Appendix E – Important SDPS Model Runs

This section provides documentation as to how the University used the SDPS program to help accomplish its research objectives. The project team is interested in making sure that predictive models used in this research study can adequately be understood by others. Paramount in this understanding is that SDPS uses the influence function method to produce changes of the surface in response to the creation of voids at depth. The influence function method implemented in SDPS calculates the surface deformations produced by a subsidence basin. In this study, the two key parameters used by SDPS to characterize the shape and intensity of the subsidence basin are the supercritical subsidence factor and the edge effect offset distance. Both of these factors are significantly impacted by the depth of the extraction area or overburden.

The influence function has its origin in a collection of reports by a German named Bals in 1931 and 1932 (Adamek and Jeran, 1982). Knothe (1957) further refined its application by considering a range of geological and mining conditions. It has since been further developed and ported to different platforms, SDPS being one. The influence functions method isn't anything like a numerical model where multiple layers can be represented, each with different material properties. These kinds of models can consider stresses and deformation within the body of the model and are often capable of predicting material failure. This is the case for the University's finite element models of Embankments #1 and #5. Models using the influence function can only predict deformation on the surface. Differences in material properties of the strata between the extraction zone and the surface can only be considered in an implicit or indirect manner. The strength of the SDPS model is its ability to produce surface subsidence predictions over a wide range of characteristics simply by adjusting input parameters.

For example in this research effort, the University adjusted input parameters until the modeled subsidence basin took on similar characteristics as those measured over Panel 15. Once an accurate subsidence model is developed, comparisons can be made between deformations predicted under ideal conditions with those measured in the field. Areas where measured values deviated from the predicted were an analysis focus. Some of these anomalous conditions are associated with the interaction of the pavement and the underlying ground surface. Others were associated with unique local conditions such as embankments.

The final step is to apply these same parameters to the extended study area only now the effects of varying topography and overburden are considered. In this way, predictions of deformations and strains are used to assess potential impacts to highway assets.

1.0 Background

Twelve SDPS models of the Panel 15 study area and over 60 (sixty) of the extended study area were run over the course of this research project. Each model consisted of a unique set of grid points prepared with the aid of two software programs. The SDPS program uses these specific grid points to execute a run. Output from each run is analyzed first in ArcGIS then Excel. Each of these model runs can take a portion of a day to complete.

2.0 Initial Pre-Undermining SDPS Model Runs for Panel 15

Prior to the undermining of Panel 15, the University was presented a report by West Virginia University's Mining Engineering Department. This report was completed for the Tunnel Ridge Mine and contains subsidence predictions. WVU utilized the CISPM-W influence function method so this was an opportunity to compare two different influence function programs. The WVU vertical subsidence prediction for Panel 15 is shown in Figure E1.
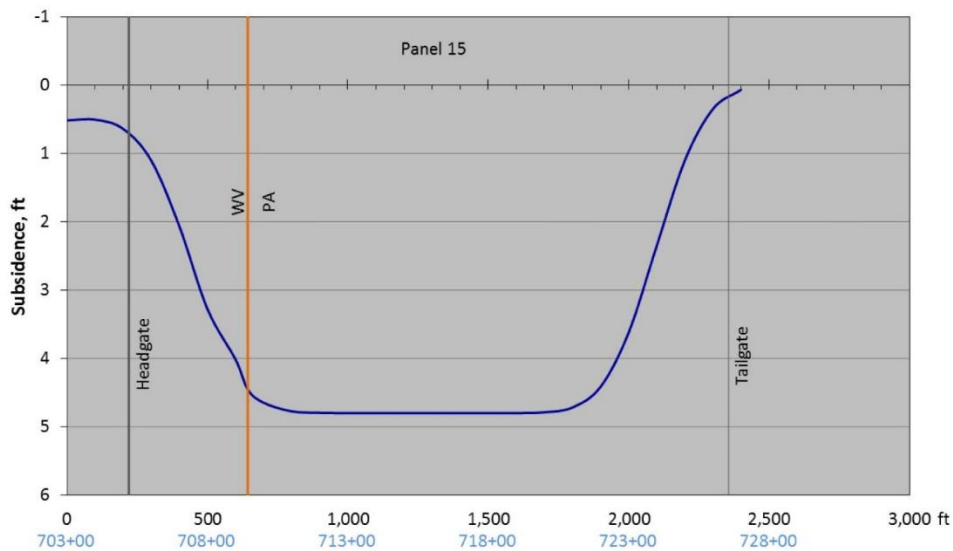

Figure E1 – Vertical subsidence prediction along I-70 highway alignment by WVU using the CISPM-W model (this information is contained within a consultant report provided by the Tunnel Ridge Mine)

The CISPM-W model assumed characteristics are shown in Table E1. The grid for this model is constructed to accommodate preset automatic construction.

