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Mine Safety and Health Administration
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Mine Waste and Geotechnical Engineering Division

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MEMORANDUM FOR IRVING McCRAE
Contracting Officer, Acquisition Management Division
MSHA - Headquarters, Arlington

THROUGH: for STANLEY J. MICHALEK
Chief, Mine Waste and Geotechnical Engineering Division

GEORGE H. GARDNER
Senior Civil Engineer, Mine Waste and Geotechnical Engineering Division

FROM: JAMES B. PFEIFER
Civil Engineer, Mine Waste and Geotechnical Engineering Division

SUBJECT: Summary of the DeltaEM Gradiometer Geophysical Void Detection Demonstration Project by Stolar Research Corporation, Mine Void Detection Project Account Number B2532531, MSHA RFP No. J53R1011

Stolar Research Corporation (Stolar) has recently completed the demonstrations of the DeltaEM Gradiometer geophysical method to detect underground mine voids at Consolidation Coal Company's Emery mine that is located near Emery, Utah. The project was performed under account number B2532534 in connection with MSHA RFP No. J53R1011. As the Contracting Officer's Technical Representative (COTR) for this project, I was responsible for monitoring and reporting on Stolar's performance on behalf of the Contracting Officer. This memorandum is intended to provide a general summary of the completed project and a discussion of the final results.

Project Objectives and Tasks

The main objective of the project was to demonstrate the use of the DeltaEM Gradiometer geophysical survey method to detect the presence of underground mine voids below the ground surface at several locations at Consolidation Coal Company's (Consol) Emery mine, MSHA Mine I.D. No. 42-00079.

The tasks completed under this contract included:

- Preliminary site data collection;
- DeltaEM Gradiometer assembly;
- Site demonstration plans;
- Geophysical data collection;
- Preparation of the draft final report;
- Confirmation drilling;
- Report review by independent experts;
- Preparation of the final report.

DeltaEM Gradiometer Theory and Description

Electromagnetic geophysical surveying was developed to locate subsurface areas of significantly contrasting electrical conductivity. To obtain measurements of subsurface conductivity, a surface-based transmitter sends electromagnetic wave energy into the ground. Typically, the transmitter consists of a power source and a loop of insulated electrical cable that is laid on the ground. Secondary electromagnetic waves are created when the induced electrical current flows through underground electrical conductors, either man-made or natural. By measuring these secondary waves at the ground surface, subsurface characteristics can be inferred.

The DeltaEM Gradiometer is a portable unit that hangs from the operator's shoulders using a harness. An accompanying battery pack typically hangs from the operator's shoulder or is worn on a belt around the waist. The gradiometer is comprised of dual independent antennas that record the amplitude (also referred to as magnitude or Mag) and phase of the secondary electromagnetic wave. The difference between the measurements from the two antennas is plotted as the gradient. The primary wave (the wave that travels directly from the transmitter to the receiver) is rejected while the gradient (magnitude difference between the two antennas) of the secondary EM wave is measured. Stolar indicates that the "primary advantages of gradient measurement are: 1) the ability to detect the significant rate of change in gradient fields that do not exist in total field measurements, and 2) the ability to reject interfering, unwanted signals that would be summed in total field measurements."

An integrated global positioning system (GPS) is used to track the location of the EM Gradiometer during data collection. Real time data, including GPS information, is displayed and recorded on a personal digital assistant (PDA).

Site Description

The Emery mine is located in Castle Valley on the western side of Emery County, approximately 140 miles south of Salt Lake City, Utah. The terrain above the mine workings is generally flat with some relatively small hills. The ground surface is generally barren sandy and silty soil or bedrock with some areas sustaining grass, weeds, and brush. The Christiansen wash is oriented in the north-south direction and is located on the eastern side of the mine workings. The wash is cut into sandstone and is approximately 30 feet deep.

Coal mining at this area began in 1937 in what was then called the Browning mine. Based on the published history of coal mining in Emery County, Utah, it is believed that the Browning mine shut down shortly after World War II ended. Consol re-opened the mine in 1975 and then ceased operations in 1991. Consol re-opened the Emery mine in 2002. According to representatives of Consol, the older areas of the mine are no longer active and have been sealed off from the newer sections of the mine.

Consol currently uses room-and-pillar underground mining techniques to remove the coal from LI-5 seam. The pillar dimensions vary at the mine and the entries are typically 20 feet wide. Partial pillar extraction (second mining) was done in several areas in the mine. The LI-5 seam dips towards the northwest and the depth of overburden over the mine ranges from approximately 50 to more than 500 feet.

The boring logs provided in the final report indicate that in the area drilled, the upper 12 to 14 feet consists of silty fine sand. Below the sand is an approximately 55 feet thick layer of bluish gray mudstone (stone comprised of clay and silt). Below the mudstone is an approximately 70-foot thick layer of medium- to coarse-grained sandstone. The LI-5 coal seam lies below this layer of sandstone and is approximately 26 feet thick. Sandstone was also encountered in the strata below the LI-5 coal seam.

