Modeling Flow Paths through Mine Tunnels Using Cost Path Analyses

by

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Abstract

For a potential cementitious grout injection project, a model was developed using the Spatial Analyst extension to estimate the path of grout along the slope of a mine tunnel floor network in an abandoned coal mine. The grout, consisting of coal combustion by-products (CCPs), would be injected through boreholes drilled into the mine voids to prevent and mitigate land subsidence. After the tunnels fill with grout, the grout hydrates and hardens to provide previously missing structural support to prevent tunnel collapse and the resulting land surface subsidence. The model was developed to better understand the required distribution of boreholes to stabilize land over a proposed technology business park. Given initial proposed injection points on the surface, the model offers an effective means to visualize the potential grout path through the mine tunnel network and efficiently adjust CCP injection points to fill mine voids and return otherwise uninhabitable land to productive use.

Introduction

The study area lies within the Mid-Atlantic Highlands where as a legacy of historical mining over 6,000 underground mines have been abandoned (Figure 1) posing subsidence and acid mine discharge risks. One such mine underlies a proposed business park (the “Site”) adjacent to Frostburg State University (FSU) located in Frostburg, MD (Figure 2). Allegany County and FSU plan to develop the Site as an incubator park for small technology related businesses; however, the site is underlain by mine voids from an abandoned coal mine. To mitigate land surface subsidence due to settlement into mine voids, the voids may be filled with cementitious grout which cures to provide structural support and encapsulate the minerals responsible for acid mine discharge.

Mine void stabilization techniques involve the injection of cementitious grout through a series of boreholes drilled from the surface into the mine voids. The boreholes are used as grout conduits to backfill and stabilize the mine voids. Without model simulations, predicting grout paths through the mine voids involves manual estimation based on a complex assortment of parameters including tunnel orientation and mine floor slope aspect. Developing automated tools in ModelBuilder and interfaces with ArcToolBox greatly enhanced the capability to predict the most likely grout path through the mine tunnel network. Mine void grouting operations require a significant field effort of drilling anywhere from 50 to 100 or more boreholes to serve as grout conduits. The boreholes are relatively expensive to drill and each borehole that does not intersect a mine void must be redrilled. Therefore, the ArcGIS modeling becomes especially useful for planning field drilling operations and optimizing the spacing of grout injection points.

The input to the cost path model includes the mine floor surface elevations within the mine tunnel, a polygon coverage of the mine tunnel network, and source and destination points. The model utilized the Spatial Analyst ArcGIS extension to create and process raster coverages, and ultimately produce a polyline tracing the path from the source to the destination point. After the cost path lines were generated, mine floor elevations were interpolated to the points along the line to permit a three-dimensional representation of the cost paths. Due to the large area of the mine (60 acres) and large volume of grout anticipated for mine void stabilization, the modeling should become an increasingly important tool in optimizing the number of boreholes as well as the cost of field operations.

For planning purposes and efficient grouting operations at the Site, the mine geometry must be known before implementation of grouting operations. For this project, the Maryland Department of the Environment, Bureau of Mines, and the GeoSpatial Research Group, Frostburg State University participated in digitizing and aligning the scanned images of historical plan views of mine maps. These digitized mine maps coupled with previous investigations and studies were used for initial mine void volume estimates and the subsequent sizing of grouting equipment, materials, and associated labor. Prior to field operations, the tunnels and orientation of the maps will be refined with field surveys including exploratory boreholes, geophysical surveys, and downhole cameras to observe tunnel configurations and orientations as defined on mine maps.

For the Site, the mine tunnels are known to be dry. In areas where the mine tunnels are flooded and below the water table, thorough consideration must be given to the hydrogeology prior to implementation of grouting operations. Groundwater that collects in mine tunnels may create high subsurface pressure. These pressures may eventually exceed confining rock strengths and create sudden tunnel blowouts or rapid releases of potentially acidic water to surrounding water ways. When grouting in areas of flooded tunnels, careful consideration must be given to changes in subsurface pressures that may be generated by grouting. With proper geologic and engineering studies, grouting in and near areas of flooded mine tunnels has been performed in a safe and effective manner (Walker et al., 2005).

