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A versatile model for the evaluation of subsidence hazards above underground extractions

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ABSTRACT
All underground extraction – oil, gas, water and minerals – results in subsidence of the surface to some degree. Subsidence can cause damage to infrastructure – roads, powerlines, gas and oil pipelines, buildings – and to the natural surface, with the development of cracking, potholes, changes in hydrogeology and destabilization of slopes. Pre-extraction estimates of the amount of subsidence and the hazards it might produce are difficult to determine with accuracy, and the most frequent approach is to model the surface movements in response to extraction using empirically based models.
There are a number of large underground coal mine projects on the drawing board in British Columbia and Alberta despite the current prolonged episode of reduced coal prices. Fortunately, almost all of these projects target metallurgical coal, for which windmills, hydro and nuclear "clean" power sources provide no substitute and in fact, on which they depend for their construction. Each of these projects will have to demonstrate satisfactory mitigation of hazards arising from potential subsidence before they will be allowed to proceed.
DMT Geosciences Ltd of Calgary, AB has recently worked with an underground mine proponent to model subsidence over an entire mine layout, in native coordinates and for multiple seam extraction, using a proprietary influence function model. Currently calibrated using a best estimate of western coal subsidence characteristics, the model itself will undergo additional calibration as monitoring data above the actual mine is obtained.
The model itself is fairly easy to use, quick to run and provides results in an easily managed format for graphical display. As well as mining subsidence, it has in the past been shown to predict surface movements due to oil and water extraction at depth. For the current project, the results obtained in the initial subsidence prediction phase have allowed areas of potentially hazardous or damaging surface movements to be determined.
KEYWORDS: subsidence; modelling; surface safety; environmental management

1. INTRODUCTION

North East British Columbia has a long history of large scale open pit coal mining targeting metallurgical coal for overseas markets. As in most coalfields, the easy coal has gone, but there remains substantial resources of good quality coal accessible by underground methods. The Wapiti Project, owned by Canadian Dehua, reported a resource in excess of 1 billion tonnes, and Glencore is proceeding with the Sukunka Project which has underground resources to be mined after an initial open pit.

All of these are major projects in an established mining area, but they will attract considerably more environmental scrutiny than they might have done in the past. The environmental issues associated with surface mines – waste rock disposal, selenium leaching, dust and habitat destruction – are well known to the local regulators. Underground mines, however, are largely a mystery to them.

Although underground mining has a number of environmental advantages, mitigating many of the disadvantages of surface mines, a significant concern is the effect of subsidence and the hazards it might present on the surface. This concern has become apparent during the environmental assessment process for another major underground coal mining project in NE BC.

This paper describes methods used to estimate the surface subsidence, their shortcomings and advantages, and to present some of the results that demonstrate how the output can be used to identify potential areas of surface hazard after undermining.

2. PROPOSED MURRAY RIVER PROJECT

The Murray River Project in the Peace River Coalfield of British Columbia is joint venture between three Chinese companies, operated by HD Mining International Ltd of Vancouver, BC. Figure 1 shows the locations of the coalfields of British Columbia. Figure 2 shows the principal property owners within the Peace River Coalfield.

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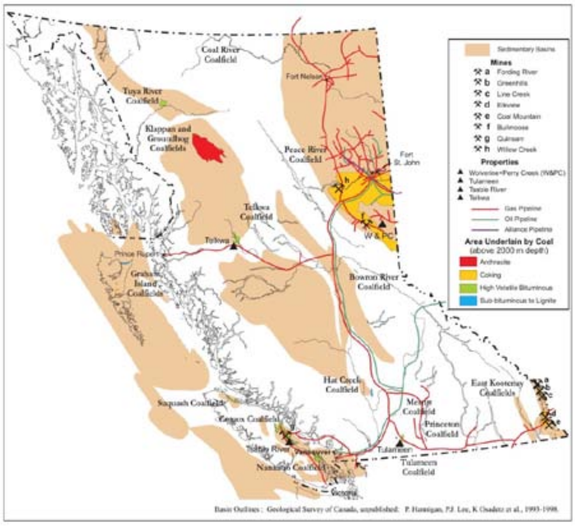


Figure 1: Coalfields of British Columbia.