Table E1 – Model characteristics used when comparing SDPS to CISPM-W

Panel	Overburden, ft	Length, ft	Width, ft (r-r)	Mining height, ft	Chain pillar width, ft (r-r)
15	590	18,000	1,232	7.5	149
16	590	18,000	1,232	7.5	

Figure E2 shows the most significant characteristics of this model. The distance between the adjoining predicted points is 100-ft and set up along the orientation of highway alignment. The grid does not use global coordinates.
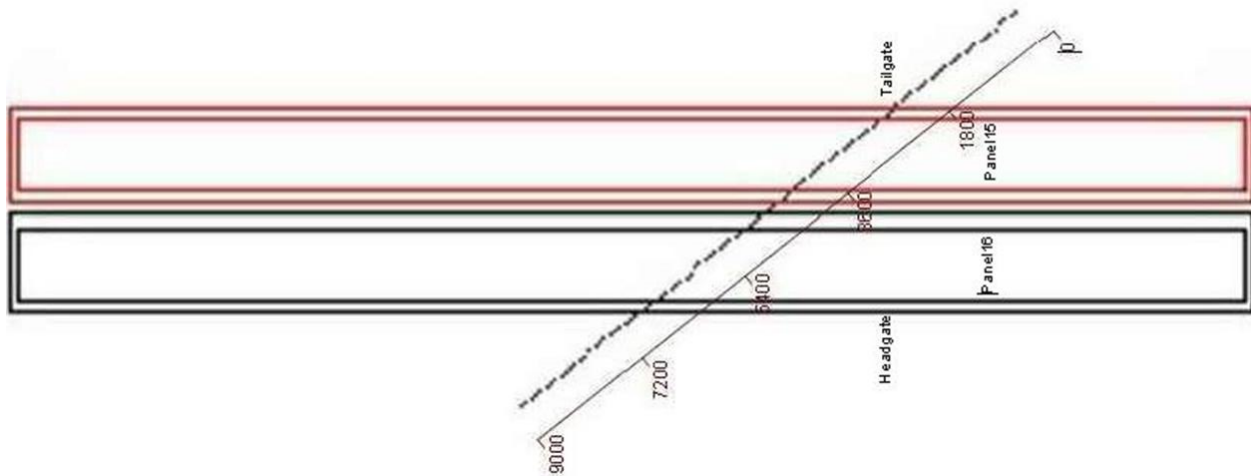

Figure E2 – SDPS two panel model showing the outline of Panel 15 and 16, their edge effect lines, and the I-70 highway alignment

