Mapping abandoned mine workings using novel surface wave seismic analysis

Patrick Mah, P.Geo
DMT Geosciences Ltd, Calgary, AB, Canada

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ABSTRACT
Historical abandoned underground mine workings can pose a significant hazard to public safety and infrastructure due to the potential risk of collapse. Identification of the location of abandoned workings prior to their collapse becomes important for this reason.

The analysis of backscatter energy in seismic surface waves provides a novel method in which tunnel features may be identified and located. Other geophysical methods such as ground penetrating radar, electrical resistivity imaging, and seismic refraction have been used to map abandoned workings, and can provide valuable information in planning and reducing risk at a particular site. Depending on local geological setting and site conditions more than one method is often required to provide assurance.

A seismic survey was acquired on a previous project where the development of a sinkhole between two residential buildings prompted an investigation in order to locate the exact location of the potential mine shaft. The seismic survey was interpreted using both seismic refraction and surface wave backscatter analysis. Prior to the investigation, the sinkhole was filled as a precautionary measure to prevent people or animals from entering the sinkhole.

Anomalies in the raw seismic data due to changes in the near surface waves provided indications of where the mine shaft was located. The occurrence of the anomalies on multiple raw seismic records provided confidence in the interpretation of the location of the anomaly. The use of signal filters on the raw seismic data provided qualitative information on depth of the mine shaft.

Observation of the raw seismic data and analysis of surface wave backscatter provided an alternative method that may be used to support other geophysical methods and add confidence in mapping potential abandoned mine workings.

RÉSUMÉ
Les mines souterraines historiques abandonnées peuvent représenter un danger important pour la sécurité publique et les infrastructures en raison du risque potentiel d'effondrement. Pour cette raison, il est important d'identifier l'emplacement des chantiers abandonnés avant leur effondrement.

L'analyse de l'énergie rétrodiffusée dans les ondes sismiques de surface offre une nouvelle méthode permettant d'identifier et de localiser les caractéristiques des tunnels. D'autres méthodes géophysiques, comme le radar à pénétration de sol, l'imagerie de résistivité électrique et la sismique réfraction, ont été utilisées pour cartographier les chantiers abandonnés et peuvent fournir des informations précieuses pour la planification et la réduction des risques sur un site particulier. Selon le contexte géologique local et les conditions du site, plus d'une méthode est souvent nécessaire pour fournir une assurance.

Une étude sismique a été réalisée dans le cadre d'un projet antérieur où le développement d'un gouffre entre deux immeubles résidentiels a entraîné une enquête afin de localiser l'emplacement exact du puits de mine potentiel. Le levé sismique a été interprété en utilisant à la fois la réfraction sismique et l'analyse de la rétrodiffusion des ondes de surface. Avant l'enquête, la doline a été comblée par mesure de précaution pour éviter que des personnes ou des animaux n'y pénètrent.

Des anomalies dans les données sismiques brutes dues à des changements dans les ondes proches de la surface ont fourni des indications sur l'emplacement du puits de mine. L'apparition de ces anomalies sur plusieurs enregistrements sismiques bruts a permis de conforter l'interprétation de l'emplacement de l'anomalie. L'utilisation de filtres de signaux sur les données sismiques brutes a fourni des informations qualitatives sur la profondeur du puits de mine.

L'observation des données sismiques brutes et l'analyse de la rétrodiffusion des ondes de surface ont fourni une méthode alternative qui peut être utilisée pour soutenir d'autres méthodes géophysiques et ajouter de la confiance dans la cartographie d'éventuels travaux miniers abandonnés.

1 INTRODUCTION

In 2014, a geophysical survey to investigate the formation of a sinkhole caused by an abandoned mine air shaft in Three Sisters Mountain Village in Canmore, AB was conducted. The sinkhole had originally appeared in 2010 along a pathway adjacent to Dyrgas Gate and was initially remediated by infilling the sinkhole with a bag of large rocks and stones; however, the location of the airshaft was never determined. The subsequent investigation in 2014 was intended to locate the airshaft and included seismic refraction and ground penetrating radar (GPR).

The seismic and GPR surveys were successful in identifying several targets of interest to be further investigated using more invasive methods. Four boreholes were drilled on the basis of the geophysical data acquired and historical information. One borehole was successful in targeting the open airshaft and resulted in the subsequent remediation of the airshaft.

In 2021, the seismic dataset was revisited in light of a novel seismic investigative method previously used in the exploration of historical mine workings in Germany to determine if it may be useful in targeting the abandoned airshaft.

