2D MASW ABANDONED MINE DETECTION

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ABSTRACT

Building settlement and the development of sinkholes at a facility in northern Minnesota prompted a multi-phase investigation. The facility was built over mine dump material, underlain by glacial drift and a Cretaceous iron formation. Review of historic mine maps confirmed that underground mines were located beneath the center and were a likely cause of the subsidence. Work conducted by others included monitoring the building settlement and cracking, and conducting a limited microgravity survey. Additional subsurface information was needed before a remedial design plan could be developed.

We conducted geophysical surveys in September 2004 in advance of drilling investigations. The results of our Multi-channel Analysis of Surface Waves (MASW) surveys indicated mine workings at depths of 100 to 150 feet and possible zones of subsidence in the overburden materials. We also performed Ground-Penetrating Radar (GPR) surveys to look for possible voids beneath the basement floor of a museum building. Our client used the geophysical results and other data to select locations for drilling into the abandoned mine.

INTRODUCTION

The Ironworld Discovery Center (IDC) is located on the south side of Chisholm, Minnesota in the middle of the Mesabi Iron Range (Figure 1). The region is well known for its iron mines, with mining in the Chisholm area dating back to discovery of the Mesabi Iron Range in 1892 (Iron Range Research Center, 2005). While open-pit mining is now the norm, some early iron mines were excavated underground.

Sinkhole development and ground subsidence has occurred on the site over the years and appeared to be related to possible abandoned underground mines (E. Billington, R. Palm, and A. Grosser, 2006). Previous investigations indicate the facility was constructed on top of about 40 feet of iron mine dump material (rock fragments in a matrix of clayey and silty sand) that is underlain by glacial drift (silts and clays) deposited on top of the Biwabik Iron Formation. A number of apparent sinkholes can be seen in the sloping surface of the mine dump material just south of the museum building and in other locations on the site.

Correlations between the IDC site and old mine maps indicated that underground portions of the Glen Mine underlie most of the IDC site (E. Billington, R. Palm, and A. Grosser, 2006). Cross-sections of the Glen mine show the workings in the museum area are typically at depths of about 70 to 90 feet below ground surface and are about 40 feet thick. The mine workings are thin and slope upwards to the north. The maps show a number of shafts and raises in the vicinity of the site. The mine was worked using the top-slicing method, where the ore was mined in horizontal floors beginning at the top of the deposit. The ore was extracted from small sections and the roof of each section was forced to cave onto a wooden floor, before mining an adjacent section. The successive mining and caving results in a mass of twisted timber that formed an artificial roof between the level being mined and the overburden.

GEOPHYSICAL INVESTIGATIONS

The 2004 field investigations included 2-dimensional Multi-channel Analysis of Surface Waves (MASW) surveys to identify low velocity zones and Ground-Penetrating Radar (GPR) surveys to look for anomalies beneath a building slab. The GPR results are not included in this paper for the sake of brevity.

MASW Survey

To evaluate subsurface conditions, we conducted Multi-Channel Analysis of Surface Waves (MASW) surveys in the vicinity of the museum building most affected by the ground subsidence. While the MASW method is not particularly effective for voids, the technique has been used often to locate loose zones in the subsurface (Xia et al, 2002, e.g.). We expected that the mine level would appear as a low velocity zone since the top-slicing mining method used for this mine typically results in a loose zone of collapsed overburden and timbers instead of an open void. Also, we hoped to identify low velocity zones that could be associated with active sinkhole development.

