Appendix D – ArcGIS Subsidence Database

All of survey data collected during the formation of the subsidence basin has been compiled in an ArcGIS geodatabase. The highway alignment, embankment and cut slope, and LiDAR survey data has each been compiled in separate individual geodatabases as well. Lastly a geodatabase was populated with roadway distress observed as the subsidence basin formed. This appendix details how each of these items are processed and stored in ArcGIS.

1.0 Highway Alignment Surveys

The highway alignment surveys were performed along I-70 at each of the pins installed in the outside asphalt shoulder adjacent to the truck lane at each contraction joint. These surveys were performed approximately once a week by PennDOT surveyors while I-70 was being undermined. Details on these global positioning system (GPS) surveys can be found in Subsection Vb of the Task 1 Report. The figure below depicts the longwall face position on the date of each survey (Figure D1). The longwall face was ~1,000-ft from the roadway when the highway pins were first surveyed on 15 January 2019 and are therefore defined as the pre-mining survey.

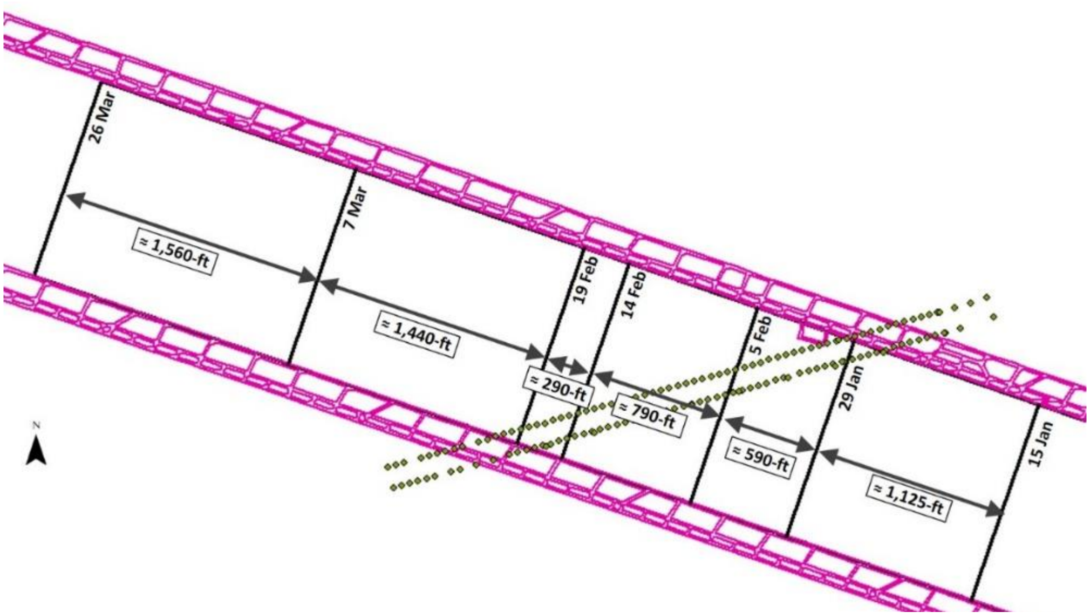

Figure D1 – Map depicting the timing of each survey and the longwall face at that point in time

1.1 Accuracy of Highway Alignment Survey

The accuracy of the highway alignment survey is assessed by comparing the coordinates of pins from different surveys before movements were expected. The University used the 15 January, 29 January, and 5 February surveys to assess positional accuracy of a subset of points in the western portion of the study area. The set of points used to assess accuracy is shown in Figure D2, along with the face position on each date.

