 meters long, 5 meters deep and 10 meters wide.

3.0 SUBSIDENCE HAZARDS

Three failure mechanisms have been identified as relevant to design. Firstly, the most important mechanism to the design of roads and utility corridors is the void migration mechanism - a progressive unraveling of the roof-rock above the mine workings. Secondly, the general collapse mechanism is a large-scale general collapse of the mine workings with a broad effect on the surface. Thirdly, the toppling mechanism, a domino-type failure of vertical beds.

3.1 Void Migration

The void migration mechanism is a process involving a progressive unraveling of the roof-rock above the individual workings of a mine and is likely to occur when large pillars of coal remain in place supporting the roof on each side of the mine roadway. As the material falls into the workings below, the material bulks on the floor creating a pile of rubble. Since the rubble pile occupies a greater volume than the roof-rock that formed the pile, and the pile is confined by the coal pillars, the size of the void is reduced. Given enough bedrock height (H_b) above the mine workings the roof-rock will bulk sufficiently to eliminate the void and the caving will terminate without affecting the surface. However, if there is not sufficient bedrock height, the caving will progress to the surface of the bedrock and the remaining void will migrate through the overlying soil and create a localized, sharp-edged sinkhole.

The void migration mechanism is controlled by the extent to which the roof-rock bulks or swells. The bulking factor, F_b, can be calculated from drill hole intersections using the following formula:

$$F_b = H_r/(H_c-H_e)$$

Where: F_b is the bulking factor;

H_r is the vertical height of the rubble pile from the floor of the mine;

H_c is the vertical height of the cave from the floor of the mine; and

H_e is the vertical height of the original mined section.

Bulking factors were calculated from drill hole information gathered during the investigation of Carey Seam, No.2 Mine, and used to define the design parameters related to void migration for the Parkway mitigation program. Figure 1 is a histogram of these bulking factors which ranged from 1.15 to 1.75, and typically depend on the properties of the rock or surficial material and the extent to which it breaks up during the void migration process.

A somewhat more useful parameter for describing the void migration process is the caving factor, F_c. The caving factor defines how much rock a void of unit thickness can migrate through. The caving factor is defined in terms of the bulking factor by the following formula:

$$F_c = F_b/(F_b-1)$$

This relationship is plotted in Figure 2

Figure 1: SWELL FACTOR MEASURED FROM DRILL HOLE INFORMATION

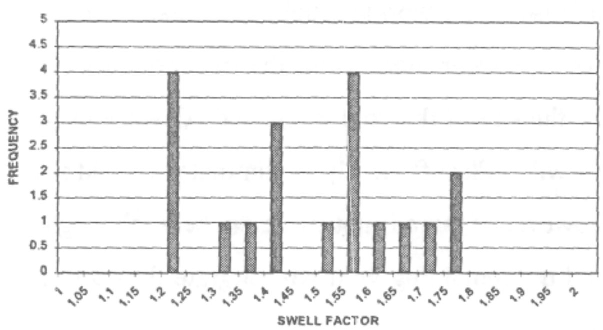
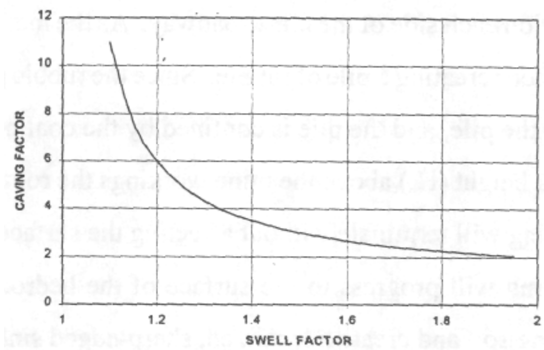


Figure 2: CAVING FACTOR VS SWELL FACTOR



3.2 General Collapse

General collapse is a term Norwest used to describe the mechanism by which a mine roof caves, over a large area, when a large percentage (>60%) of the coal is removed, leaving only remnant pillars. General collapse in room-and-pillar mines differs from void migration in that the mechanism is not a progressive, migrating process, but a rapid downward movement of the roof and overlying strata over a large area caused by overburden pressures that exceed the support provided by remnant coal pillars. The collapse normally forms a broad depression on the surface. This process can affect the surface in areas with much more bedrock cover than is required to halt the void migration process. No evidence of such a failure has been found on the Three Sisters Property.

3.3 Toppling

A topple is the forward rotation out of the slope of a mass of soil or rock about a fixed point or axis below the center of gravity of the displaced mass. An example of the process is the way in which a row of books on a shelf fall over when a bookend is removed. The process is sometimes driven by forces exerted from material up-slope.

Toppling occurs when the lateral support of a steeply bedded rockrnass is removed or reduced by mining, excavation or weathering. The failure is characterized by separations in the bedding of the rock mass and tension scars in overlying unconsolidated overburden. The failure will continue to retrogress until the tilting beds are supported or have all fallen over.