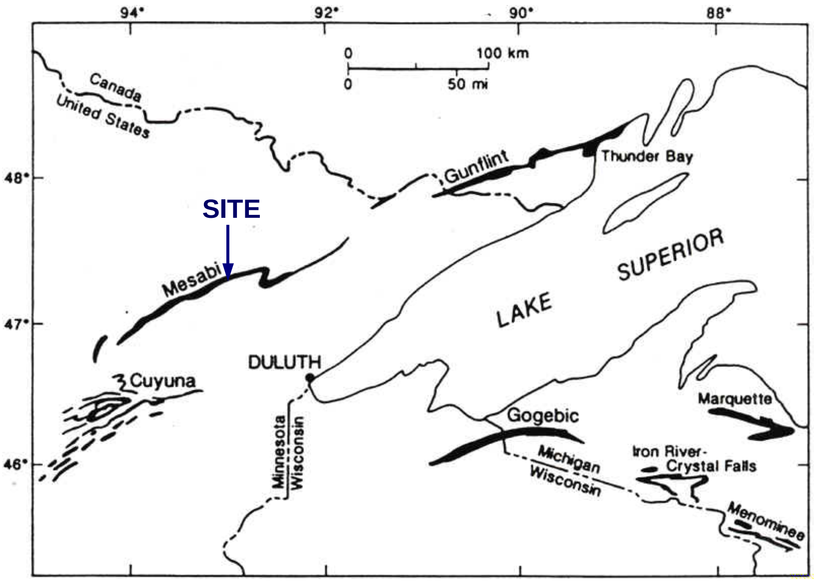

Figure 1: Map of iron range formations in the upper Midwest and the location of the investigation site on the Mesabi Iron Range.

The MASW data were collected along three parallel survey lines located on various surface conditions, including concrete, asphalt, and grass, and mine dump material (Figure 2). The surface wave energy was generated using a Digipulse Accelerated Weight Drop (AWD) source mounted on the back of a pickup truck. The surface wave motion was recorded using a land streamer, consisting of 42 to 48 4.5 Hz geophones mounted on the streamer at 5-foot intervals. The 235-foot long geophone array was towed by the pickup truck at a set distance behind the AWD energy source. The AWD source was offset from the first geophone by 35 or 40 feet; this distance was determined through initial testing in order to maximize the fundamental mode surface wave energy.

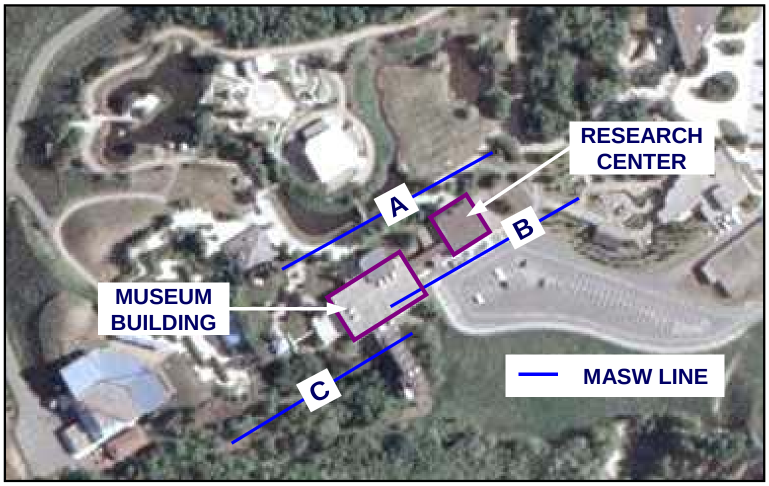

Figure 2: Aerial photograph of site showing the Museum Building, the Research Center, and the approximate location of the MASW survey lines.

The geophone array was connected to a pair of RAS-24 digital seismographs, in turn controlled by a laptop running a data acquisition program. The computer program allowed for quality control of the data recorded for each weight drop prior to stacking the data. The seismic data were collected using a sample interval of one millisecond (ms) and a record length of 1024 ms (1.024 seconds). No filters were applied during data acquisition. Data were acquired on Line B and Line C using 42 channels and on Line A using 48 channels.

Line A was located along the sidewalk in front of the Museum and Research Center buildings (Figure 2). Line B began in the basement of the Museum building and extended out of the basement and along the north edge of the parking lot behind the Research Center. Line C was located along a trail on a topographic bench that was downslope from the Museum building. Data were first acquired by rolling through the starting array location using 25 geophones at a time and operating the source 35 or 40 feet from the nearest geophone used for each shot. When the end of the array was reached using 25 geophones, successive shots used the entire array of 42 or 48 channels, towing it northeast 5 feet for each shot. Lines A and B were located on concrete, asphalt, or mowed grassed and had relatively high data quality. The data collected on Line C suffered from poorer coupling with the ground surface due to loose, shaley rock fragments and weeds on the ground surface. Ambient noise was not a problem, as the site had very little activity at the time of the survey.