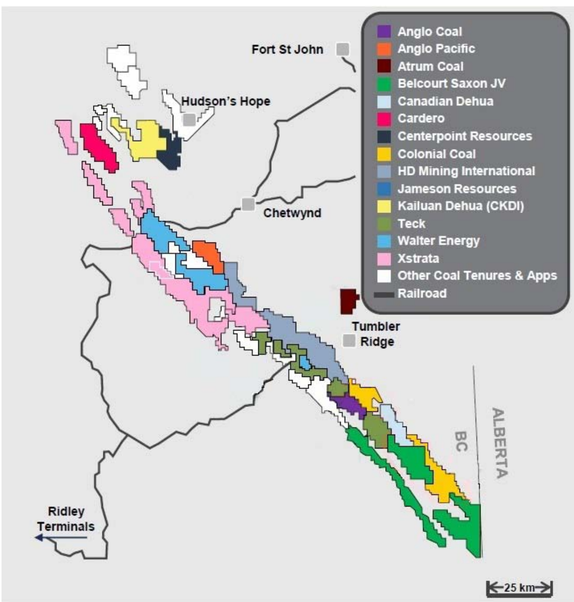


Figure 2: Principal Property Holders in the Peace River Coal Field.

The Murray River Project property lies centrally in the Peace River Coalfield between the historic open pit properties of Quintette and Bullmoose. Anglo American and Walker Energy have also operated open pit mines in the immediate area, now mothballed due to low prices.

The coal is found in the Gates Formation of the Upper Cretaceous period and sits at depths of between 500 m and 1300 m (Figure 3).

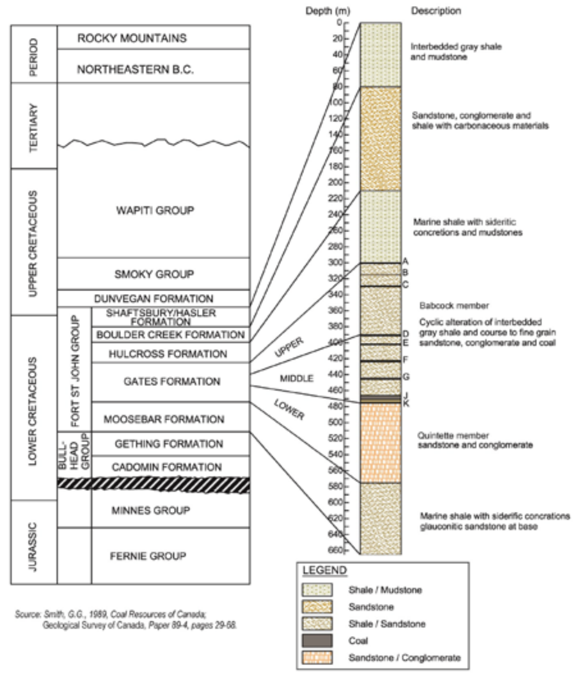
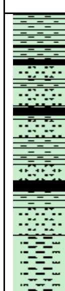
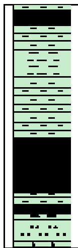
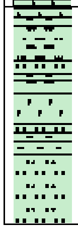


Figure 3: Typical Strata Column at the Murray River Property.

The proposed underground mine extends about 10 km along strike (NNW-SSE) and about 5 km to the dip. There are five target seams, identified as D through J from the top down (Table 1), with a total extraction of about 25 m, all of it from superimposed longwalls, many of them using the longwall top coal caving method. The proposed layout is shown in Figure 4.

Table 1: Target Coal Seams.

	Thickness	Lithology
	70-80 m	Mudstone, siltstone and coal. The lower part of the group is a thick layer siltstone. Contains A, B and C seams, none of which are mineable.
	> 55 m	Sandy mudstone, mudstone and coal, including three minable coal seams: D; 0.4 – 5.71 m, 2.12 m avg. E; 0.05 – 6.52 m, 2.32 m avg. F; 0.67 – 7.51 m, 3.46 m avg.

	>40 m	Mudstone, sandy mudstone and coal, including two workable seams: G/I; 0.4 – 3.52 m, 1.6 m avg. J; 2.6 – 9.2 m, 6.19 m avg.
	100 m	The lithology consists of thick-layer sandstone, included with thin-layer mudstone. Mainly medium sandstone, followed by gritstone, included with mudstone.

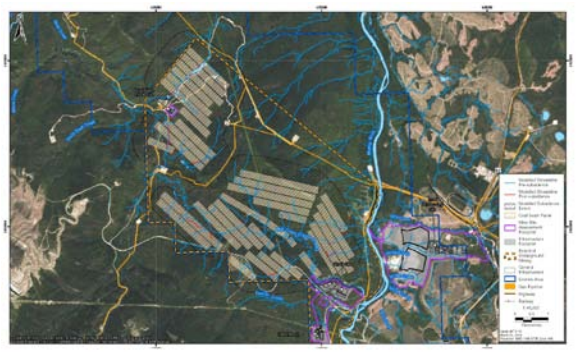


Figure 4: Layout of the Proposed Mine Panels showing planned and current infrastructure.

The mine extends beneath boreal forest as well as oil and gas exploration and production infrastructure – pipelines, well-heads and compressor stations. The terrain itself is a valued environmental component, as it is home to a number of species including caribou and some valued fish species. Disturbance to rivers and streams including the potential for slope instability in some of the deeply incised valleys, is a major concern.