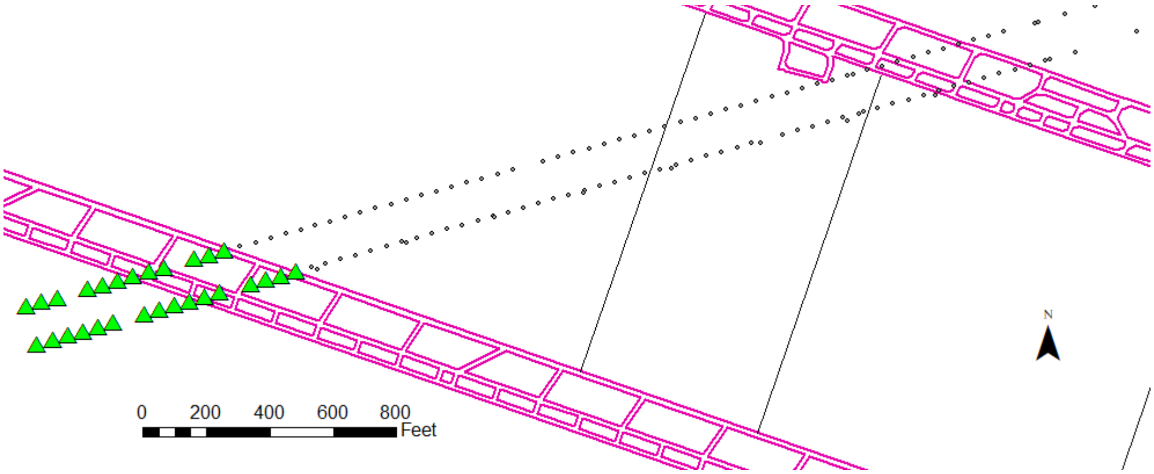

Figure D2 – Subset of highway alignment pins used for the accuracy assessment

The summary of the accuracy assessment is as follows:

- MIN Horizontal Distance – 0.08-in
- MAX Horizontal Distance – 1.37-in
- MEAN Horizontal Distance – 0.72-in

- MIN Vertical Difference – 0.00-in
- MAX Vertical Difference – 2.77-in
- MEAN Vertical Difference – 0.97-in

The surveys were originally stated to have a horizontal accuracy of 0.02-ft (0.24-in) and a vertical accuracy of 0.05 to 0.10-ft (0.6 to 1.2-in) (Subsection IIIa, Task 2 Report).

1.2 <u>Database Description</u>

The State Plane Coordinate System (SPCS) is used and the project coordinate system for the highway alignment surveys is:

- Name: United States/State Plane 1983
- Datum: NAD 1983 (Conus)
- Zone: Pennsylvania South 3702
- Geoid: GEOID12A (Conus)

The SPCS measures distances to the north and east from an establish point of origin. These measurements are in northing and easting attribute fields and the elevation is provided in another field. The coordinates for each highway alignment pin are assigned to a unique station identification (ID) (i.e., EB 0+00) with a name that is based on the PennDOT highway alignment tracking system.

The stations from each survey are plotted in ArcGIS using easting, northing, and elevation, information and then converted to a classification feature in the Highway Alignment Point geodatabase. The attribute for identical points tracked in each survey are linked by a unique station ID. This allows movements to be tracked in each dimension, i.e., movements were analyzed in the horizontal and vertical directions. Additionally, two attribute fields are added to include coordinates that were transformed from easting and northing to the direction parallel and perpendicular to I-70.

Table D1 includes an example of attributes for the 5 February 2019 survey. Each point attribute table includes location information from the pre-mining survey, the previous survey, and the most current survey. The survey performed on 5 February included coordinate information from the pre-mining survey (15 January) and the survey directly before the current survey (29 January). Movement information in each dimension is calculated both cumulatively and incrementally from the pre-mining and previous survey, respectively.

2.0 Embankment Slope Surveys

Survey stakes were installed along the embankment and cut slopes amid the study area. The stakes are organized into clusters. The stakes are located on Embankment #1 with clusters two on the cut slopes in the western portion of the study area and two on the cut slopes in its eastern portion. Embankment #2 has one cluster installed over the gate road entries. Each cluster was provided a base target that was tracked via GPS, and a total station was used to measure the stake locations from that base target. The embankment stake surveys were performed one to three times per week.