Data Processing

The seismic shot records were processed using Surfseis, a surface wave analysis program produced by the Kansas Geological Survey. The processing steps included pre-processing to recognize the surface wave energy (Figure 3), conversion to the frequency domain to make frequency-phase velocity plots (normal algorithm), and selecting dispersion curves (phase velocity variation with frequency). The dispersion curve for each shot record was plotted geographically in the center of the array location used for each source location, thus producing dispersion curves every 5 feet along each survey line. For the inversion modeling step, the set of dispersion curves for each line were processed as a group to produce a data set for contouring and presentation. The half-space depths and the number of layers were varied to optimize the inversion. Otherwise, default inversion parameters were used. The final result for each shot record was a model of shear wave velocity versus depth with a calculated dispersion curve that best matched the observed dispersion curve in a least-squares sense.

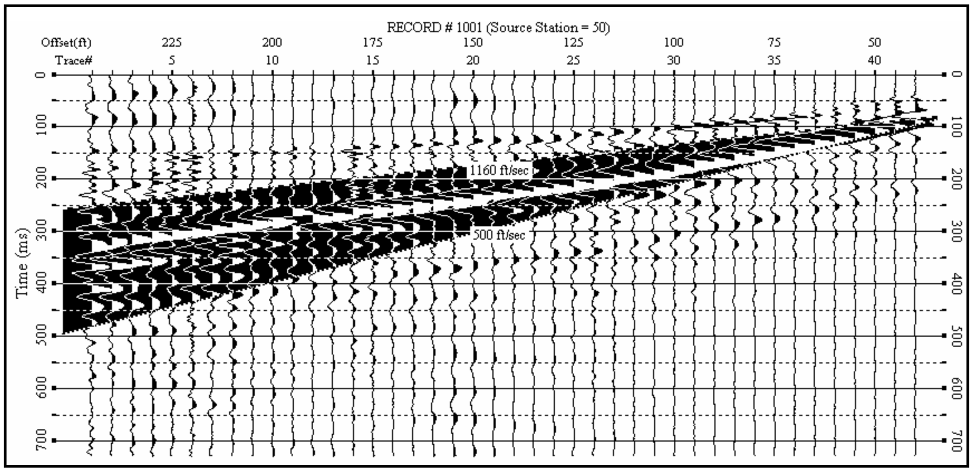

Figure 3: Example seismic data from one 42-channel array location with surface wave energy highlighted and apparent phase velocities shown.

Data acquired using the first 25 channels were processed separately to produce relatively shallow models of the upper 80 feet for each line. Using the 25 channels nearest to the energy source maintained more of the higher frequency surface wave energy, allowing higher vertical and lateral resolution in the near surface (Figure 4). Lateral resolution was also improved for the shallow sections since the velocities were averaged over the shorter array length of 120 feet, compared to the longer array lengths of 205 feet (42-channels) and 235 feet (48-channels) for the full array data. The full array data were processed to maximize lower frequency energy, producing deeper models of about 180 feet on Line A and 150 feet on Lines B and C.

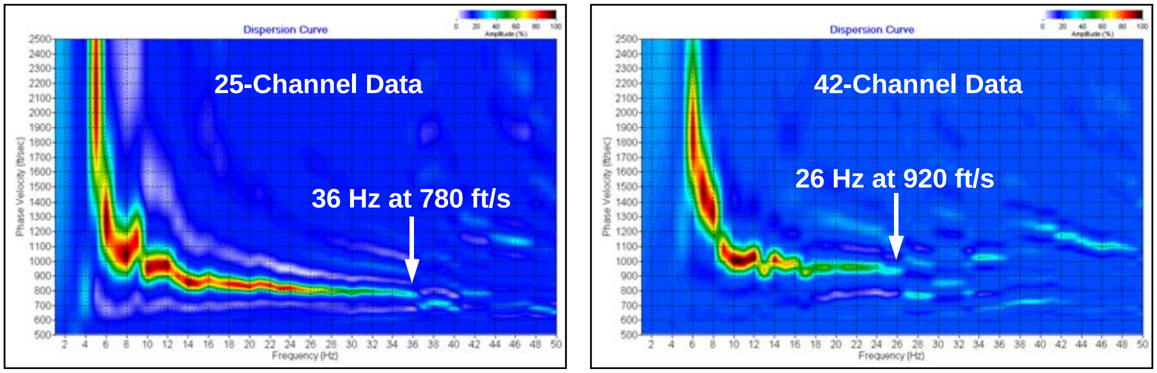

Figure 4: Dispersion curves from the same record shown in Figure 3 using first 25 channels (on left) and all 42 channels (on right). The 25-channel data show higher frequency content with coherent data to 36 Hz. The full 42-channel data have lower frequency content but better coherence in the lower frequency range.