Almost the entire oil and gas industry infrastructure is protected in the mine plan by pillars left in the coal underground. However, service roads and power lines criss-cross the area and the effects of subsidence must be assessed

3. SUBSIDENCE ASSESSMENT

The project proponents were asked to provide an assessment of the effects of subsidence on surface features which included some deeply incised river valleys, and specifically on valued environmental components. Regulators were concerned that large amounts of subsidence could occur as a result of multiple superimposed panels with extracted thicknesses of up to 25 m and that subsidence might result in stream reversals, wetland destruction and slope instability in sensitive areas.

The initial subsidence estimates were made by consultants with experience of subsidence estimation in western North America. The estimates were made using a proprietary influence function model. Because there was no local data to use to calibrate the model, subsidence parameters known to provide reasonably accurate estimates of subsidence under similar conditions in the western United States were used.

The subsidence estimation model used required the translation of the panel coordinates into a Cartesian coordinate system with the panels parallel to either the x- or y-axis and the size of the model limited subsidence estimation to a single mining district, although all five seam extractions were modelled. The simplification of the panel layouts resulted in the elimination of the pillars between the panels.

Although there was no concern over the resulting estimates, the model used for the initial assessment was limited to 3,000 data points which results in either long distances between estimation points or the segmentation of the mine plan. It was thus not able to provide coverage of the entire mine area without segmenting the mine layout and converting coordinates, and analysis of linear features was thus made very difficult.

On reviewing the initial set of results, the regulators asked for a mine-wide subsidence estimate as well as subsidence estimates along the courses of the major streams. The additional information required from the environmental reviewers dictated a change in approach to the subsidence modelling. The modelling software originally selected would require too much time and post processing and another option was sought.

4. SPS 4D SOFTWARE

DMT’s SPS 4D subsidence prediction software based on the stochastic prediction model of Sroka (1978). The software is designed to predict multi-panel and multi-seam subsidence influences both on objects at surface and on objects within the rock mass. The software is especially suited for calculating subsidence effects of inclined seams and inclined overburden strata with respect to unsymmetrical rock mass behaviour. In addition to predicting subsidence by longwall coal mining, the software has been successfully used to estimate subsidence caused by oil, gas and water production.

4.1 Theory

The process of subsidence starts with the extraction of material (oil, gas, water or coal and other minerals) from underground. The shape of the occurring subsidence trough depends on various, often hardly known parameters. For a model description of mining effects a relation between cause (material extraction) and effect (ground movements) is necessary. This relation can be set up by a transformation function describing the rock mass behaviour (Figure 5a).

The main influences in the case of longwall coal mining are the thickness of the mined seam, the depth of the mining works, the inclination of the seam and the dimensions and shape of the panel. Also important is a time factor, describing the delay in time between the extracted coal volume and the occurrence of the corresponding subsidence trough. However in this study only final subsidence values were sought, so the time factor model was not implemented.

For calculating the subsidence of a longwall operation with the computer program the mined area can be divided into small mining elements (Figure 5b).

The subsidence potential of one mining element is calculated within the program by using the Gaussian distribution as influence function. Using super-positioning of all mining elements, the software is able to calculate the final subsidence trough induced by mining of the whole longwall (Figure 5c). Consequentially it is also possible to estimate subsidence in every stage of face advance.

Final surface subsidence induced by mining a single mining element can be calculated using equation 1.

$$s(x,y,z) = \frac{k}{\pi}\frac{aV}{R^2} \cdot exp\left(-k\frac{d^2}{R^2}\right) \quad (1)$$

where: $k = -\ln(0{,}01)$, the fixed parameterization value of Ruhrkohle method

$a =$ mining factor ($a \in [0{,}1]$), volume of subsidence trough divided by extracted volume

$V =$ volume of mining element depending on element area and mining height

$R =$ radius of influence, $H \cdot cot\gamma$

$H =$ mining depth

$\gamma =$ angle of influence

$d = \sqrt{(x - x_A)^2 + (y - y_A)^2}$ distance between mining element $(x_{A,} y_{A,})$ and calculation point (x, y)

The parameter k is necessary because the Gaussian function used to determine vertical subsidence is asymptotic. The value of k forces a vertical subsidence value of zero at the edge of the subsidence trough although it reduces the estimate of subsidence very slightly at the maximum subsidence point.

The volume and location of every mining element is known and depends on the specific layout and dimension of the longwall panel. The only parameters that depend on the mining site specific geology characters are the mining factor and angle of influence. These parameters have to be determined from *in-situ* observations or estimated based on similar locations. In this case, the initial modelling used parameters selected by consultants with experience in similar conditions, and these values were used in the SPS 4D computations.