3.4 Hazard Investigations

In managing the mine subsidence risks at the Three Sisters Resorts Inc. property, the first step is to identify and classify the hazards. This is accomplished through surface reconnaissance, excavations and drilling.

In preliminary investigations a detailed walk-through of an area is performed to identify if any evidence of the different subsidence mechanisms are present on the surface. Particular attention is payed to locations of surface disturbance, subsidence features, fissures, and possible shaft and portal sites. These locations are marked in the field, surveyed and placed on a plan for reference. These locations may then be targeted for excavation or a drilling program for a more detailed investigation.

The information collected during the surface reconnaissance includes the physical dimensions and the shape of the subsidence feature, and an estimation of the thickness of the soil in the area. An estimation of the amount of bedrock cover is obtained from the soil thickness and mine plan elevations or any drilling data in the vicinity. Bedrock cover is one of the most important parameters affecting the impact of mine subsidence on the surface.

Excavations and drilling are used for subsurface geotechnical investigations. Air-track drills, reverse circulation rotary, and diamond core drilling systems are used when needed. For the most part, reverse circulation rotary drilling is the preferred method for these investigations. Drilling, Excavations and surface reconnaissance provide important data for the development of empirical relationships and statistical analysis of the behavior of the subsiding rock mass. The data collected from the investigations are tabulated in a computer database for processing. Figures 3 through 6 are some examples of the data collected from these investigations.

Figure 3: Feature Occurance

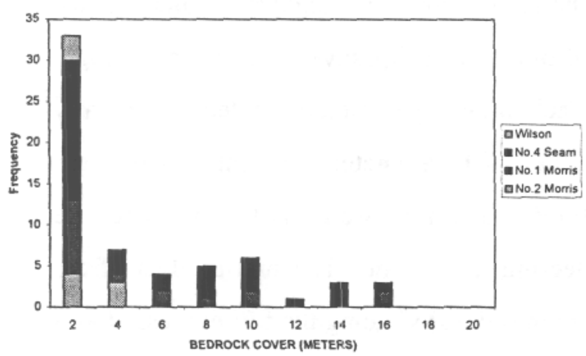


Figure 4: Feature Geometry

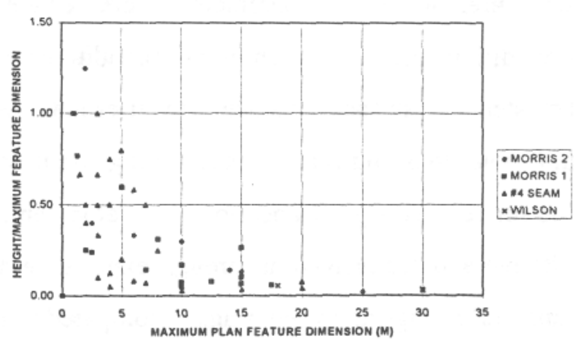


Figure 5: Caving Height Occurance

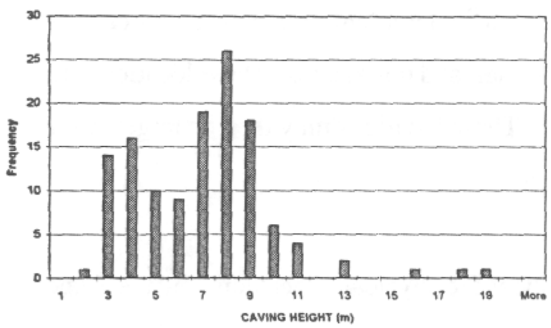
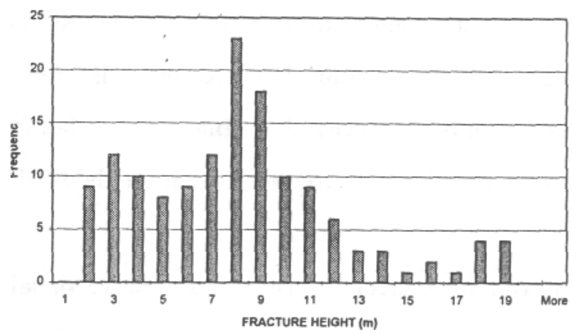


Figure 6: Fracture Height Occurance



4.0 RISK ASSESSMENT

This risk assessment process is used to evaluate the suitability of a site for a particular land use. That is, as a planning aid for development. The risk assessment process considers two elements:

- the potential for on-going subsidence.
- the consequences and severity of the subsidence.

These elements are composed of many qualitative and quantitative parameters, which can be combined into two indices, the Subsidence Potential Index, and the Consequence-Severity Index.

4.1 Subsidence Potential Index

The Subsidence Potential Index (SPI) is an evaluation of the likelihood that additional subsidence will occur in the future. Some of the parameters addressed are bedrock height to extraction height ratio, pillar status, roof condition, residual voids, mine pool conditions, surface hydrology, seam dip, adverse structural geology, and existence of surface subsidence features in the vicinity. Each of these parameters is rated individually from 0 (low) to 5 (high) as an aggravating circumstance and then each parameter is weighted against the others for relative significance to the development. The ratings and relative weights of a parameter are qualitative and are arrived at through experience and engineering judgement. The sum-product of the parameters' ratings and weightings is compared to the maximum (all 5's) yielding the SPI expressed as a percent.