MASW Velocity Models

The shallow 2D shear wave velocity models show what appears to be the layer of mine dump/fill materials overlying the glacial drift soils (e.g., Line A, Figure 5). The upper layer of possible mine dump/fill material is characterized by an average shear wave velocity of about 700 feet per second (ft/s) while the velocity of the underlying layer of possible glacial drift is typically between 1000 to 1600 ft/s. Several low velocity anomalies below elevation 1540 may represent zones of softer (less stiff) soils that could be related to sinkhole formation.

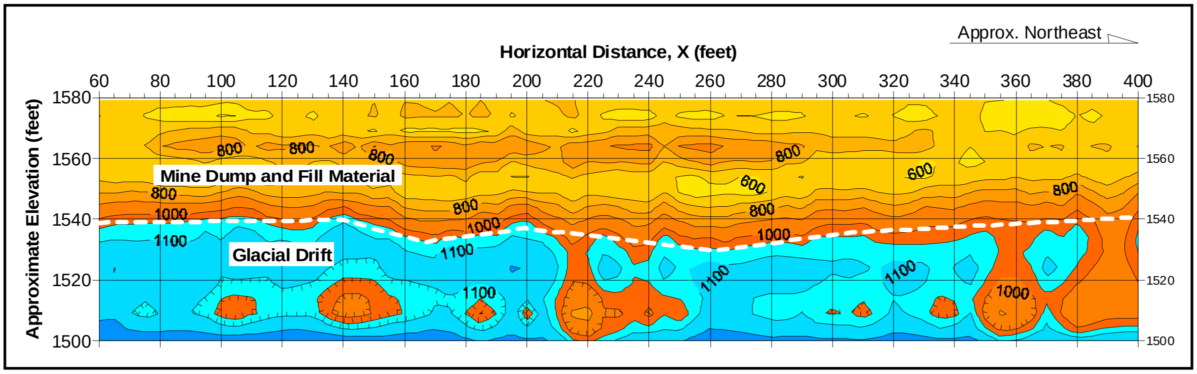

Figure 5: Example shallow shear wave velocity model for Line A. The shallow models were produced using 25-channel data for higher resolution. The model shows low velocity zones (orange) in the glacial drift (blue) that overlies the mined iron formation. Velocity contours are in feet/second.

The deeper 2D shear wave velocity models also show a low velocity upper layer, although the apparent transition between the mine dump/fill material and the underlying glacial till is less distinct than on the shallow models, likely due to the loss of higher frequencies for the full array data. On the deep models, this upper low velocity zone is generally followed by an increase in velocities with depth.

The deep model for Line A shows a general increase in velocity beginning at about elevation 1520 feet followed by a very distinct low velocity zone from about elevations 1480 feet to 1440 feet (Figure 6). are plotted on the deep 2D models for reference. A close correlation is seen between the low velocity zone and the top and bottom of the mine workings obtained from historic mine records. Of particular interest is the low velocity zone above the apparent top of the mine workings from X = 160 to 260 feet and between elevations 1480 and 1500. This zone may represent additional mine roof weakening or collapsing of the overburden beyond what was originally collapsed during mining. An apparent low velocity zone also extends upwards from this area to elevation 1520 from about X = 220 to 250 feet and corresponds to a low velocity zone noted on the shallow section. This low velocity zone may represent further weakening of the soil due to the mine roof collapse.

The high velocity zones from elevation 1520 to 1480 on Line A may represent an increase in velocities above the mine workings due to increased stress of the mine roof and overburden materials (Figure 6). These high velocity zones also correlate with the location of the adjacent buildings and their basements. Although not likely, the presence of the building basements could have affected the surface wave data and caused or partially caused these high velocities anomalies.