The graph of the vertical subsidence along the I-70 highway alignment is shown in Figure E3. Note the smaller amounts of predicted vertical subsidence over the gate road entries between Panel 15 and 16.
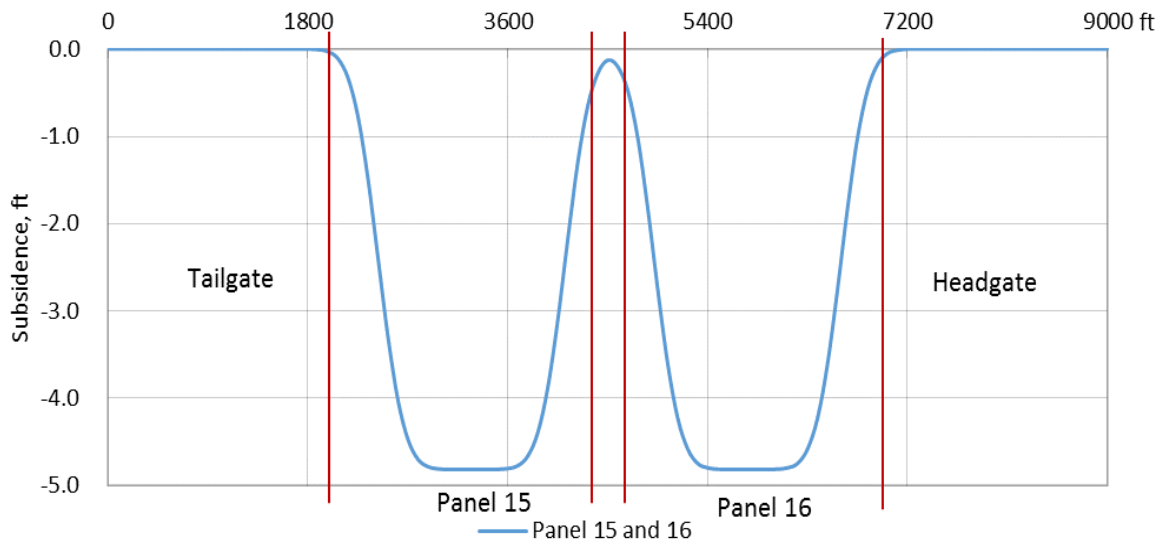

Figure E3 - Predicted vertical subsidence profile along the highway alignment over Panel 15 and 16

Table E2 shows the comparison between the CISPM-W and SDPS models. The maximum vertical subsidence value of both models are virtually the same but the minimum vertical

subsidence value occurred over the gate road entries is considerably higher for the CISPM-W model. This difference is likely attributed to unknown input parameters that define the influence of the gate road entries.

Table E2 - The difference between the SDPS and CISPM-W in term as vertical subsidence of Panel 15

Predicted tools	Max. subsidence value, ft	Min. subsidence value over gate road entries, ft	Location occurred the flat bottom
SDPS	-4.82	-0.17	~400-ft inside and perpendicular to the edge of panel
CISPM-W	-4.80	-0.5	

A refined pre-undermining SDPS model was next developed that incorporated global coordinate systems and increased the overburden to 675-ft and reduced the extraction thickness to 7.25-ft. There were numerous models tried during this stage of the research project before arriving at the refined pre-undermining SDPS model.

3.0 After-Undermining SDPS Model Runs of Panel 15

As additional site conditions were understood, pre-undermining models were updated and used to refine predication more closely matching actual conditions in the Panel 15 area. A selection of Panel 15 SDPS models are shown in Table E3. Further investigations found the following SDPS parameters to be most representative of Panel 15 subsidence conditions:

- Extraction thickness of 7.25-ft,
- Tangent of Influence Angle of 2.31,
- Influence Angle of 66.6-deg,
- Strain Coefficient of 0.35,
- Hard rock designation of 20-pct,
- Supercritical subsidence factor of 59.5-pct
- Average overburden of 675-ft
- Edge effect of 175-ft,
- Global coordinates to match existing surveys,
- Variable topography, and
- Scattered point grids for plotting diagonal profiles.

Table E3 – Examples of selected SDPS models used to predict subsidence associated with extracting Panel 15

Name	Edge Effect, ft	Supercritical Subsidence Factor, pct	Surface Point Type	Surface Elevation	Avg. Overburden, ft
Pre-undermining	135	64.2	PG[1]	F[4]	675
Flat surface	175	59.5	PG	F	675
3D-Grid	175	59.5	PG	V[5]	653
3D-Parallel	175	59.5	SP[2]	V	653
3D-Split Middle	175	59.5	SP	V	653
No Emb[3]	175	59.5	PG	V	653
29 Jan 2019	175	59.5	SP	V	653
5 Feb 2019	175	59.5	SP	V	653
14 Feb 2019	175	59.5	SP	V	653
19 Feb 2019	175	59.5	SP	V	653
7 Mar 2019	175	59.5	SP	V	653
26 Mar 2019	175	59.5	SP	V	653

[1]PG – Points on a Grid

[2]SP – Scattered Points

[3]Emb – Embankment

[4]F – Fixed

[5]V - Variable

4.0   Guide to using SDPS to Model Panel 15

Adelsohn (2020) wrote a partial SDPS Modeling Guide for subsidence prediction caused by longwall mining of Panel 15 under I-70. Excerpts from this guide, along with other comments, provide a detailed view of the development and use of SDPS model in the Panel 15 area. These comments are meant to supplement directions provided in the SDPS User's Manual (Agioutantis and Karmis, 2015). Two models, the Flat Surface and 3D Parallel (split-middle), are used to assist in this discussion.