Background

The Maryland Department of Natural Resources (MDNR) Power Plant Research Program (PPRP) was formed in 1971 to ensure that Maryland meets electricity demands at reasonable costs while protecting the States valuable natural resources. A component of ensuring reasonable costs is the cost efficient and environmentally friendly management of Coal Combustion by-Products (CCPs) continually generated by coal fired power plants in and around the state. PPRP (Hemmings & Associates, 2005) has developed CCP blends that behave similar to conventional (i.e., portland cement based) grout when mixed with water and have excellent structural and engineering properties.

CCP based grout is a viable and less costly alternative to conventional cementitious grout, and can be used to effectively fill abandoned mine voids and restore structural integrity to the subsurface as well as mitigate acid mine discharge. Using CCPs has an added benefit of reducing the stress on existing landfills to continually stockpile an ever growing inventory of CCPs from coal fired power plants.

In Western Maryland, PPRP has undertaken pilot projects and studies to demonstrate the effectiveness of CCP grouting in abandoned underground coal mines. As part of these projects, the cost path model is being developed to visualize grout flow through the mine tunnel networks, and to help refine selection of borehole locations and field investigation activities associated with mine void stabilization. With the mine geometry defined, the model can refine the required number of boreholes and drilling locations to help optimize the overall cost of the mine grouting project.

Site Mine Geometry

Based on stratigraphy extracted from borehole information and studies adjacent to the Site, the mine tunnel voids are approximately 8 to 12 feet high. From these boreholes, elevations of the coal seam were used to create an extrapolated surface with Spatial Analyst extending over the area of the tunnel network within the site boundaries. From the coal seam elevation data, the dip of the seam is generally towards the southeast averaging approximately 3 to 4 degrees (5 to 7 percent). The slope gradient and aspect of the mine floor is expected to approximate that of the coal seam.

Based on the digitized polygons of the mine tunnel network, calculations with Spatial Analyst estimated the total area of the mine tunnels (excluding coal pillars) within the Site boundary to be approximately 18 acres over the 60 acre site area. Based on tunnel heights the void volume is approximately 292,000 yd^3. In the area of the Site, boreholes records indicate that portions of the upper mine may be partially collapsed. Therefore, the actual mine void (and grout) volumes are anticipated to be somewhat lower than the volumes calculated from the digitized mine maps and tunnel heights since one hundred percent of the mine void cannot be filled due to obstructions and barriers (e.g., areas of collapsed mine roof rock). Based on previous studies (Healy and Head, 1984) and experience, approximately 50 to 60 percent of the total mine void volume may be expected to be filled by the grouting.

Modeling Tools

To create a flexible model that is applicable to different geographical areas in the Mid-Atlantic Highlands, the model consisted of modular components (Figure 3). To use the cost path analysis for mine modeling purposes, raster coverages of the mine tunnel networks were required. The digitized mine tunnels were converted to an integer-valued raster coverage with a sufficiently small (1 foot) cell size to capture the tunnel details. Since the tunnels were approximately 8 to 12 feet wide, the cell size was adequate to capture the slope of the mine floor across the tunnel areas in the resulting raster. To restrict the model calculations to valid cells in the mine raster (i.e., cells within mine tunnel walls), all cells outside of the tunnels were assigned an integer value designated for exclusion from the model calculations.

The mine floor elevation raster, calculated based on geologic borehole stratigraphy, was converted to a slope raster with units of degrees. The raster slope values were then divided into equal intervals based on units of degrees. Nine to ten divisions of the slope was sufficient to represent the relatively shallow overall dip (3 to 4 degrees) of the mine floor (coal seam). The reclassification of the mine raster to valid calculation cells, and the slope (in degrees) of the mine floor created the two rasters needed for the raster overlays and weighting of the next modeling step.

Utilizing the mine tunnel raster populated with valid calculation cells, and the reclassified mine floor slope raster, the two rasters needed to be combined to create a cost surface. Created in parallel, the mine tunnel and mine floor slope rasters were combined to create a common measurement scale of values for generation of the cost surface that incorporated both the confined travel path in the tunnels and the slope aspect of the mine floor. When combining these two rasters, each raster was assigned an equal weight for the resulting cost surface to ensure each raster cell value was scaled proportionally.