The derivation of equation 1 yields the tilt in x- and y-direction of the calculation point.

$$T_x(x,y,z) = \frac{\partial}{\partial_x} S(x,y,z) \quad (2)$$

$$T_y(x,y,z) = \frac{\partial}{\partial_y} S(x,y,z) \quad (3)$$

When calculating horizontal displacement it is assumed that horizontal displacement is proportional to tilt. In this way it is possible to calculate ground deformations. Equations 4 to 6 show the calculation of horizontal displacement in x- and y-direction and for a point at surface.

$$\mathrm{U_x} = -\mathrm{B} \cdot \mathrm{T_x}(\mathrm{x,y,z}) \quad (4)$$

$$\mathrm{U_y} = -\mathrm{B} \cdot \mathrm{T_y}(\mathrm{x,y,z}) \quad (5)$$

$$\text{with: } \mathrm{B} = \frac{\mathrm{R}}{\sqrt{2\mathrm{k}}} \quad (6)$$

Field measurements of subsidence in North America and elsewhere show that maximum tilt does not occur directly above the edge of the panel but is instead located in a distance d towards the mined panel (the so-called edge effect). The edge effect is integrated in the model by applying a specific roof convergence model which is parameterized by value d – the edge effect distance.

For full details of the model theory and development, refer to Zimmermann (2011).

4.2 Implementation

In significant contrast to the modelling software originally selected, SPS 4D applies a finite element based processing approach, which enables non-rectangular panel processing directly using the native coordinate system. This makes a comprehensive prediction for a multi-panel and multi-seam mine layout, presented in this article, very easy. For example, the initial software deployed could only process 3,000 points of data, so the larger the area being modeled, the lower the resolution of the output data. SPS 4D allowed up to 100,000 data points, in native coordinates, and has recently been expanded to 400,000 points. If a data point spacing of 1/20th of the depth is followed (NCB, 1975), this would allow single pass subsidence estimation of a 1,000 m deep

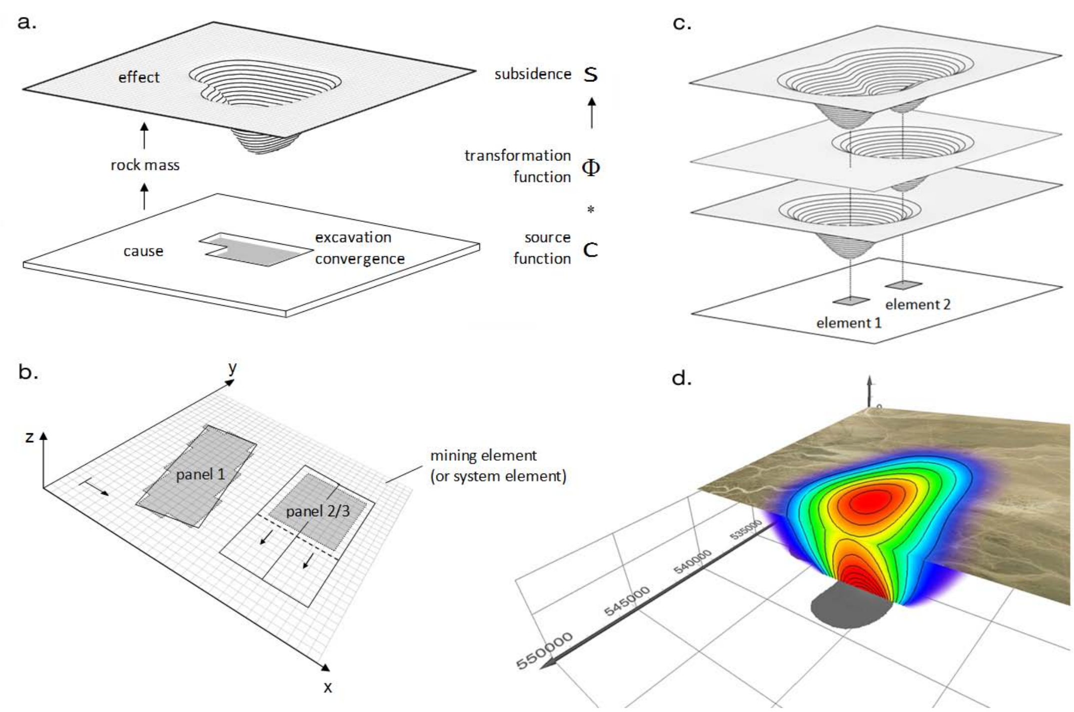


Figure 5: Illustration of the subsidence modelling principals and method (after Sroka et al, 1988 and Zimmermann, 2011).

coal mine over an area of about 900 km^2 This is large enough for most practical purposes.

SPS 4D is implemented in conjunction with a proprietary data manipulation package, Surfer™. Using a front-end and back end processing package already on the market greatly simplified implementation. Surfer™ is relatively inexpensive, easy to learn and widely used, making it an ideal partner in this process.