Table D1 – Example schema for the highway alignment attribute table

Field Name	**Survey Date**	**Description**
FeatureCode	15-Jan-19	Unique station ID name (i.e., WB 0+00)
Northing	15-Jan-19	Distance to the north of the PA State Plane origin point (ft)
Easting	15-Jan-19	Distance to the east of the PA State Plane origin point (ft)
Northing_Ori70	15-Jan-19	Northing value, transformed to match the orientation perpendicular to I-70
Easting_Ori70	15-Jan-19	Easting value, transformed to match the orientation parallel to I-70
Elevation	15-Jan-19	Elevation above sea level (ft)
FC_0129	29-Jan-19	Unique station ID name (i.e., WB 0+00)
North_0129	29-Jan-19	Distance to the north of the PA State Plane origin point (ft)
East_0129	29-Jan-19	Distance to the east of the PA State Plane origin point (ft)
North_0129_Ori70	29-Jan-19	Northing value, transformed to match the orientation perpendicular to I-70
East_0129_Ori70	29-Jan-19	Easting value, transformed to match the orientation parallel to I-70
Elev_0129	29-Jan-19	Elevation above sea level (ft)
FC_0205	5-Feb-19	Unique station ID name (i.e., WB 0+00)
North_0205	5-Feb-19	Distance to the north of the PA State Plane origin point (ft)
East_0205	5-Feb-19	Distance to the east of the PA State Plane origin point (ft)
North_0205_Ori70	5-Feb-19	Northing value, transformed to match the orientation perpendicular to I-70
East_0205_Ori70	5-Feb-19	Easting value, transformed to match the orientation parallel to I-70
Elev_0205	5-Feb-19	Elevation above sea level (ft)
Vert_0205	--	Cumulative vertical subsidence since the *pre-mining* location
Horiz_0205	--	Cumulative horizontal movements since the *pre-mining* location
Dist_0205	--	Cumulative total movement (3D) since the *pre-mining* location
Angle_0205	--	Cumulative directional movement (0.0-359.9-deg) from the *pre-mining* location
Parallel_Movement	--	Cumulative horizontal movement parallel to I-70 since the *pre-mining* location
Perp_Movement	--	Cumulative horizontal movement perpendicular to I-70 since the *pre-mining* location
Inc_Vert_0205	--	Incremental vertical subsidence since the *29 January* location
Inc_Horiz_0205	--	Incremental horizontal movements since the *29 January* location
Inc_Dist_0205	--	Incremental total movement (3D) since the *29 January* location
Inc_Angle_0205	--	Incremental directional movement (0.0-359.9-deg) from the *29 January* location
Inc_Parallel_Movement	--	Incremental horizontal movement parallel to I-70 since the *29 January* location
Inc_Perp_Movement	--	Incremental horizontal movement perpendicular to I-70 since the *29 January* location

2.1 Accuracy of Embankment and Cut Slope Surveys

The positional accuracy of the embankment and cut slope surveys is assessed by comparing the coordinates of stakes from different surveys before movements is expected, i.e. 15 January, and 22 January surveys. The location where this set of points was obtained is provided in Figure D3, along with the face position on each date. On 15 January, the stakes on Embankment #2 and the southern cut slope are used, while on 22 January the stakes on Embankment #1 and the northern cut are used. The longwall face was over 650-ft away from the nearest stake used in the accuracy assessment to reduce the possibility that subsidence would have caused any vertical movements in these stakes during this time period.