The next step included the use of cost distance function to apply distance scaled by cost for creation of two rasters: a cost distance raster for calculating the least accumulative cost distance over the surface to the source; and a cost back link raster that defines the direction to the neighboring cell along the least accumulative cost path to reach the source. In combination, these two rasters are used in the cost path module to define the least cost path raster from the source to the destination through the mine tunnel network. The resulting cost path raster is converted to a polyline (Figure 4) with the raster to polyline conversion module using values calculated from the cost path module.

Elevations of the points along the resulting polyline nodes are then extracted from the mine floor elevation raster. The resulting nodes on polyline were then converted to point-elevation data for incorporation into three-dimensional representations (Figure 5) and animations developed with the Mining Visualization Software (http://www.ctech.com) application.

Model Assumptions and Limitations

Although the model is a simplistic representation of grout flow through a tunnel network, the model capabilities are effective in achieving the objective of visualization of grout pathways, helping to minimize the cost and number of boreholes required to be used as grout conduits, and planning field investigations to refine mine maps and plan borehole locations for initial field investigations. The initial boreholes can be fitted with downhole cameras for a visual inspection of subsurface tunnel conditions and will serve to refine the mine geometry as well as model parameters. These initial exploratory boreholes are also later used as part of the overall grout injection grid during the mine void stabilization.

Unlike the path lengths capable of being generated by the model, grout has limited flow length due to the corresponding grout material properties, the roughness of the tunnel floor, and obstructions (mine debris) encountered along the flow path. Based primarily on a range of water contents (generally 60 to 70 percent), material properties of grout can be engineered to flow variable distances, or set up as a paste with minimal flow. With the properly engineered mixture, maximum flow lengths of grout are on the order of several hundred feet. Typically in mine void stabilization projects, sections of the mine are sealed with a paste grout barrier, and filled in between the barriers with a more fluid grout. This allows a controlled and systematic filling of the tunnel corridors starting at the lower elevations of the mine tunnel network and working towards the higher elevations. Although the model cannot simulate physical mine floor obstructions such as mine debris, the paths simulated by the model can be used to determine sections of the tunnel network amenable to isolation for systematic mine void grouting. The capability to identify sections of mine tunnels for grouting is particularly effective in planning the order of field operations during a mine grouting project which may span a period of months.

The modeling calculates a path from a fixed source to a fixed destination. Clearly this is not the only path that would contribute to flow at a destination given multiple borehole injection points. However, the path calculated by the model is valid given slope and confines of tunnel network and does prove that the destination is reachable from the source. Given that mine void stabilization typically proceeds by grout injection at only a few boreholes at any one time, the path from a fixed source to a fixed destination is a valid assumption and not a severe model limitation.

Summary

The cost path model developed provides an effective tool for planning a mine void stabilization project. Prior to any mine void stabilization grouting, a sound site conceptual model must be developed to define the mine geometry and hydrogeology. The model is intended to serve as a means to drive field investigations which are an integral part of mine void stabilization projects for refining mine geometry and understanding the complex hydrogeology often associated with mine tunnel networks. Although the tunnel networks are shown on many historical mine maps, not all tunneling activity was recorded, particularly during the end of the mine life cycle. Therefore, field surveys and investigations are a vital component of confirming the tunnel configuration and mine geometry, and serve to refine parameters of the cost path model.

Over fifty percent of mine void stabilization project costs are associated with labor (Erdman et al., 2005) for on site field operations. A portion of this labor is associated with drilling boreholes to act as grout conduits into the mine voids. The model provides a tool to optimize borehole spacing, and therefore help minimize grouting costs given the mine geometry and grout material properties. When grouting with CCP-based grout, project costs are driven down further due to the negligible cost of CCPs obtained from coal fired power plants. CCP based grout is environmentally benign (ERM, 2005), has excellent structural and engineering properties (Hemmings & Associates, 2005), and provides a beneficial use of material that may otherwise end up in a landfill.

Mine void stabilization using CCP grout is a proven technology that has been used successfully in Maryland (ERM, 1996), Ohio (Walker et al., 2005), Pennsylvania (Harper, 2004), and West Virginia (Black and Ziemkiewicz, 2000) over the last several years. Examples include the Winding Ridge project (ERM, 2006) in western Maryland where approximately ten years after mine void grouting, results include an approximately 80 percent reduction in acidity and harmful metals in the mine discharge water with cured grout strengths equal or exceeding that of typical surrounding rock.