4.1   Creating a Grid File

A detailed AutoCAD mine map was provided to this study by the Tunnel Ridge Mine. The mine map uses the West Virginia State Plane Coordinate System. The mine drawing showed the location of the panels and all the associated pillars located in the gate road entries. The mine plan is then simplified to a single polyline inside of the gate road entries to demonstrate the area of coal extracted (Figure E4). This polyline is then exported as an object from AutoCAD and saved as a .dxf file to be imported into SDPS.
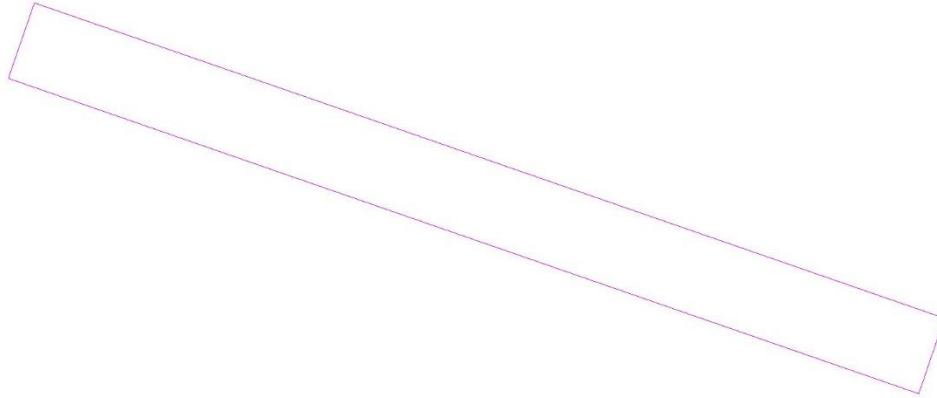
Figure E4 – A polygonal outline of Panel 15 using a global coordinate system in AutoCAD

Prediction points are next assigned in SDPS. This is complicated when these points are oriented along an alignment representing the highway and include variable surface elevations. To generate this file, the Carlson software was downloaded to add capabilities to AutoCAD. The following steps are then used to generate the file.

1. Import the elevation contours for the study area into the Carlson software. This should be in .dwg format
2. Click the Make 3D Grid File tool in the Grids tab. The Grid File to Create – (grd) menu opens up.
   a. Browse to the folder that you want to store the grid file in and name you grid. Click Save. The Make 3D Grid File menu opens.
   b. In the "Make 3D Grid File" menu, ensure that the Source Data option is set to Screen Entities. The Source data is going to be the elevation contours.
   c. Make sure the Range of Elevations/Values to Process encompasses the minimum and maximum elevation values in the elevation contours data file.
   d. Leave the Modeling Method to Triangulation, the Triangulation Mode to Auto Detect, and make sure Use Inclusion/Exclusion Areas is unchecked.
   e. Ensure Set Grid Position is set to Screen Pick
   f. Ensure Specify Grid Resolution As is set to Dimensions of Cell
      i. X = 50
      ii. Y= 50
   g. Press OK
      Please note – a 50 x 50 was used for Panel 15 and the District 1 and District 2, while 25 x 25 was used for asset analysis within Panel C and Panel N of the extended study area.
3. The menu disappears and prompts the user to pick the features which will populate the elevation values of the Grid file. Start by clicking the corner of the contour dataset, then drag the mouse to the opposite corner and click that corner of the contour (Figure E5). Press Enter. Again, do another screen selection of the contours. Press Enter again. The software may pause for a second, which is an indication that it is creating the Grid file.
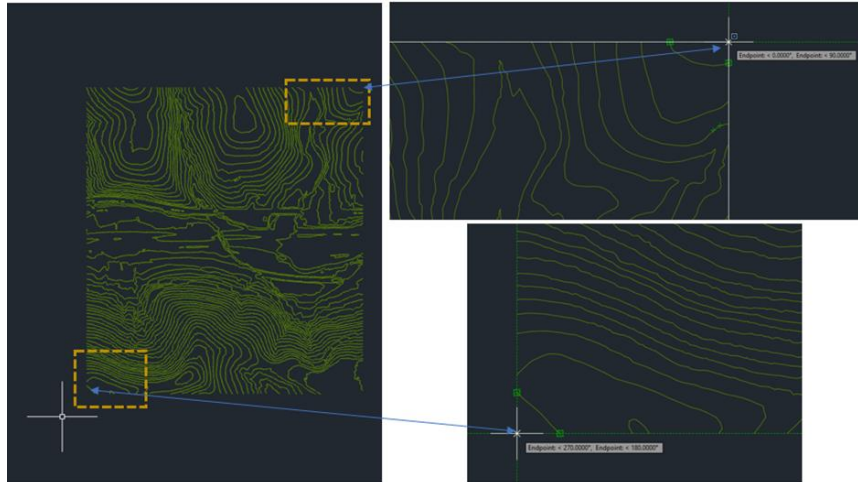
E6