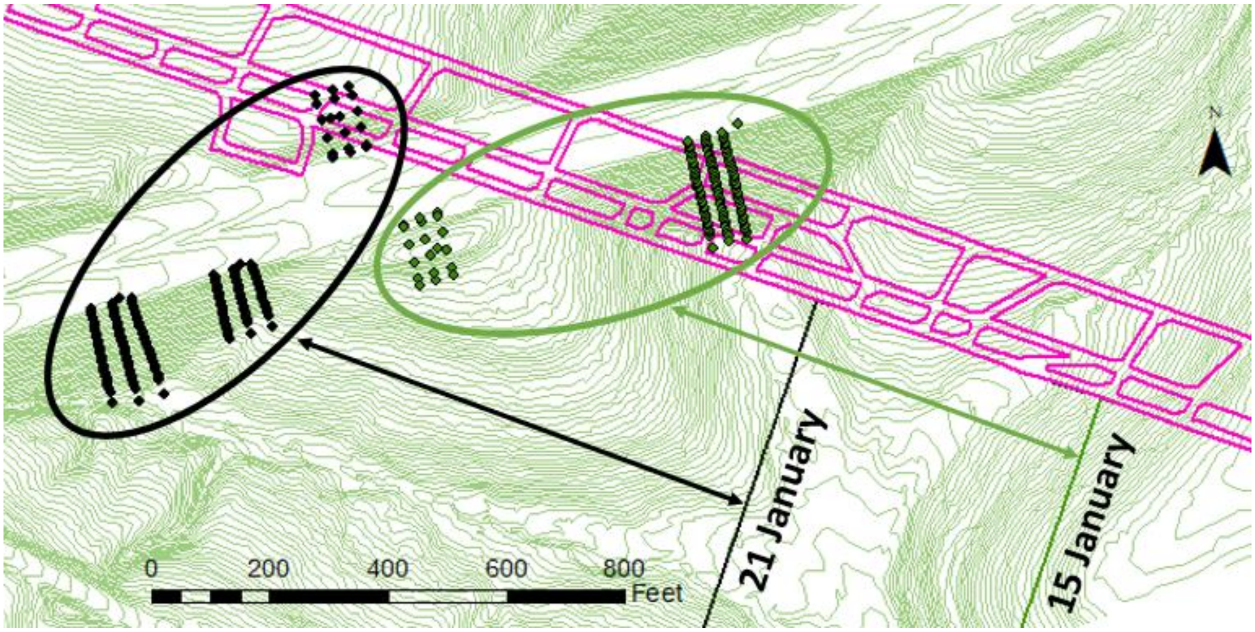

Figure D3 – Subset of embankment and cut slope survey locations used for the accuracy assessment

A summary of the accuracy assessment is as follows:

- MIN Horizontal Distance – 0.02-in
- MAX Horizontal Distance – 1.14-in
- MEAN Horizontal Distance – 0.24-in

- MIN Vertical Difference – 0.00-in
- MAX Vertical Difference – 1.88-in
- MEAN Vertical Difference – 0.13-in

The accuracy and precision of the slope surveys were originally reported by the surveyors to be within 0.03 to 0.04-ft (0.36 to 0.48-in) (Subsection IIIb, Task 2 Report). This is confirmed by the results of this accuracy assessment.

2.2 Database Description

As with the previously discussed survey data, these measurements are stored in northing, easting and elevation attribute fields with each stake assigned a unique station ID. The stake locations are plotted and then converted to a feature field in the Slope Survey geodatabase in ArcGIS. The stake coordinate information from each survey date is linked using the unique station ID so that cumulative movements from the pre-mining location could be determined and included in the dataset.

Table D2 - *Example schema for the embankment and cut slope attribute table*

Field Name	Survey Date	Description
G_ID	4-Feb-19	Unique station ID name (55)
G_Northing	4-Feb-19	Distance to the north of the PA state plane origin point (ft)
G_Easting	4-Feb-19	Distance to the east of the PA state plane origin point (ft)
G_Elevation	4-Feb-19	Elevation above sea level (ft)
ID	pre-mining	Unique station ID name (55)
Northing	pre-mining	Distance to the north of the PA state plane origin point (ft)
Easting	pre-mining	Distance to the east of the PA state plane origin point (ft)
Elevation	pre-mining	Elevation above sea level (ft)
Vertical	--	Cumulative vertical subsidence since the *pre-mining* location
Horizontal	--	Cumulative horizontal movement since the *pre-mining* location
Distance	--	Cumulative 3D movement since the *pre-mining* location
NEAR_ANGLE	--	Cumulative directional movement (0.0-359.9-deg) from the *pre-mining* location

3.0 LiDAR Surveys

LiDAR surveys were conducted in order to create highly detailed point clouds of the interstate and its surroundings. The point clouds produced from each survey are used to create Digital Elevation Models (DEMs) in ArcGIS. Sequential DEMs are used to track the change in elevation during subsidence. Elevation change detection models are created from each survey.

3.1 Accuracy of LiDAR Surveys

The accuracy of the LiDAR survey is based on two factors. The most important of these two is the accuracy of the control network. A control network is a set of highly accurate points that are used to register the location of the points in the point cloud. The points, which are collected in a GPS survey before each LiDAR scan, are much more accurate and are therefore used to differentially correct the position of the LiDAR points. The second factor is the accuracy of the laser pulses produced by the LiDAR scanner. The LiDAR scanner that was used for these surveys was the RIEGL VMX-1A, and according to its technical documentation has a laser pulse accuracy of 0.2-in.