The model described in this study is an initial step in developing a predictive tool for the simulation of grout flow through mine tunnels. Previous work has been done in the simulation of aggregate flow through small confined spaces (Martys, 2005 and Martys et al, 1999). Based on this previous work and work presented in this study, future efforts are planned to develop a model incorporating grout material properties into simulations of flow through large voids such as mine tunnels. The resulting model will be a valuable asset for optimizing grouting costs, and evaluating grout formulations and performance metrics specific to an individual underground mine reclamation project both within and beyond the Mid-Atlantic Highlands.

Figures

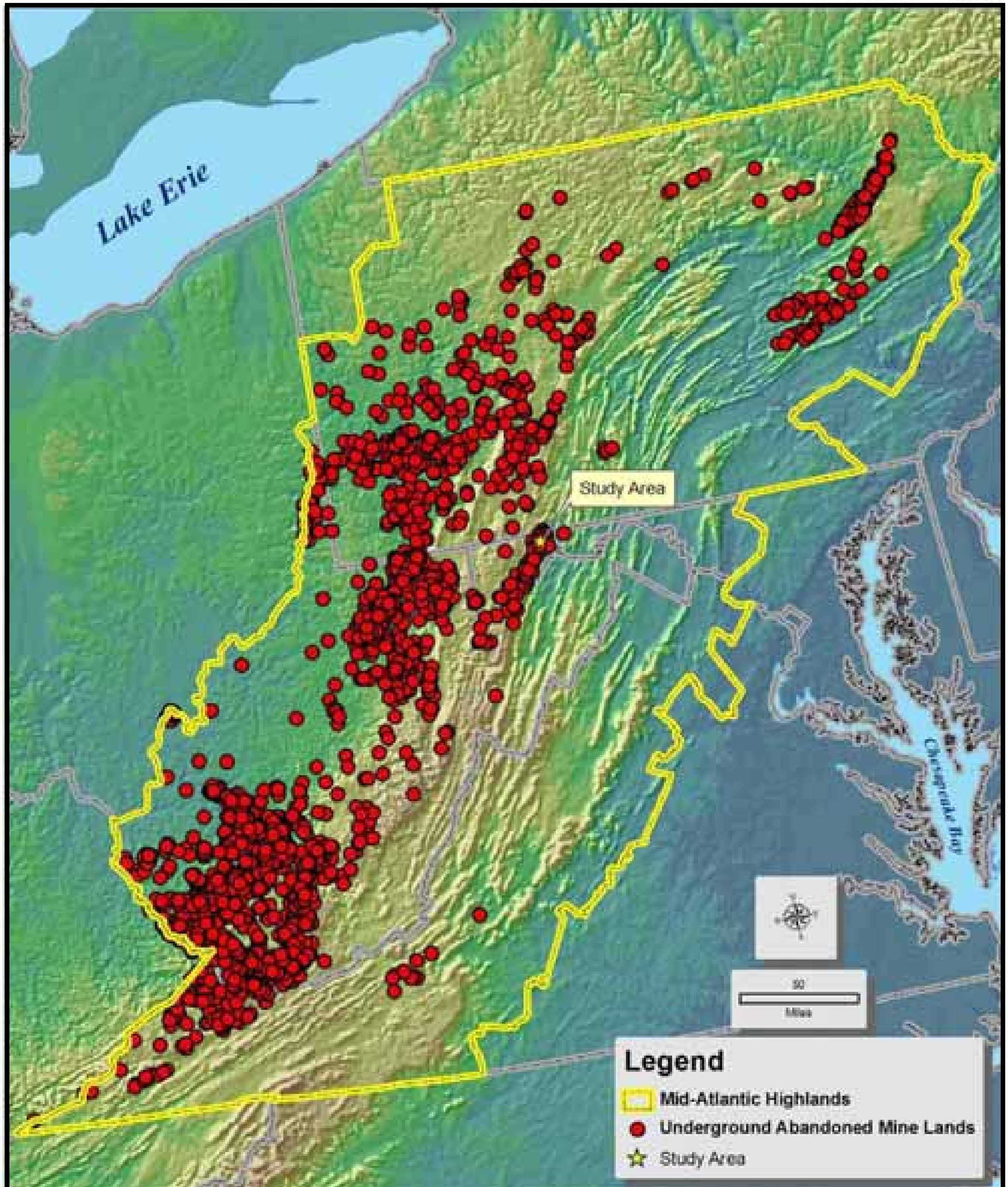


Figure 1. Overview of Underground Abandoned Mine Lands in Western Maryland and the Surrounding Mid-Atlantic Highlands.