2 METHODOLOGY

The analysis of seismic waves is done by imparting an energy source (dropping a weight or explosive) at the near surface and measuring the arrival time of the propagated energy through subsurface layers using sensors (geophones). Figure 1 presents how seismic energy propagates through the surface.

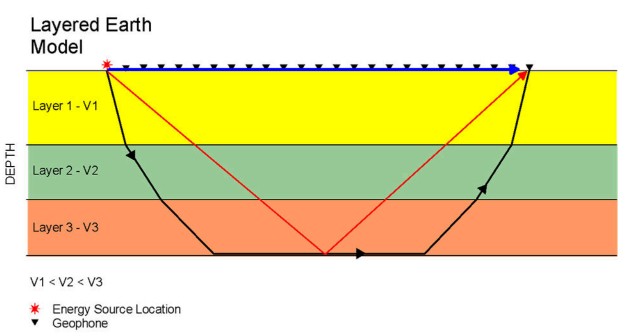

Figure 1: Layered earth model presenting how seismic waves may propagate in the subsurface. Black line indicates seismic refraction, red line indicates the path of seismic reflection, and blue line indicates the path of the surface wave

A seismic record is a compilation of the recorded energy at each geophone (Figure 2). The reflected, refracted, and surface waves are characterized by their arrival time at the geophone locations.

Surface wave backscatter analysis is a method to map changes in the subsurface by observing changes in the surface wavelet characteristics in the raw seismic records. Changes in phase characteristics (ie. polarity changes, phase shifting, and phase splitting) of the surface wave suggest a variation in density or velocity has occurred along the seismic profile. These variations can be related to faulting, weak zones, abrupt elevation changes along the seismic profile, and voids (Orlowsky et al. 1997). The backscatter anomaly occurs when a surface wave with the same velocity is observed in the opposite direction of the surface wave in the seismic records (Figure 3). The intersection of this point denotes the potential location of an anomaly in the subsurface.

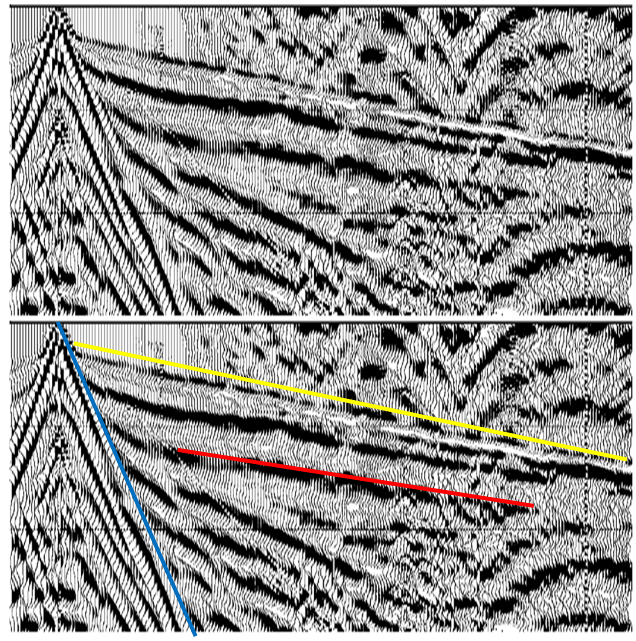

Figure 2: A raw seismic record presenting the reflected (red), refracted (yellow), and surface waves (blue).

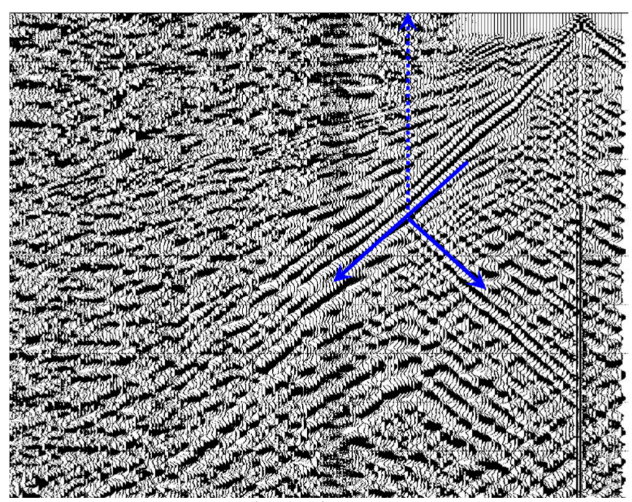

Figure 3: An exampleof a surface wave backscatter anomaly on a seismic record.