Figure E5 – Examples of grid creation

4. Go to the Grid file in the folder you created it in and open the file with Notepad. The file may contain "N" values, i.e. "Null" values. These null values are of cells beyond the extent of the elevation contours and therefore, should not have an effect on the prediction model. However, SDPS will not accept these values, so replace them with the value of the average elevation in your study area. To do this use the Replace tool in Notepad. Save your Grid. The Grid file is now complete (Figure E6).
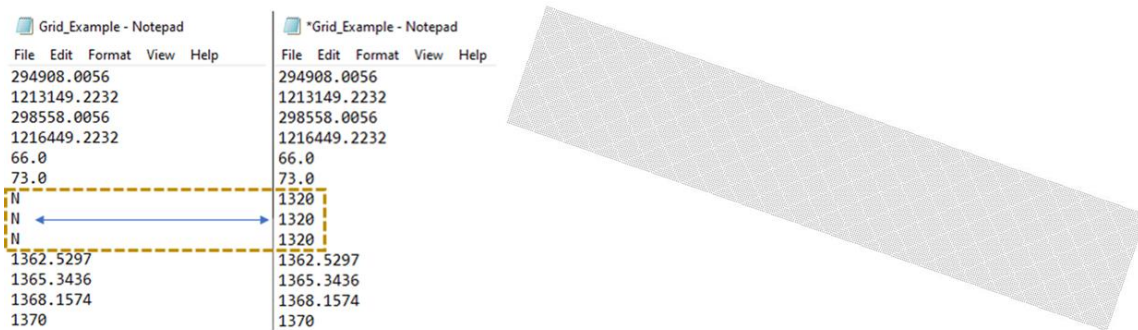

Figure E6 – 3D Parallel (Split-Middle) grid and global coordinate system with topography

Once the prediction points and the mine plan are generated, these parameters are input into SDPS for analysis. The following steps were taken to create and run the SDPS model.

5. Open SDPS and click the influence function button to launch the software.
6. Go to the file drop down and save the project file. This will save all the subsequent components that are created.
7. Use the File drop down and click Import SDPS Components.
    a. Import the mine plan by clicking the AutoCAD MinePlan [DXF] tab.
        i. Browse for the .dxf file created for the mine plan

ii. Ensure that the name of the Active Panel Layer matches the name of the layer used in the AutoCAD file generated previously.

iii. Click on the Longwall option in the Extracted Area/Panel Type box.

iv. Click on the Average Elevation option in the Elevation box and set the average elevation to 600-ft, which is the average elevation of the Pittsburgh Coalbed in the location of Panel 15

v. Click on the Use Percent Hardrock option in the Subsidence Parameters box and set the average Percent Hardrock to 30-pct, which is the calibrated value for this area of overburden. The calculated supercritical subsidence factor for 30-pct Hardrock should be 59.5-pct.

vi. Import the mine plan. One panel should be successfully imported.

b. Import the prediction points by clicking the Carlson Software Grid tab. Browse for the txt file created. Click import and points throughout the study area should be imported.