Outline coordinates of 84 individual longwall panels in 5 seams at depths ranging from 500 to 1400 m were entered in BC Provincial grid coordinates. Panel outlines, depths and seam thicknesses are entered as individual text files. The seam model can be displayed before processing begins (Figure 6).

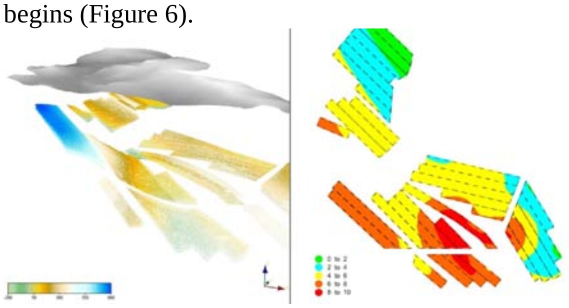


Figure 6: Illustration of model parameters; Left – 3D plot of surface and mine panels with depth referring to zero level [m], Right – Plan plot of seam thickness [m].

4.3 Calibration

Subsidence models are “calibrated” to produce estimates which match, as closely as possible, the subsidence experience of the area by adjusting three major model parameters: the influence angle, the subsidence or mining factor and the edge effect distance. The most accurate estimates from subsidence models are obtained when there is sufficient data from actual subsidence profiles to estimate the values of these parameters. Even then, parameters are chosen which err on the conservative side and model estimates tend to overpredict.

When no site specific *in-situ* data is available, data from sites with similar structure, rock properties and conditions are used to determine initial parameter values for initial subsidence estimates while the required data is collected and aggregated into the model to improve the accuracy of estimates.

There is no observed data for the Murray River coalfield. The original subsidence estimates used model parameters were based on past experience and knowledge of subsidence in the western part of the USA (the closest similar mining conditions for which subsidence measurements were available). This is a common approach to subsidence estimation in new mining areas.

The initial model parameters were reviewed by DMT and compared to the very limited subsidence data available in western Canada. The high percentage of “hard rock” in the overburden was also considered. The parameters used in the initial model were ultimately accepted as applicable for implementation in SPS 4D.

There was thus no argument with the assumptions used in the initial model, but it was important to be able to show the environmental review panel that the change in model mid-process was irrelevant. A comparison of the two models using the same parameters was performed.

Figures 7 and 8 show the subsidence profile results of the two models after one, two and four panels extracted. The only significant difference between the models is the appearance of reduced subsidence over pillars in the SPS 4D results. The SPS 4D model could accurately resolve pillars between panels, whereas the initial model could not, so they were omitted.

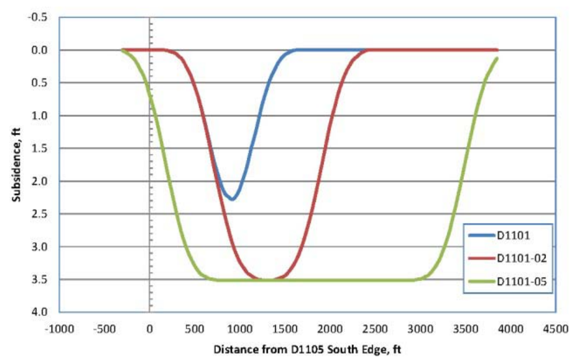


Figure 7: Subsidence Profile from the First Model.

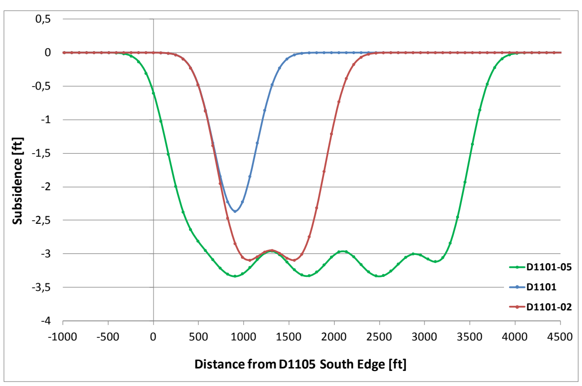


Figure 8: SPS 4D Subsidence Profiles.

The similarity of the results, and the additional resolution of the DMT model, convinced the reviewers to accept the new model.

Although neither of the models has had the benefit of observed subsidence data with which to calibrate it, every effort has been made to use representative subsidence parameters which will give a conservative estimate of the subsidence effects.

Both the project proponent and the regulators understand that the results obtained are *estimates*, even though they have been designed to err on the conservative side. Both the project proponent and the regulators understand the importance of gathering accurate subsidence measurements to refine the model and allow accurate site specific calibration for future assessments.