An accuracy assessment has been performed on the control network stations. The summary of the accuracy assessment for the control network is as follows:

- MIN Horizontal Distance – 0.03-in
- MAX Horizontal Distance – 0.70-in
- MEAN Horizontal Distance – 0.42-in

- MIN Vertical Difference – 0.00-in
- MAX Vertical Difference – 1.18-in
- MEAN Vertical Difference – 0.26-in

The accuracy of the LiDAR survey is stated to be 0.4-in (1-cm) (0.36 to 0.48-in) (Subsection IIIg, Task 2 Report). The combined results from this accuracy assessment and the laser pulse accuracy indicate that it may have been closer to ~0.6-in.

3.2 Data Description

The LiDAR files are stored in the LAS file format. LAS files are a traditional format designed for storing LiDAR point cloud data. The most important fields associated with each point are the coordinates (easting, northing, and elevation), the intensity, and the class code. The same SPCS used in the previous two surveys was employed here as well. The intensity output is a measure of the return strength of the laser back to the scanner. The value is dependent on the reflectivity of the object the laser hits, with higher reflectance resulting in a higher intensity. The class code, as defined by the American Society of Photogrammetry and Remote Sensing (ASPRS), defines the type of object each point represents. For these files, points were classified as belonging to ground (2), low vegetation (3), medium vegetation (4), or high vegetation (5). Objects such as guiderails, safety cones, vehicles, etc. were grouped based on their height into these different vegetation classes.

LAS files were uploaded into LAS datasets in ArcGIS. These datasets are in a LiDAR data format that is designed to store and reference one or more LAS files. Eight LAS files are created during each LiDAR survey, but only four are needed to cover the extent of expected influence. As such, for each survey date, only four of these files are included in the LAS datasets.

The ground points in the LAS datasets are used to create digital elevation models (DEMs) of the highway surface elevation. Each DEM is given a spatial resolution of 1-ft, meaning each pixel of the DEM surface is 1 by 1-ft. The DTMs produced by each survey are used to create elevation change detection models as the subsidence basin formed. The DEM and change detection model is then saved as a TIFF image.

4.0 Distress Feature Geodatabase

The University was responsible for recording the location and timing of distress that developed along the roadway during undermining. The type of distress exhibited included transverse and longitudinal cracking, lane-to-shoulder separation, widened contraction joints, longitudinal shear cracking, blowups, compression bumps, and guiderail displacement. Each distress observed was transcribed onto scroll maps and then later digitized into an ArcGIS geodatabase. The various types of distress were coded in the geodatabase as follow:

- 0 = Longitudinal Crack
- 1 = Transverse Crack
- 2 = Compression Bump/Blowups
- 3 = Longitudinal Shear Crack
- 4 = Lane-to-Shoulder Separation
- 5 = Widened Contraction Joint
- 7 = Guiderail Displacement

The schema for the distress geodatabase can be found below in Table D3.

Table D3 - Schema for the distress attribute table

Field Name	Description
Type	Coded value for the type of distress
Date	The date on which the distress began to form
Feature	The type of distress
Photo	An attached photo of the distress (if one exists)

5.0 Data Processing Procedures

5.1 Directional Change between Highway Alignment and Embankment Surveys

The University tracked the directional movement of the highway alignment pins and the embankment and cut slope stakes. For each survey, cumulative and incremental directional changes are determined. Cumulative movement indicates directionality from the pre-mining location, while incremental indicates directionality since the most previous survey. This information is determined in ArcGIS using the Generate Near Table geoprocessing tool. This tool calculates the distance and direction of movement between features among two different datasets. The tool creates a new table with distance attributes between each feature to the near feature. The "NEAR_ANGLE" attribute stores the directional movement between features in the form of degrees. With the "Geodesic" option chosen, the degrees will range from -180 to 180-deg, with 0 to the north, 90 to the east, 180 (or -180) to the south, and -90 to the west. Values less than zero are then identified and 360 is added to the value to match the geographic rotation style in ArcGIS (Figure D4).