Field Demonstration

Stolar collected subsurface geophysical data at seven different locations above the mine workings during four trips to the Emery mine. The data collection locations were selected by Stolar and were identified as Area 1 through Area 6, and the Old Workings Area. Areas 1 through 6 were over active mine workings and the Old Workings Area was over an inactive section of the mine. The data was collected during March 4 - 5, 2005, June 1 - 2, 2005, August 23 - 25, 2005, and February 28 – March 2, 2006. MSHA representatives (Jim Pfeifer, COTR, and Ron Gehrke, District 9) were on site to observe the data collection except during the trip that occurred in June 2005. It should be noted that data was not collected from all areas during every visit. The overburden thickness ranged from approximately 40 feet at Area 1 to approximately 400 feet at Area 6. The overburden thickness at the Old Workings Area was approximately 145 feet.

The data was collected by walking (with the EM Gradiometer) along a relatively straight line between two previously determined locations in each survey area. The locations were marked by stakes and were determined so that the EM Gradiometer would pass nearly perpendicular to the mine entries and the ribs (sides) of the coal pillars. Typically, multiple passes were made over the same traverse line at each operating frequency. The data was collected (approximately ten readings per second) at 2, 20, 80, and 200 kilohertz (kHz) operating frequencies and was automatically recorded by a PDA. The plotted data (signal magnitude, signal phase, and receiver synchronization) could be observed on the screen of the PDA during and after each survey. The majority of the traverse lines selected by Stolar to be included in the final report were run at 2 kHz and 20 kHz.

Several modifications to the EM Gradiometer were made throughout the project. Between the March and August 2005, demonstrations, the EM Gradiometer design was enhanced by improving ergonomics and incorporating a PDA to store the data. Between the August 2005 and March 2006, demonstrations, the EM Gradiometer was upgraded so that it could be calibrated in the field prior to conducting surveys.

Data Interpretation

The final report indicates that when the EM Gradiometer passes over a mine void, the signal magnitude data plot will look like the letter M. More specifically, "the M-Curve is a double-peak response centered on a null-point. At this location, both of the gradiometer's receiver antennas are detecting equal signal levels, therefore, their gradiometric (differential) response is to equally cancel the signals out, or create a null value."

Although many null points (with various M-curves) can be identified on the data plots presented in the final report, not all of them correspond to subsurface mine voids. The criteria for selecting null points that correspond to mine voids were experimentally determined by Stolar. The null points from the field data that met the experimentally-determined criteria were manually selected by Stolar. The selection of null points that correspond to mine voids was not done on site and was likely done at Stolar's office.

Confirmation Drilling

Based on the results of the EM Gradiometer demonstrations, Stolar selected two locations at the Old Workings Area to drill vertical bore holes from the ground surface in an attempt to intersect the mine voids. The bore holes were drilled during four separate occasions between November 16, 2006, and January 7, 2007. Both bore holes encountered solid coal rather than mine voids.

Discussion of Results

The final report indicates that 190 null points were identified after analyzing the data from 43 traverse lines and that 75% of the manually-selected null points correspond to air/coal boundaries, 18% correspond to coal pillars, and 7% correspond to no obvious subsurface features. The selected null points were associated with a subsurface feature (on the mine map) if they were within the accuracy of the GPS (± 10 feet).

It is indicated in the report that there was a low probability of success for the confirmation bore holes to intersect the mine voids due to the errors associated with the GPS used to track the EM Gradiometer (accurate to ± 10 feet) and the fact that the bore holes may have deviated from their intended vertical path by some relatively small angle. The report also indicates that the location of the void-related null point "may have some lateral error associated with the actual radiated magnetic field created by the void space." Stolar's final report also indicates that the deviation angle of the drill rods can be as much as 5 degrees off of vertical.

We believe that a few of the manually-selected null points may have been incorrectly associated with subsurface mining-related features because the accuracy of the GPS (± 10 feet) was applied to every null point. It is unlikely that the horizontal position of every null point, as determined by the GPS, was always 10 feet away from their actual location. Therefore, the reported percentage of null points associated with the ribs of the pillars and entries is likely to be lower than the 75% reported by Stolar.

A cursory review of the figures in the final report that show the traverse lines over the mine workings, shows that there are a number of ribs (approximately 40%) that the EM Gradiometer crossed over with no associated null points.

Conclusions

The results of Stolar's field testing indicate that the DeltaEM Gradiometer, as demonstrated at the Consolidation Coal Company's Emery mine, was marginally successful in identifying the subsurface mine voids. Approximately 40% of the ribs crossed by the EM Gradiometer were not identified with a null point and approximately 7% of the null points were associated with no obvious subsurface features. The two confirmation boreholes failed to intersect any mine voids.

It should be noted that, in the authors' opinion, these results were not completely successful. However, they were not uncommon when compared to the results of other surface-based geophysical exploration methods such as electrical resistivity, seismic, and time-domain electromagnetics.

Please contact us at 412-386-6810/4470 if there are any questions regarding this memorandum.

cc: D. Chirdon - TS