5. MODELLING

The first stage of the model was to obtain a digital elevation model (DEM) of the topography above the mining area. The DEM was constrained to a distance of 900 m beyond the mining limits to reduce the number of data points for which subsidence was to be predicted. Even so, the Lidar data was too dense to allow timely modelling, so a subset of the elevations at 15 m northings and eastings was produced. This resulted in slightly less than 200,000 data points. The end of mine life subsidence was subsequently calculated for each of these points.

The spacing of the points, 15 m, was a compromise between the accepted "bay length" over which strains associated with subsidence are conventionally calculated and the data density required to properly describe changes in topography.

The "bay length" (distance between measurement points) is usually recommended as 0.05 times the depth (NCB, 1975).Any less, and calculations become too time consuming; any more, and the strain estimates are affected. The range of depths of working at Murray River is 500 m to 900 m, resulting in bay lengths of 25 m to 45 m respectively.

Terrain changes are quite substantial over short distances over much of the mine area, and DMT felt that a 25 m DEM would not be effective, hence the 15 m discretization chosen.

Once the surface DEM had been prepared as a simple x,y,z data file, the mine layout was digitized in AutoCAD and the coordinates of each of the 84 panels were prepared as another simple data file. At this point, the data files could have been prepared with elevations and seam thicknesses for each corner point, and the software would have interpolated these values across each panel at 10 m intervals. This interpolation interval is user selectable, but 10 m seems to produce adequate results.

Instead of interpolating between panel corners, AutoCAD 3D-polyline files of base of seam elevation and seam thickness were prepared as simple x,y,z strings. The software accepts these files and interpolates both depth and thickness more accurately than if corner points alone were used. By way of example the base of seam elevations for the lowermost J seam derived for each panel and contoured using the integrated "Surfer package, are shown in Figure 9.

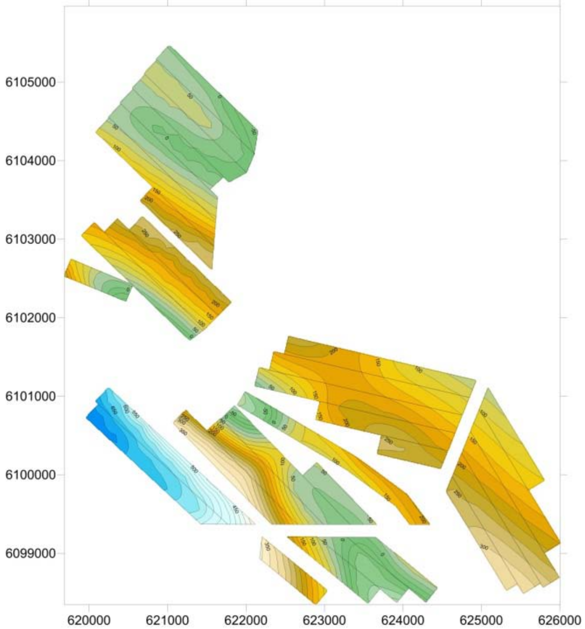


Figure 9: Contoured Seam Elevations from Data.

The effect of subsidence on a fish-bearing creek in the area was of particular interest. To assess potential hazards, elevations along the creek bed were interpolated from the GIS system at roughly 5 m intervals, resulting in about 14,000 points.

Once the data sets were completed, the model was allowed to run. Total subsidence after completion of mining was determined for each of the DEM surface points and for each of the M20 Creek bed data points. Despite the capacity of the model, the surface DEM exceed the number of points that it could handle, and the mine layout model was completed in two sections, although the model has subsequently been modified to allow up to 400,000 points to be modelled

6. RESULTS

Figure 10 shows the surface elevations contoured from the DEM subset. The dark line is the creek of interest. Towards the east end of the creek it runs through a deeply incised valley and the stability of the slopes was in question.

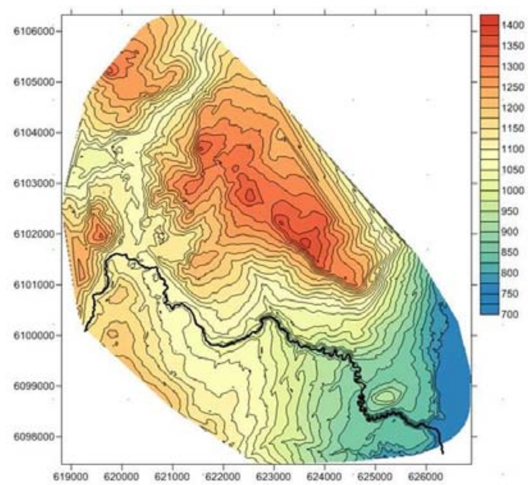


Figure 10: Contoured Surface Elevations and the Major Creek.