The presence of these anomalies on multiple records affirms the location of a potential void or abandoned mine feature. To estimate the approximate depth of occurrence of where the anomaly may originate, a series of filters based on spectral analysis of each seismic record can be applied to the seismic record. Anomalies associated with low frequency filters are interpreted as “deep” and anomalies associated with the high frequency filter are interpreted as “shallow”. This relationship between depth of occurrence is defined by the following formula:

$$\lambda = \frac{v}{f}$$

Where:
λ = wavelength in m (equated to approximate depth)
v = velocity of the surface wave in m/s
f = frequency of the surface wave in Hz

3 SEISMIC SURVEY RESULTS

The seismic survey consisted of three seismic lines; S1, S2, and S3 (Figure 4). From the previous survey, the data on S3 was used to target the borehole that hit the airshaft, so for the purposes of this investigation the data from S3 was examined for backscatter analysis. The seismic survey parameters are presented in Table 1.

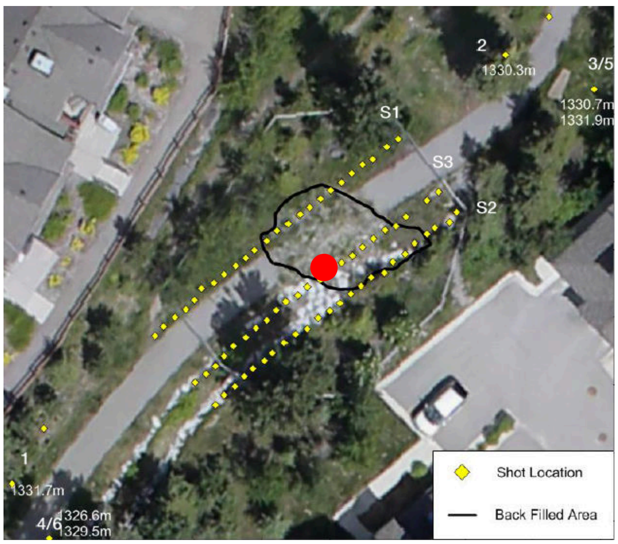

Figure 4: A map of the seismic lines conducted at site. The airshaft location is marked in red.

Table 1: Survey parameters

Parameter	Parameter Value
Acquisition System	Geometrics Geode
Number of Channels	24
Geophone Type	3C – 10Hz
Geophone Spacing	1.0m
Energy Source	Sledgehammer
Shot Spacing	1m
Sample Interval	0.125 ms

Observation of the raw records indicated the surface wave had a speed of 182m/s and spectral analysis revealed a frequency range between 5-125Hz. The raw records clearly indicate the presence of an anomaly at geophone 10 through 12 where the airshaft is located (Figure 5) as well.

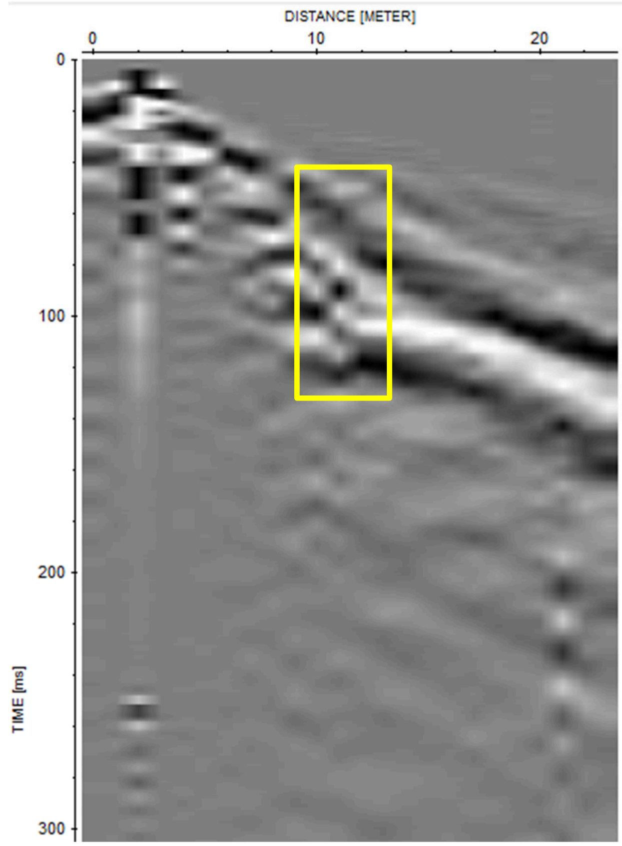

Figure 5: Raw seismic record showing an anomalous feature.

Three filters were applied to the dataset to determine depths at which the anomaly is present: 10-60Hz, 20-80Hz, and 30-100Hz (Figure 6). In all the filtered datasets, the anomalous event is present. On the basis of the range of the frequency filters used (100Hz-10Hz), the anomaly is present between the depth range of 1.82m and 18.2m.