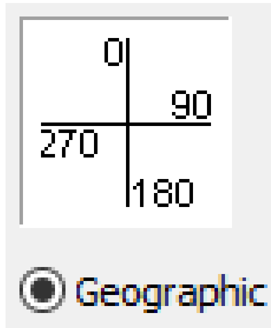

Figure D4 – Orientation of the degrees used to indicate directional movement

5.2 <u>Detecting Elevation Change between LiDAR Scans</u>

For each LiDAR survey, an elevation surface is created from the point clouds. Each point in the LiDAR point cloud represents a physical location projected in the PA state plane south coordinate system. These points, which are projected in 3D, are used to create Digital Elevation Models. The DEMs are created in ArcGIS by converting the LiDAR points into a raster surface that represented elevations. More specifically, the coordinate and elevation for each point is converted to individual pixels of the DEM. The DEMs have a spatial resolution of 1-ft, meaning each pixel in the DEM was 1 by 1-ft.

In order to create an elevation change detection model, the Raster Calculator tool is utilized in ArcGIS. This tool takes raster surfaces and performs user specified mathematical equations on each overlapping pixel between the raster datasets. In this case, the pre-mining DEM is subtracted from the most recent DEMs. The resulting change detection model presented a surface with the vertical subsidence established at each pixel location.

5.3 <u>Populating the Transverse Joint Database using the LiDAR Point Clouds</u>

The University identified the transverse joints in the travel lanes to be the most appropriate targets in the study area for tracking within the LiDAR point clouds. The proximity of the transverse joint to the LiDAR scanner made them more identifiable in the point cloud with the point densities being higher in the travel lanes. Maptek's I-Site Point Studio is utilized to digitize the transverse joints for each survey. The transverse joints are digitized from end to end, extending from the inside of the paint stripe on outer edge of each of the travel lanes (Figure D5).

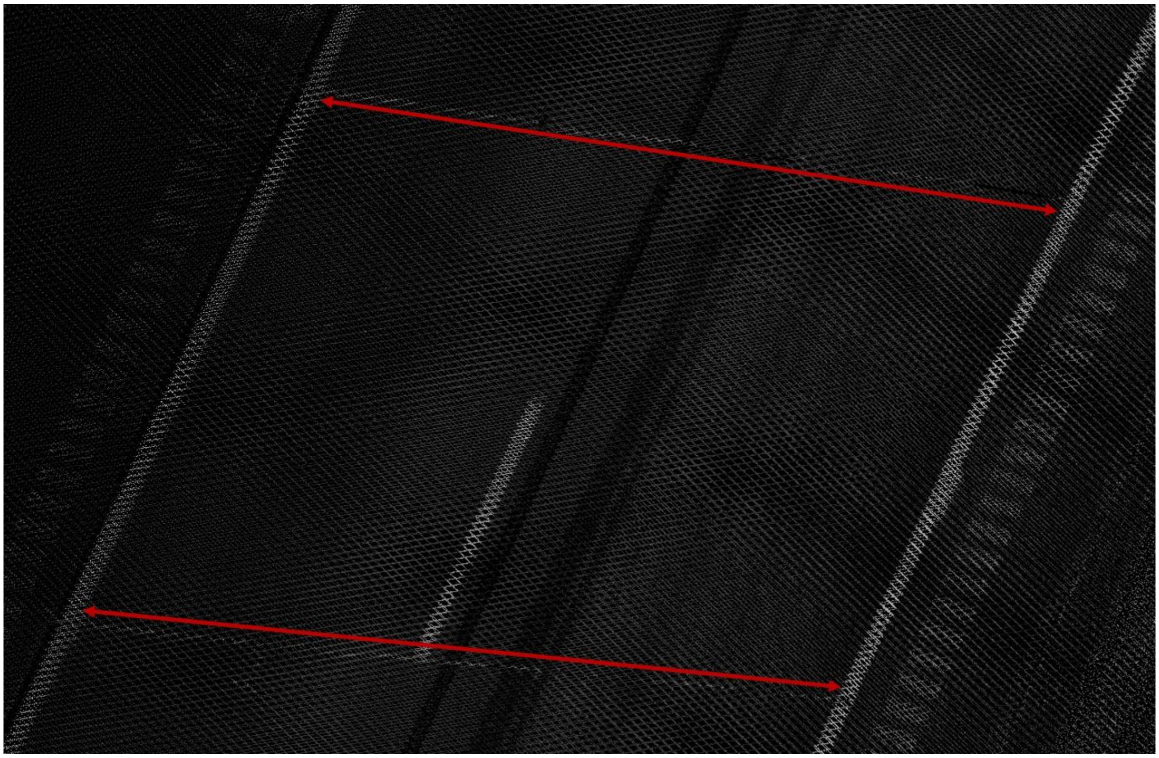

Figure D5 – Snapshot of the roadway surface as it appears in the LiDAR point cloud. The arrows indicate the approximate location of the transverse joints