8. Use the Edit drop down and click Rectangular Mine Plan. One panel should be detailed in the parcel management tab. Using the Edge Effect Management tab, define an edge effect of 175-ft around all sides of the panel. This value was determined to match with the collected survey data. If the Edge Effect Management tab is greyed out, check the box to enable edge effect management.

9. Use the Calculate drop down and click Calculate Deformations. Change the output path to ensure that the calculations are saved in the proper location. Check the output options desired; the options used for this analysis were to calculate subsidence, calculate horizontal displacement, calculate horizontal strain, and calculate ground strain (grid). Change the Output Format to XYZ Data, which will allow the data to be analyzed in Excel or ArcGIS. Click Calculate and wait for model to run.

Once the model calculates, it is complete. The SDPS data can be previewed using the SDPS graph function or imported into Excel or ArcGIS.

4.2   Preparing the SDPS Output files

1. Start by opening a new excel spreadsheet. Next, navigate to the folder where the SDPS DAT files were output. Drag the DAT file of interest (for example, a vertical subsidence file with the 'Su' suffix) into excel.

2. Three columns should appear with the Easting, Northing, and predicted value at each point. However, the values are not actually separated into separate columns.

a. To separate them, select column A so that it is highlighted. In the Data ribbon, click Text to Columns in Data Tools tab. A window pops up called "Convert Text to Columns Wizard – Step 1 to 3". Keep the defaults and click Next, then click Finish. The columns should now be separated.

  b. Insert a new row at the top and name each column "Easting", "Northing", and "Subs" (or whichever SDPS predicted value was chosen") in that order.

  c. Select each column and covert each to Number datatype. Make sure to increase the decimal places to three. This step is critical or they will upload to ArcGIS as integers.

  d. Save the excel file as a CSV.

4.3 <u>Interpolating the Values in ArcGIS and Wxtracting as Points</u>

1. Start by opening up a new map document in ArcGIS. Next, navigate to the folder where the CSV was created in the last step.

2. Create a point feature class of the predicted values from SDPS
  a. Right click the CSV and click "From XY Table…" from the Create Feature Class option. For the X field choose the Easting, for the Y Field choose Northing, and leave the Z field blank. Save the data as either a feature class in a geodatabase or a standalone shapefile (be aware that shapefile field names have a 10 character limit).

3. Interpolate the predicted movements from the points.
  a. In the Search bar, search for the Spline geoprocessing tool.
  b. Open the Spline tool, then import the point features. In the Z value field option choose the predicted value that will be used for the interpolation. In the Output raster option navigate to where the raster will be saved and name the raster file with the .tif extension. Set the output cell size for the raster, the unit is based on the projection that ArcMap is using (It should be 2011 PA State Plane South, which means the unit is in feet). Leave the rest of the options as defaults. **if multiple predicted values are to be interpolated, try using the Batch Processing of the Spline tool. This allows multiple rasters to be created at once**

4. Extract values from the interpolations to exact points
  a. Now that multiple raster's have been created for the various movements (horizontal deformation in the X and Y directions, vertical subsidence, strains), the data is ready to be extracted to exact points.
  b. Import a survey feature class (for example, the highway alignment data).
  c. In the Search bar, search for the 'Extract Multi Values to Points Geoprocessing tool.'
  d. Open the Extract Multi Values to Points tool, then import the highway alignment feature class to the input point features table. Input the interpolated rasters from the last step. Run to tool. The output adds columns with extracted values for each point from each interpolated surface.

5. Export the attribute table with the newly added predicted values to a CSV. Next, open the CSV in excel and save it as an excel workbook (XLSV file). The data is ready graph.

4.4   Creating Profiles of the Assets from the Interpolated Surfaces

1. Start by opening up a new map document in ArcMap. Import the interpolated surfaces of the predicted movements created in the last step.
2. Create a profile of an asset
   a. If not done already, digitize a line feature over the asset of interest. This line feature of the asset will be used for the next step.
   b. Search for **Stack Profile** tool. With the asset of interest selected, import the feature class into the Input Line Features Drop option. Import the interpolated surfaces into the Profile Targets option. Save the table in the desired folder. The output fields from the tool are as listed:

- `FIRST_DIST`—Distance to the first vertex in the profile segment.
- `FIRST_Z`—Height of the first vertex in the profile segment.
- `SEC_DIST`—Distance of the second vertex in the profile segment.
- `SEC_Z`—Height of the second vertex in the profile segment.
- `LINE_ID`—Unique ID of the line feature used to define the profile.
- `SRC_TYPE`—Data type of the profile's source, which is either a surface or multipatch.
- `SRC_ID`—Unique ID of the multipatch feature being profiled. Not applicable for surface inputs.
- `SRC_NAME`—Name and path to the profile's source.