Figure 2. Mine Tunnel Void Network and Site Boundary

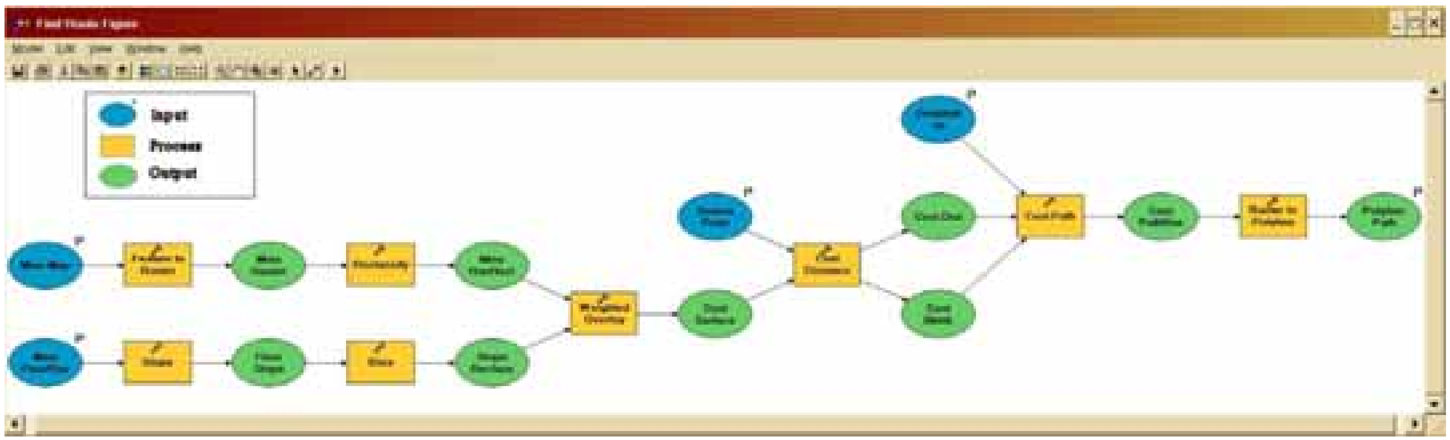


Figure 3. Model Component Configuration.