The lines that are digitized in Point Studio were exported to a CAD file, then imported into ArcGIS where they are converted to a geodatabase feature class. A protocol is utilized in ArcGIS that first extracts point coordinates for the beginning, middle, and end points of the transverse joints, then creates point feature classes for each point and adds an attribute column with transformed coordinates matching the orientation of the highway (see Section 4.6).

5.4 Overburden Map

Overburden is defined as the thickness of the strata between the earth's surface and the extraction zone of the underground coal mine. Overburden influences several key characteristics of the subsidence basin, including maximum vertical subsidence, horizontal deformation, and horizontal strains. To create an overburden map, two datasets are needed: the structure contour map of the Pittsburgh Coalbed and the elevation of the earth's surface. By subtracting the Pittsburgh Coalbed elevation from the surface elevation, the overburden is calculated.

The Pittsburgh Coalbed dataset consisted of linear contours with elevation values. As is depicted in Figure D6, the Pittsburgh Coalbed contours is constructed with 50-ft increments. To convert it to a raster elevation surface, the "Topo to Raster" tool in ArcGIS is utilized. This tool takes vector data with elevation values and converts it to a raster surface. Figure D6 depicts the dataset before and after the conversion.

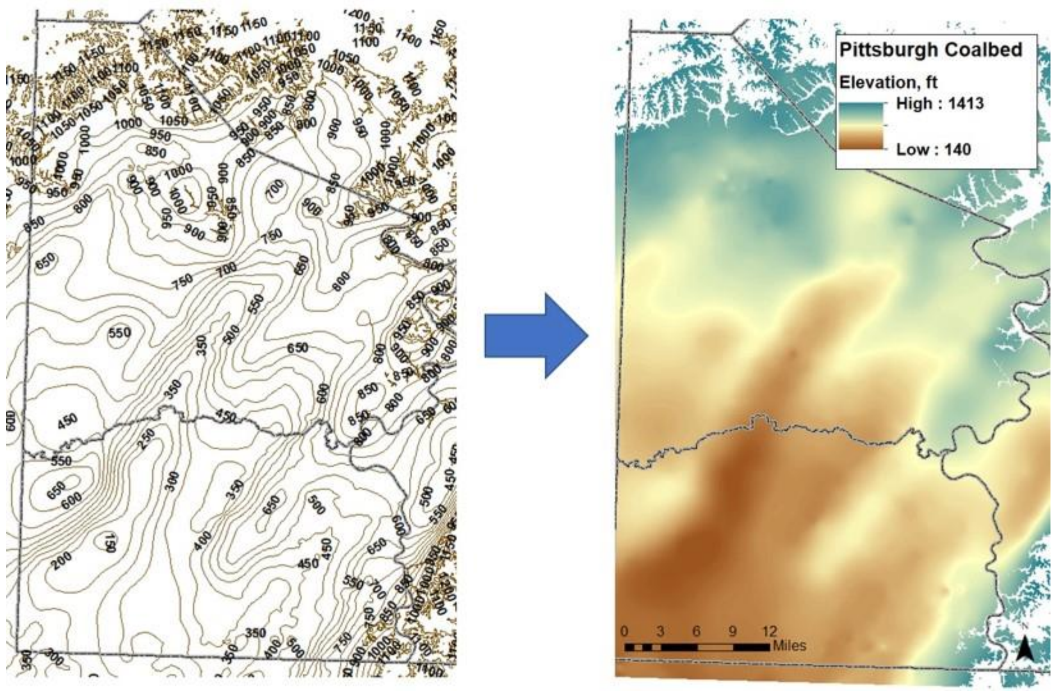

Figure D6 – Illustration of the Topo to Raster tool used to convert the topographic contours of the Pittsburgh Coalbed to a raster surface

The source of the surface elevation dataset came from the Pennsylvania Department of Conservation and Natural Resource (DCNR) PAMAP project. This project was conducted from 2006-2008, and consisted of collecting high-resoultion aerial photography and LiDAR data across the state, in order to create an accurate DEM of Pennsylvania. The DEMs were created with a spatial resolution of 3.2-ft, or 1-m, per pixel.