Figure 11 shows the contoured total subsidence, which reaches close to 10 m under shallow, multiple thick seam workings. This area was identified as having potential for hazardous crack or surface fracture development. Fortunately it is largely wilderness and the risk to people and infrastructure was assessed as low.

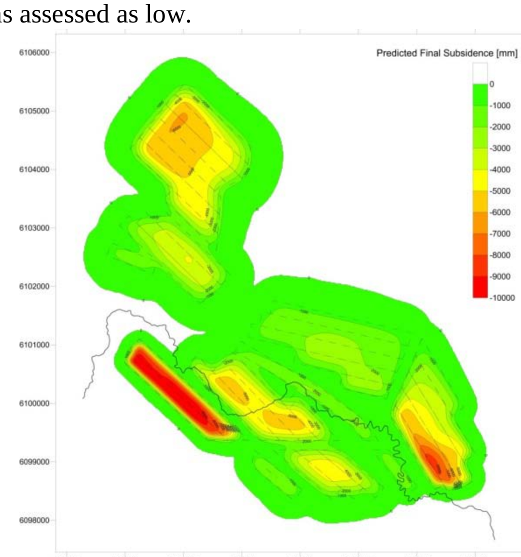


Figure 11: Contoured Total Subsidence.

Figure 12, showing areas of concentrated tensile and compressive strain, matches the areas of major subsidence as expected.

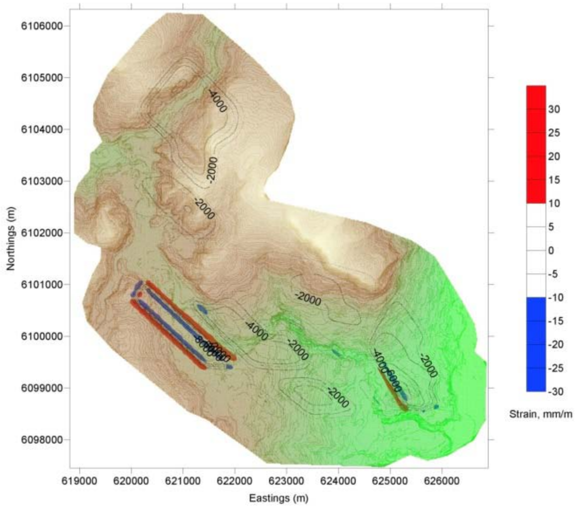


Figure 12: Contoured Strain.

Figure 13 shows a unique feature of the SPS 4D model, its ability to estimate subsidence along non-linear features in significant detail. The stream trace is represented by 14,000 points which, and the results indicate the areas of greatest potential surface hazard. This allows the project proponent to plan mitigation for habitat loss based on a realistic assessment of the physical requirements. Figure 14 shows the stream bed profile from which possible flow reversals or changes to stream bed morphology can be determined. Steepening will result in increased erosion and possible destruction of spawning beds. Flattening will result in deposition and silting up potential.

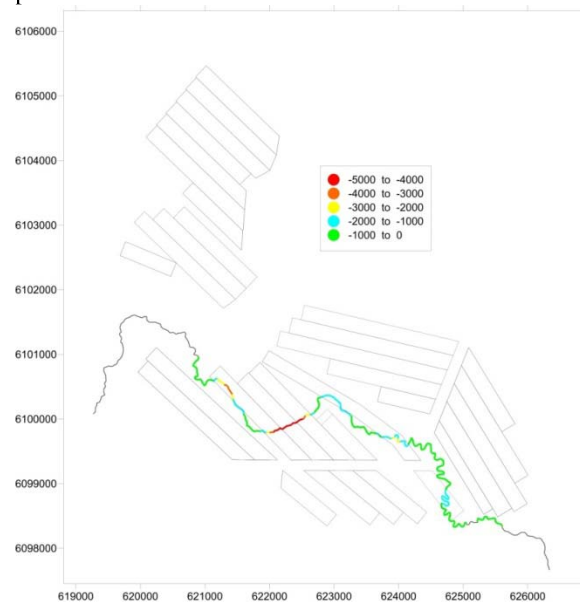


Figure 13: Subsidence along the Stream Bed.