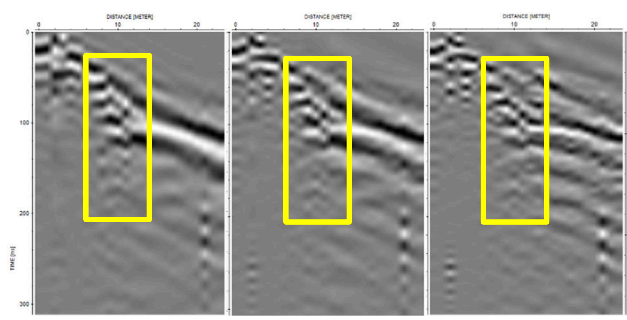

Figure 6: Seismic shot records with various filters applied. From left to right (10-60Hz, 20-80Hz, and 30-100Hz).

4 DISCUSSION

The results of the surface wave backscatter analysis suggest the method was effective at determining the location of the airshaft. It was able to determine the location of the airshaft by observing the raw seismic records without processing suggest that the surface wave backscatter method may be an effective tool in the field while collecting other seismic datasets.

The previously acquired geophysical dataset was successful at determining secondary effects of the presence of the airshaft. The GPR data was able to determine slumping features into the airshaft and allowed for the determination of a general area of impact (Figure 7a) and general direction of material flow into the location of the airshaft. The seismic refraction surface was able to identify low density/velocity areas which corresponded with areas of unconsolidated and infill material that may have slumped towards the airshaft (Figure 7b).

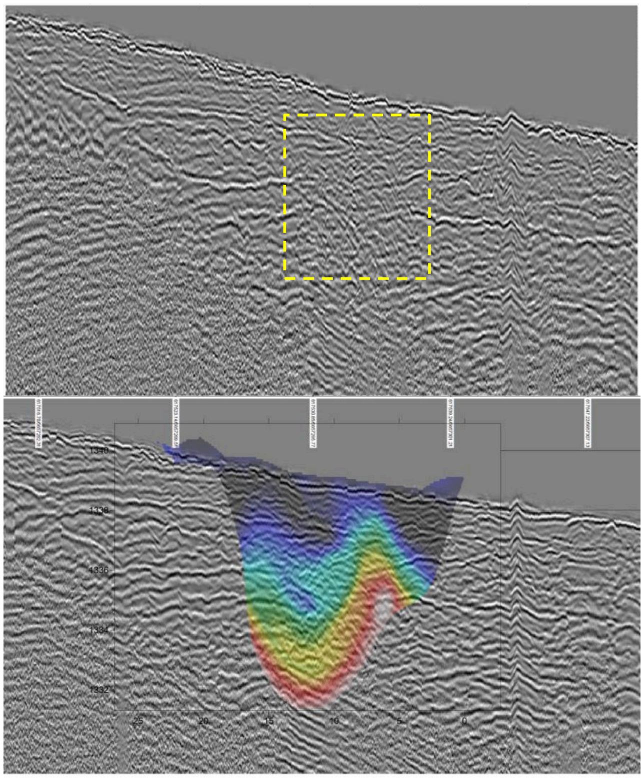

Figure 7: a) GPR cross-section over the airshaft. The yellow box outlines the subsidence features above the airshaft. b) Seismic refraction inversion over the same line. Black and blue hues indicate lower density/velocity zone.

In the results of the previous survey, the GPR and seismic refraction methods were effective in highlighting the influence of the void (Nolan et. al. 2011), but were unable to determine a precise location of the airshaft. Should the surface wave backscatter had been completed at the time of the survey, a more definitive interpretation of the airshaft location may have been completed, which may have resulted in fewer boreholes being drilled.

It is worth noting the surface wave backscatter analysis was only completed on the seismic line where the known airshaft was present. It would be expected that those sections show similar seismic records at the near surface (high frequency filter sections) due to presence of infill material and surround slumping, but not at deeper depths (low frequency filters).

The method may be useful and applicable for similar abandoned/historical mine settings. In particular, mapping horizontal mine shafts across lateral distances. It should be used in tandem with other geophysical methods and drilling to verify findings.

5 REFERENCES

Orlowsky, D. and Swoboda, U., 2016, Combination of CMP-refraction seismic with reflection seismic to investigate flat structures in urban areas, EAGE, Barcelona, Spain

Nolan, J., Sloan, S., Broadfoot, S., McKenna, J., and Metheny, O., 2011, Near Surface void identification using MASW and refraction tomography techniques, SEG, San Antonio, Texas, USA