3. Open the data in excel and delete all fields except for the "FIRST_DIST", "FIRST_Z", "LINE_ID", and "SRC_NAME". The Stack Profile tool organizes all of the data in one column, so they need to be separated in order to graph them easily. Scroll to the row that restarts at "0" in the FIRST_DIST column. Cut all of the data from this row down and paste it back at the top to the right of the SRC_NAME column. Make sure the zeros are all aligned. This step makes sure the profiles for separate surfaces are in separate columns. See below for a visual illustration of this process:

5.0   SDPS Models of the Extended Study Area

A key objective of this research project is to take the knowledge gained from studying subsidence in the vicinity of Panel 15 and apply it to a larger region of future longwall mining referred to as the 'extended study area.' Applying the SDPS model to these new areas requires two significant considerations:

- Account for the influence of lower overburden caused by topographic changes and
- Project the size, shape, and locations of future longwall panels (See Task 3 Report).

5.1   Overburden and Supercritical Subsidence Factor

The influence of overburden is partially taken into account by SDPS through the supercritical subsidence factor. Variability in the overburden of projected panels in the extended study area is shown in Figure E7.
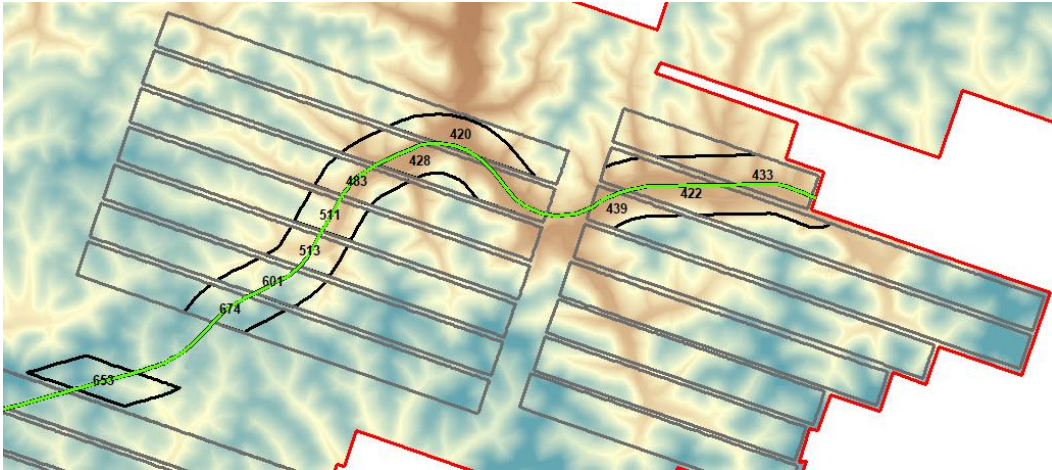

Figure E7 – Average overburden within 1,000-ft of I-70

Peng and Cheng, 1981 and Peng, et. al, 1995 used over forty subsidence case studies in the Pittsburgh Coalbed to develop an empirical relationship between supercritical subsidence factors and overburden (Equation 1). Using this empirical equation yields the Panel 15 S_{max} for is 4.19-ft.

$$a = 0.6760821 \text{ x } (0.9997678\text{^}h) = 0.578 \qquad\qquad \text{[Eq. 1]}$$

$$S_{max} = a \text{ x } m = 0.578 \text{ x } 7.25 = 4.19\text{-ft} \qquad\qquad \text{[Eq. 2]}$$

Where:
  a = supercritical subsidence factor
  h = overburden, ft
  m = extraction thickness, ft
  S_{max} = maximum vertical subsidence, ft

The SDPS program allows the users to input supercritical subsidence factors but it also provides another approach to determine the supercritical subsidence factor where the geology and thickness of the overburden are loosely accounted (Table 2.1, Agioutantis and Karmis, 2015). For Panel 15 with a w/h of 1.8 and a hard rock percent of 30, a supercritical subsidence factor of 60-pct yields S_{max} of 4.35-ft.