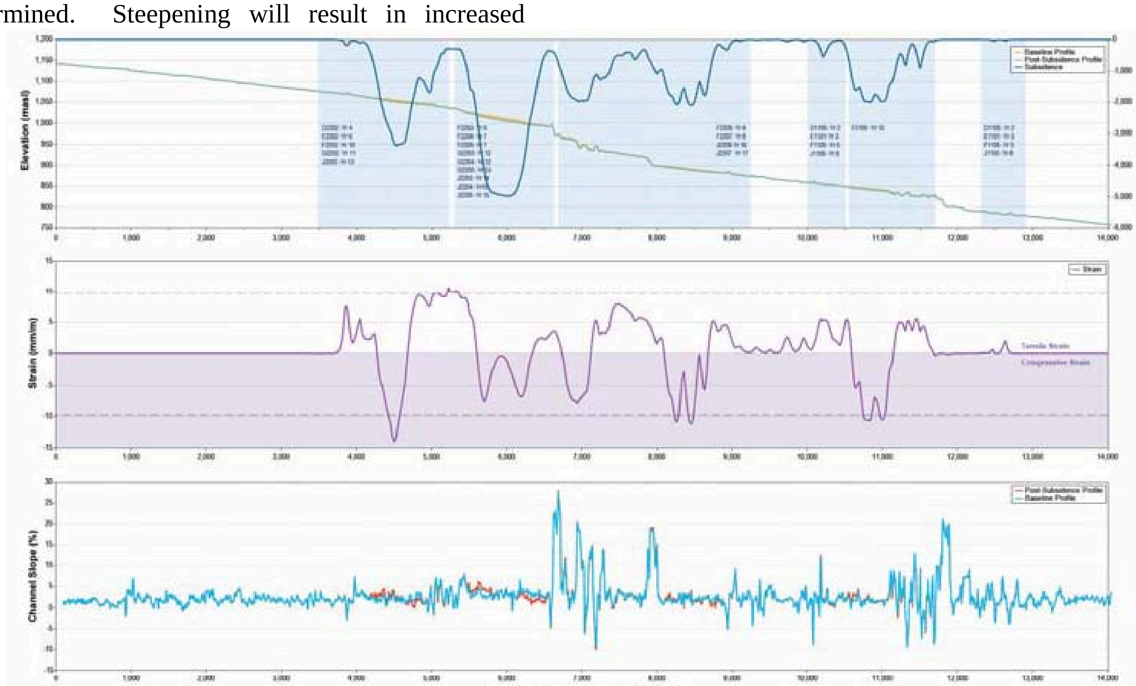


Figure 14: Subsidence along the Stream Bed Illustrated as a Stream Bed Profile.

7. CONCLUSIONS

The modelling work demonstrated firstly that the SPS 4D model could produce results in North America similar to North American models. In areas where large amounts of subsidence data exists this isn't a problem – models can be calibrated to local conditions. However, in a new mining field with no existing data it is important to be able to have a degree of confidence that the results are meaningful.

Secondly, the formulation of the model and the use of a proprietary front and back end made data input and visualization and more importantly, results visualization, very easy. The identification of zones of significant subsidence and the potential for surface hazards, and the effects of subsidence on stream courses and wetlands was made significantly easier using the proprietary visualization software.

The presentation of the results, albeit with a number of caveats regarding the nature of the estimates and the need for extensive subsidence monitoring and observation to verify the results and confirm the mitigation strategies, was successful.

Subsidence estimation is a tricky field. Model results are only estimates, approximations of the actual result. The only sure way to increase the reliability of the model outputs and hence the assessment of the hazards, is to calibrate the model with as much field data as possible. The proponent in this case has committed to a multi-year Lidar and surface survey monitoring program to ensure that the subsidence estimates become increasingly more accurate and hence the potential hazards are more accurately identified for mitigation.

8. ACKNOWLEDGEMENTS

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The views expressed are those of the authors alone and may not represent the views of HD Mining International or their employers.

9. REFERENCES

NCB (1975) “Subsidence Engineers Handbook” National Coal Board Production Department, London, UK, 1975

Shadbolt, C. (1987) “A Study of the Effects of Geology on Mining Subsidence in the East Pennine Coalfield” PhD Thesis, University of Nottingham, March, 1987.

Sroka, A. (1978) “Teoria S. Knothego w ujęciu czasoprzestrzennym”, Geodezja 24, S. 73-85, Kraków, 1978 (in Polish language)

Sroka, A. et al. (1988) “Vorausberechnung von Gebirgsbewegungen bei geneigten flözartigen Lagerstätten unter Berücksichtigung anisotroper Gebirgseigenschaften, des Durchbauungsgrades und des zeitlichen Konvergenz- und Verzögerungsverhaltens des Gebirges; Abschlussbericht des Forschungsvorhabens” Ha 526/15-1 am Institut für Markscheidewesen; Technische Universität Clausthal (Deutschland), 1988 (in German language)

Tandanand, S, and Powell, LR. (1984) “Influence of Lithology on Longwall Mining Subsidence” Mining Engineering, December pp 1666-1670.

Zimmermann, K and Fritschen, R. (2007) “Study about the dynamic influences of longwall mining in the US on surface objects” Proceedings of the 26th International Conference on Ground Control in Mining, Morgantown, WV., 2007

Zimmermann, K. (2011) “Prediction and Analysis of Dynamic Ground Movements induced by Near-Surface Coal Mining in the USA” PhD Thesis, University of Freiberg, 2011 (in German language)