5.5 Using Zonal Statistics to Extract Overburden Characteristics for Specified Zones

To determine overburden statistic associated with features and areas such as Panel 15, Embankment #1, and the extended study area, the "Zonal Statistics as Table" geoprocessing tool is utilized in ArcGIS. This tool summarizes the values of a raster within a feature or a set of features. In this case, the overburden raster was summarized within features, such as the aforementioned. The average overburden derived for these features is used as an input for other models, such as the empirical formula used to determine subsidence characteristics described in Subsection IIIa of the Task 3 Report.

5.6 Transforming Northing and Easting Coordinates to the Orientation of I-70

To calculate movement parallel and perpendicular to the direction of travel along I-70, a coordinate transformation is calculated. The coordinate transformation was performed by rotating the easting and northing planes on their point of origin until they are aligned with the roadway. I-70 crosses the easting plane at 15.7-deg. The formula used to transform the easting and northing coordinates is shown in Equations 1 and 2. Additionally, an illustration of the transformation can be found in Figure D7. Movements in this orientation are more indicative of the types of distress that occurred on the roadway surface. Attributes with these transformed coordinates are suffixed with "Ori70".

$$\text{Easting\_Ori70} = (Easting * cos(radians(15.7))) + (Northing * sin(radians(15.7))) \quad \text{(Eq. 1)}$$

$$\text{Northing\_Ori70} = (Northing * cos(radians(15.7))) - (Easting * sin(radians(15.7))) \quad \text{(Eq. 2)}$$

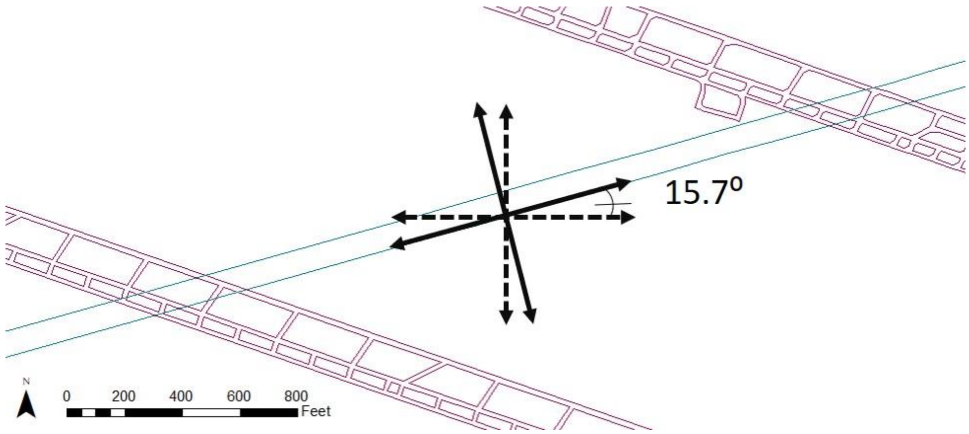

Figure D7 – Transormation that was performed for each highway alignment survey

5.7 Horizontal Strains along the Highway Alignment

The point features from the highway alignment databases are utilized to calculate strains on the outside shoulder of I-70. Strain is calculated by taking the change in distance between two neighbor highway alignment pins and dividing it by the original distance. For this analysis, 1D strain was calculated in correspondence to the direction of travel (only utilizing transformed easting values derived from Eq. 1) as these movements are more indicative of roadway distress given its orientation and linear construction. The calculation is shown in Equation 3.

$$\left(\frac{(EB2+50-EB\ 2+00)-(EB2+50-EB\ 2+00)}{(EB2+50-EB\ 2+00)}\right) * (1 * 10^3) \quad \text{(Eq. 3)}$$

blue = the distance between the highway alignment pins on 5 February

red = the distance between the highway alignment pins on 29 January