The deep velocity model for Line B also showed some correlation with the top and bottom of the mine workings on the southwest side of the model. A low velocity anomaly present above the approximate mine depth may represent additional mine roof weakening or collapsing of the overburden beyond what was originally collapsed during mining. The model for Line C showed relatively consistent velocities in the zone corresponding to the mine workings. There were no significant low velocity zones associated with the mine roof on Line C.

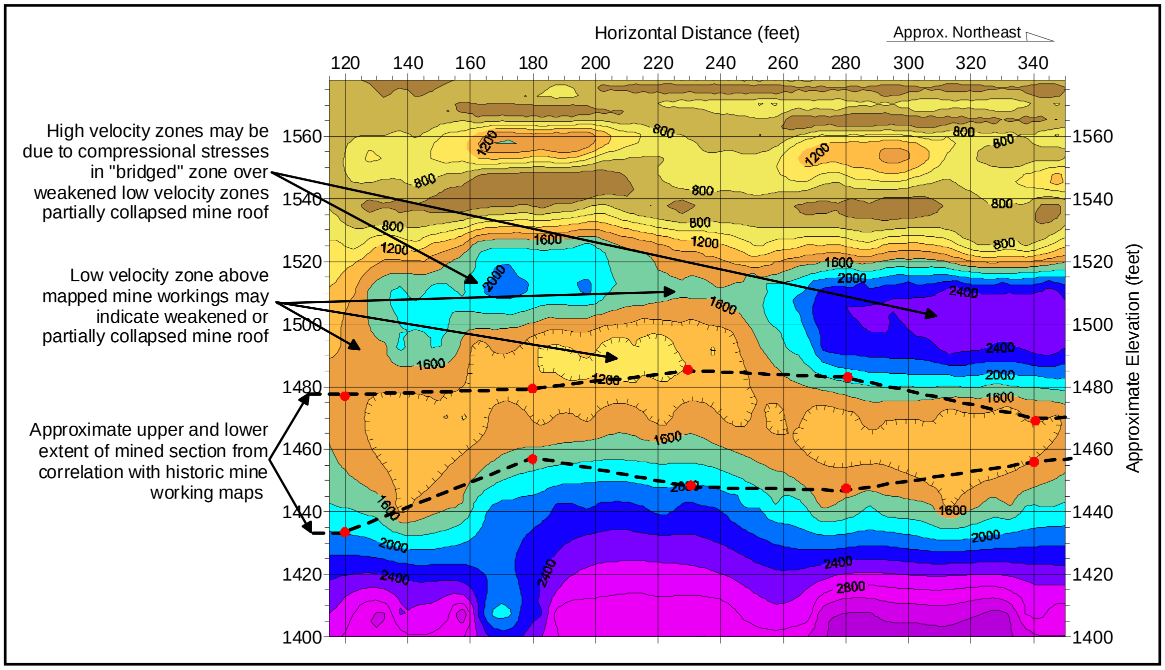

Figure 6: Example deep shear wave velocity model for Line A. The deep models were produced using the full array data (42 or 48-channels) to preserve lower frequency (longer wavelength) surface waves. The color scale differs from that shown in Figure 5 (shallow model). Velocity contours are in feet/second.

Drilling and Sampling Investigation

Our client conducted a drilling investigation to verify results of the MASW surveys at two representative locations on MASW Line A and Line C (E. Billington, R. Palm, and A. Grosser, 2006). Because of the varied conditions and possible difficult drilling scenarios (possible caved workings, timbers, boulders, sinkholes, and intact bedrock), a rock boring rig was used instead of a traditional soil boring rig. The boring rig was a trailer-mounted, Hagby core drill typically used for mineral exploration.

Boring B-1 was located north of the Interpretative Center at Station 180 feet on MASW Line A. A shear wave velocity inversion (high velocity over low velocity) was noted in the glacial till zone, indicating possible collapse of the till into the mine. In addition, geophysical results and historic mine working sections indicated a rise in the floor of the mine at this location. The boring extended through the mine dump material, native glacial till, and collapsed mine workings, and bedrock.

Boring B-2 was completed near the southwest corner of the Interpretative Center on MASW Line C. This boring also extended through the mine dump, glacial till overburden soils, and bedrock. Evidence of mining was apparent at a depth of 122.5 feet (elevation 1422.6) where timbers were encountered.