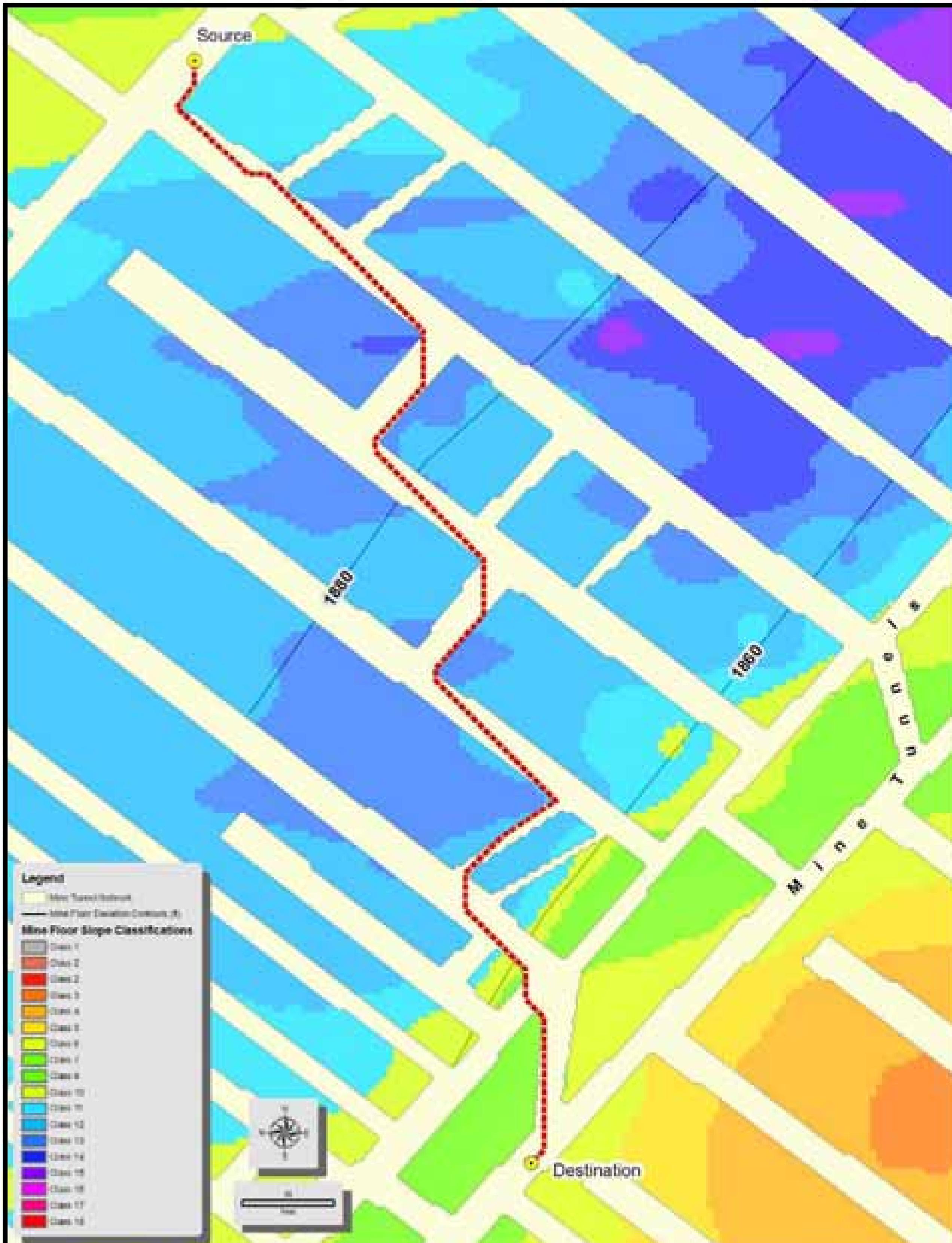
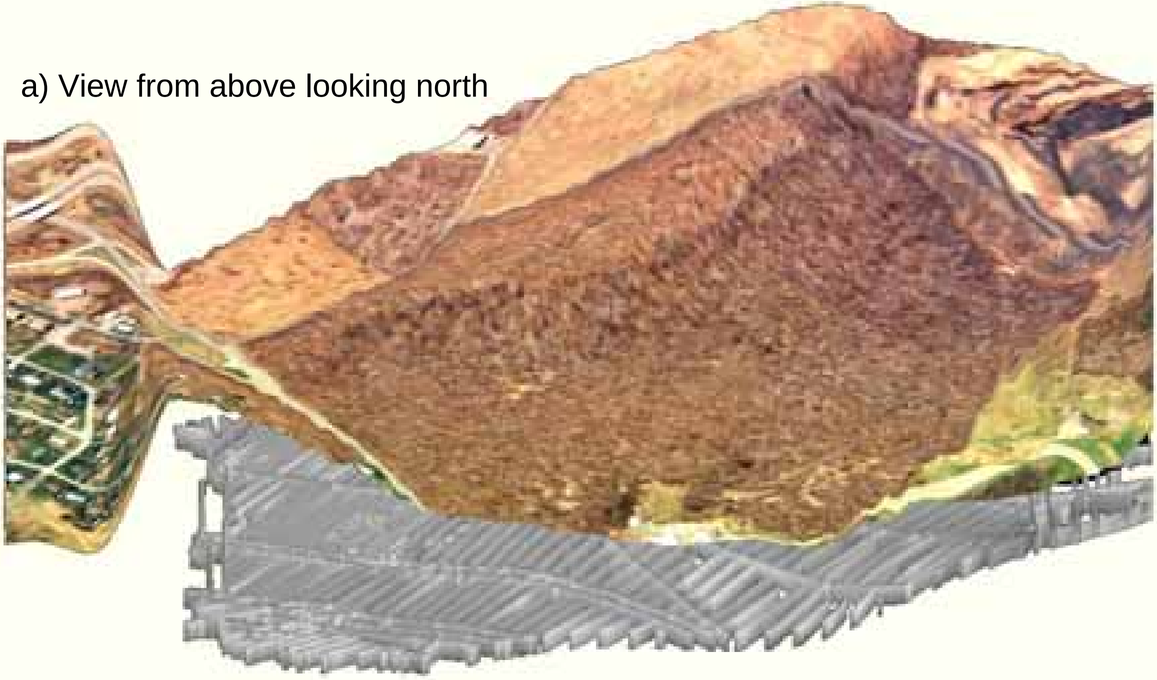