The SPI for a site is calculated for all applicable subsidence mechanisms, commonly void migration and general collapse of the workings. The greater of the two is usually used for the evaluation.

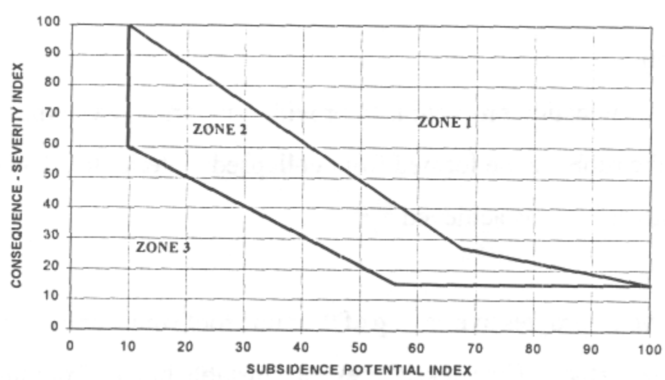
4.2 Consequence-Severity Index

The Consequence-Severity Index (CSI) is an evaluation of the sensitivity of the proposed landuse, both physically and politically. Some of the parameters addressed are structure footprint size and shape, number of stories, structural sensitivity, ownership sensitivity, and usage. Each of these parameters is rated individually and then each parameter is weighted against the others. The CSI is calculated as the SPI above. Each land use tends to have a different CSI for the same location; the consequence of a 0.1m surface deflection is significantly different for a parking lot than for a masonry structure on footings at the same site.

4.3 Risk Matrix Application

Once the SPI and CSI have been arrived at they are then plotted on the matrix shown in Figure 7. The further to the top right the greater the risk to a development. The matrix has been divided into three zones which indicate the type of mitigation approach which would be necessary for a given development. The developments are evaluated on a site-by-site basis.

Figure 7: Risk Matrix



4.4 Matrix Zones

Zone 1 is the area on the Matrix in which either the subsidence is severe or the consequences of the subsidence is severe. Developments with cross plotted indices which fall into this zone require major and extensive mitigation - pressure grouting for example.

Zone 2 is an intermediate zone where the severity of the subsidence is such that modifications to conventional construction practices is sufficient to protect the structure. Foundation reinforcement, Geogrid reinforcement of a roadway, or bore-hole extensometer installation are all examples of Zone 2 risk management.

If a development falls into Zone 3, no mitigation for undermining is required

5.0 RISK MANAGEMENT THROUGH MITIGATION AND INSPECTION

The risk associated with undermining can be divided into two broad categories:

- Risk of physical injuries to individuals or public safety
- Risk to structures and roadways

In order to reduce the risk associated with the mining hazards on the site, the mine workings are mitigated in a method appropriate for the intended land-use.

5.1 Public Safety Mitigation

Public safety mitigation is performed in areas with high pedestrian traffic such as golf courses and parks and within 500 m of a development. Typically, there are three means of public safety mitigation; geogrid mats, geogrid encapsulated fills (GEF's) or concrete caps and plugs. Areas where shallow mining has taken place, but no subsidence has yet occurred, are visually inspected regularly for any signs of new subsidence.

5.2 Grout Injection Mitigation

The purpose a drilling and grout injection program is to provide support between the mine roof and, either the floor of the workings, or the rubble zone formed from collapsed material that had caved from the roof of the workings. Ground stabilization was achieved by:

- Providing support that prevents progressive caving of the mine roof strata, or up-dip rib pillars in steeply dipping seams, towards the surface. The backfill prevents unstable blocks from falling into open voids and does not allow progressive unraveling to occur.
- Consolidating and partially in-filling areas containing caved rubble zones. The pressure of the backfill as it is injected is very similar to the vertical overburden stress levels (at least 85%). Thus, loose rubble and caved zones will be consolidated during backfilling.
- Providing structural support that would resist overburden loads. The unconfined compressive strength of the backfill material (minimum of 1Mpa) is sufficient to resist at least 40m of overburden stress against ground settlement.

6.0 CONCLUSIONS

The risk assessment process provides a consistent framework that guides development for the property, and also provides a means with which to convey risk to the developer, investors, regulators, and the general public. Furthermore, the process also provides a consistent means of determining the mitigation strategy.

7.0 ACKNOWLEDGMENTS

The methods presented in this paper were developed under contract to Three Sisters Resorts Inc. It would not have been possible for Norwest to develop these procedures and methods without the full support of the directors, management and staff of Three Sisters Resorts Inc. The risk assessment procedure was developed at a five day workshop with technical guidance provided by Colin Brown of Wardell Armstrong, UK, Pat Gallagher of CTL Engineering, West Virginia, USA, and Drum Cavers of AGRA.

8.0 REFERENCES

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