Since the drilling method could not provide complete or undisturbed samples of the subsurface materials, select portions of the borings were visually inspected using a one-inch diameter SEE Snake camera system The video inspection was performed in B-1 at the following depths where voids or mine workings were present: 101 to 101.5 feet, 102 to 107 feet, 112 to 116 feet, and 117 to 126 feet. The video images indicated that the mines workings contained timbers with numerous small voids partially filled with soil. The voids in B-1 range from about two inches to 1.5 feet in size.

Correlation of Drilling Results with MASW Models

The logs of the geotechnical borings were plotted on the deep MASW shear wave velocity models (Figure 7). The mine dump, glacial till, mine workings and mine base/bedrock layers generally correlate with velocity changes in the shear wave data. The shear wave velocities of the mine dump materials generally range from 300 to 1500 feet per second (ft/s). Shear wave velocities in the glacial till layer range from 900 to 2500 ft/s. The low velocity inversion layer of Lines A and B ranges from 900 to 1500 ft/s while the overlying high velocity layer in the till of Line A ranges from 1500 to 2500 ft/s. The shear wave velocity of the mine workings ranges from 1300 to 2000 ft/s. Bedrock at the base of the mine has associated shear wave velocities of 2000 to 3300 ft/s.

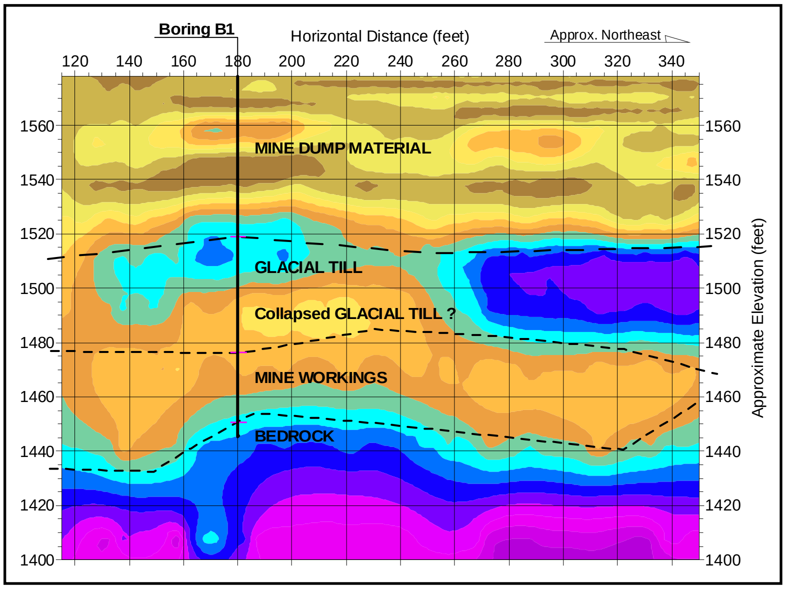

Figure 7: Results of Boring B-1 superimposed on the deep shear wave velocity model for Line A. The combined interpretation differs slightly from that shown on Figures 5 and 6. (See Figure 6 for velocity contour values.)

Anomalously high velocity zones in materials overlying voids noted in previous investigations using MASW have been attributed to stress concentration within the upper part of a roof bridging over a void (Burton et al, 2003). At this site, the high velocity overburden layer may coincide with higher compression stress due to the subsidence of underlying soils caused by roof failure in the underlying mine workings.

SUMMARY

The 2D MASW surveys we conducted at the Ironworld Discovery Center in 2004 were successful in identifying the presence of low velocity zones associated with the abandoned mine workings and and several low velocity anomalies that appear to represent mine roof collapse with potential future sinkhole development.

The drilling and sampling investigation confirmed our interpretation of the MASW velocity models and provided specific information on the vertical extent and condition of the old mine workings. The thickness of the mine workings varied from 4 feet at Boring B-2 to 21 feet at Boring B-1. Our investigations indicate that 1) the IDC facility was constructed on top of mine workings and 2) the mine workings have partially collapsed and roof collapses may be propagating upwards towards the ground surface. These findings support the postulated mechanism of mine subsidence as being responsible for sinkhole development and ground movement at the site.

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