Figure 4. Mine Tunnel Network, Mine Floor Elevations Contours, Mine Floor Slopes, and Resulting Cost Path Polyline from Model Output.



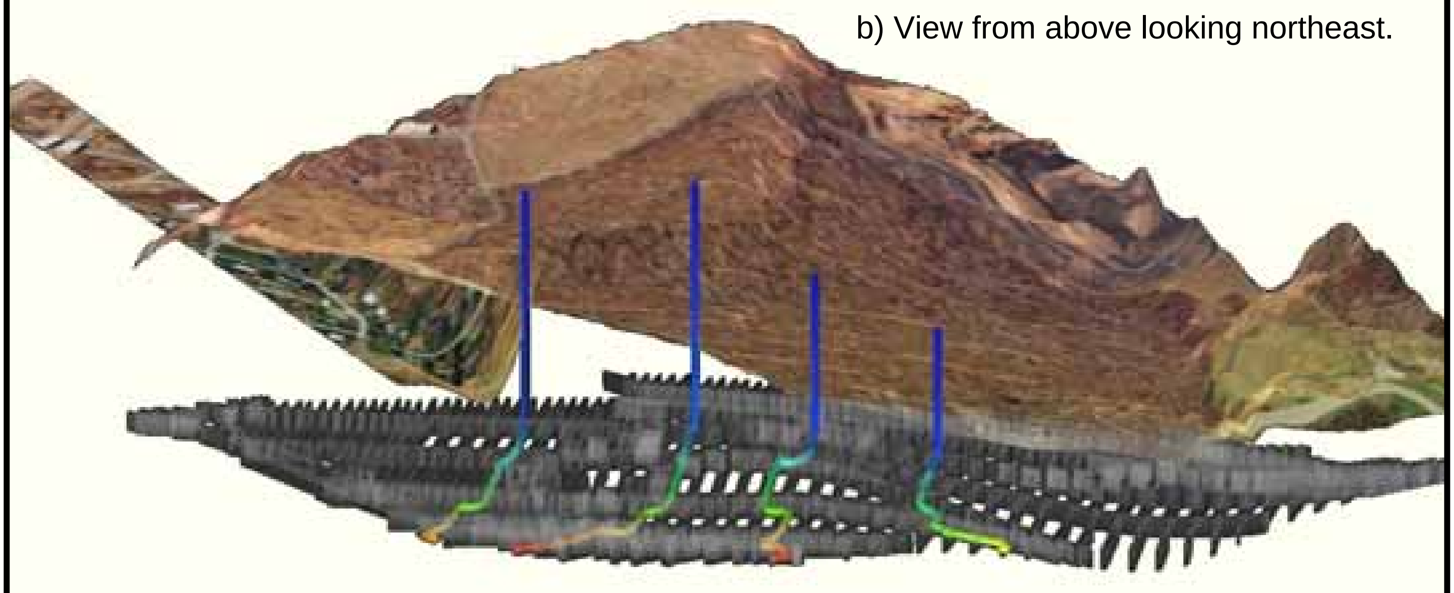


Figure 5. Aerial Views of a) Surface Topography and Mine Tunnel Network, and b) Surface Topography, Mine Tunnel Network, and Simulated Flow Paths.

Acknowledgements

The work described in this paper is part of a larger scope that involved beneficial use of CCPs sponsored by the Maryland Department of Natural Resources Power Plant Research Program (PPRP). Within the project area, extensive work has been done by the Maryland Bureau of Mines and the Geospatial Research Group at Frostburg State University, MD in developing mine maps and associated spatial information from historical documents. Maps developed by these organizations were used extensively as overlays and for development of mine geometry.

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