The average overburdens for individual panels in the extended study area was determined and is provided in Table E4. All SDPS models used an extraction thickness of 7.25-ft, scattered points, variable surface elevation, and edge effects of 175-ft. The supercritical subsidence factors applied to all modeled panels within the extended study area are provided in Table E4.

Table E4 – Examples of average overburden verses the supercritical subsidence factor for each panel in the extended study area

District	Panel	SSF[1] (Eq.1), pct	Selected SSF, pct	Avg. Panel Overburden, ft	Avg. Overburden 1,000-ft from I-70	w/h[2] Ratio
1	A	57.8	60.6	673	674	1.81
	B	57.9	62.0	664	601	2.03
	C	58.6	63.8	612	513	2.38
	D	58.9	63.8	594	511	2.39
	E	59.5	64.4	548	483	2.53
	F	60.0	65.5	511	428	2.85
	G	59.8	65.7	526	420	2.90
2	H	58.1	61.1	650	NA	-
	I	59.0	62.3	588	NA	-
	J	58.5	61.7	620	NA	-
	K	58.7	62.0	604	NA	-
	L	58.9	62.3	590	NA	-
	M	58.6	65.3	611	439	2.78
	N	59.5	65.6	546	422	2.89
	O	60.8	65.4	457	433	2.82

[1]SSF – Supercritical subsidence factor
[2]w/h – panel width to average panel overburden

5.2 Dynamic Subsidence Simulations

Approximately sixty SDPS models were constructed to simulate the dynamics subsidence wave moving through portions of the I-70 highway alignment in the extended study area. These models were split between two areas where detailed incremental subsidence basin formation was needed to analyze subsidence impact to assets (see Task 3 Report). The dynamic simulations models represented approximately 1-day of longwall face advance. For example, each face position shown in Figure E8 represented an SDPS run, producing a significant amount of information to digest and process. The University was able to use these individual face position models to accurate assess incremental changes in the formation of the subsidence basin.
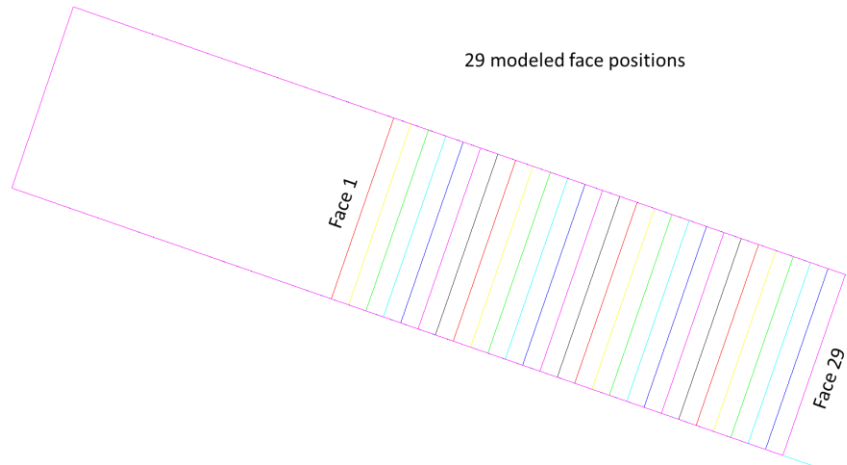
Figure E8 – Twenty-seven SDPS model face positions within the Panel N area

6.0   SDPS Limitations

The SDPS program utilizes the influence function which considers the displacements caused by subsidence on the surface as a function of the sum of surface subsidence due to the extraction of an infinite number of elements represent the extraction zone. Not surprising, this method requires a lot of assumptions to model displacements and strains. For example, SDPS does not account for material properties or geologic features in the overburden nor does it consider gob compaction characteristics. Because of these, and other limitations, SDPS subsidence prediction models are best used to build judgement and test theories.

Reference

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