3.5.2 Advantages for Mapping Subsurface Voids

The refraction method can detect voids in multiple ways. First, in certain geologic settings, voids will induce fracturing in the overlying rock. The fractures result in a localized decrease in seismic velocity, which results in a delay of the travel time of the first arrival of energy. Second, if the void is near the seismic interface, a localized decrease in seismic amplitudes will occur on the refraction record. This method is also more cost effective than other seismic methods.

3.5.3 Limitations for Mapping Subsurface Voids

Seismic refraction is more cost effective than other seismic methods; however, the information gained from seismic refraction is limited. In the case illustrated in figure 10, the seismic refraction method does not directly map the void. The amplitude attenuations and delayed travel times may also be caused by other geologic features. However, if the void were beneath a refractor then its existence may be more definitively identified. The fieldwork may also be time consuming.

3.5.4 Case Studies for Mapping Subsurface Voids

Seismic refraction was also used to locate subsurface voids at Jackson County, Ohio. The procedures and results for this survey are outlined in a report titled *Identifying Potential Collapse Features Under Highways* [(9)]. Both P-wave and S-wave data were collected parallel to the road over potential voids. A 36 channel seismograph with 30 Hz geophones was utilized in both surveys. Positioning was accomplished using a theodolite.

In phase I of the research project conducted at the Jackson County, Ohio site, drilling confirmed the presence of the Clarion coal seam at a depth of 1.5 m and 4.6 m (4.9 ft and 15.1 ft) below the subsurface. Variance in the depth is in part due to mining and possible collapse features. The overlying material consists of clay, limestone, and shale layers. P-wave refraction data were collected along two lines. The data were analyzed using two different software programs. The first program is SIP by Rimrock Geophysics. SIP models are generated from the first break times giving depth models for each profile. The depth profiles were in error due to the voids in the subsurface that decrease the velocity of the seismic wave. However, variations in the travel times of the first arrivals in seismic traces provided information about the location of the voids, since longer travel times were evident over the voids. The valleys in the data corresponded well with the locations of the voids mapped at a later date.

P-wave signal attenuation was also used to locate voids. The signal attenuations are possibly the result of wave scattering caused by the fracturing above a void or by the absorption of energy of the waves traveling from the bottom of the coal layer, through a mined area, and to the surface. Trace displays of the attenuation data were generated with Promax, a computer program for processing seismic data. P-wave attenuation was observed on both a north survey line and a south survey line. After ground truth was collected, it was shown that the areas of signal attenuation correlated with voids.

3.5.5 Application of Seismic Refraction at LBNM

Even though the seismic refraction method has successfully located voids, this method was not tested at LBNM. Since the geological setting consists of layers of basalts, it would be difficult to distinguish which fractures were caused by voids from fractures formed during lava's natural cooling process. Also, other seismic methods (e.g. high-resolution shear wave reflection) have proved more successful in mapping subsurface voids.

3.6 SEISMIC REFLECTION

3.6.1 General Background and Data Acquisition

When a seismic wave traveling into the subsurface encounters an interface providing an impedance contrast (change in velocity and/or density) part of the wave is reflected back to the ground surface, while the remainder propagates to greater depths where it may again encounter an impedance contrast repeating the phenomena described above. This phenomenon will continue to occur as the wave propagates deeper into the ground until the seismic energy dissipates. Producing the seismic waves and recording the reflected signals is the basis for the seismic reflection method. Both P-wave and S-wave data can be used in the seismic reflection method. Figure 11 is an illustration of the seismic reflection method.

3.6.2 Advantages for Mapping Subsurface Voids

In the case illustrated in figure 11, the seismic waves are directly influenced by the void and its presence may be inferred, although probably not uniquely, from the seismic records. S-waves are usually used to locate voids since they cannot propagate through liquids or gases. Also, seismic reflection can provide information about the size of the void and the depth beneath ground surface.

3.6.3 Limitations for Mapping Subsurface Voids

Voids are interpreted in shear wave reflection data mostly from diffraction patterns and amplitude attenuation, which are sometimes caused by other features. Field data recording of reflection seismic data is fairly labor intensive. Processing of the data requires a significant amount of knowledge and specialized training. Likewise, interpretation of the data requires knowledge and experience, since the anomalies from lava tubes may not be obvious. Figure 12 is a seismic reflection cross section showing several voids, visible mostly because of amplitude attenuation and reflector discontinuities.

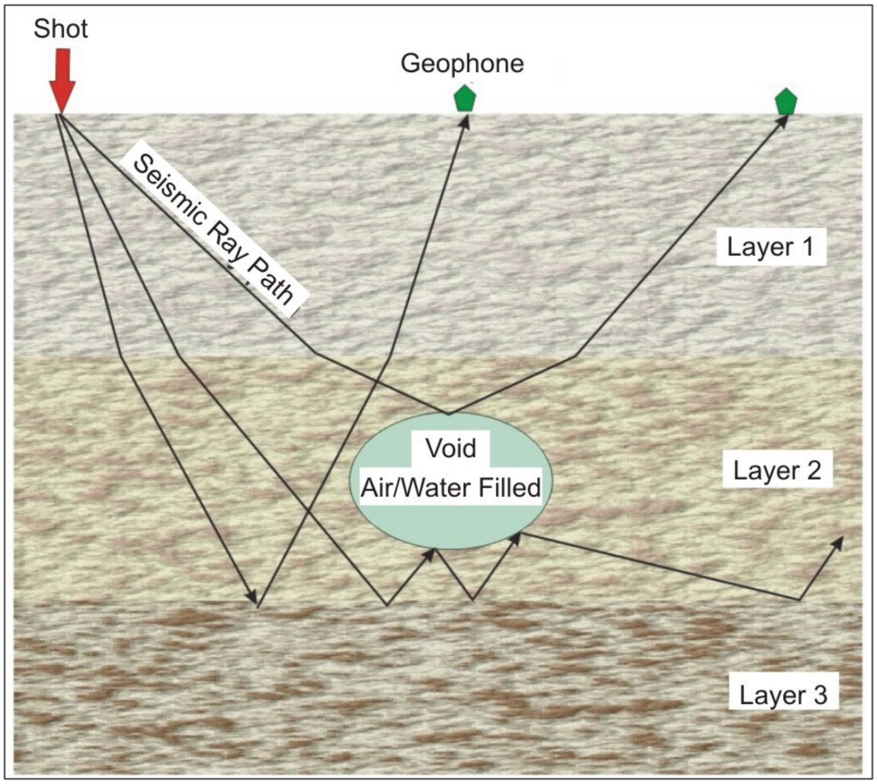

Figure 11. Drawing. Shear waves over an air/water-filled void. [7]

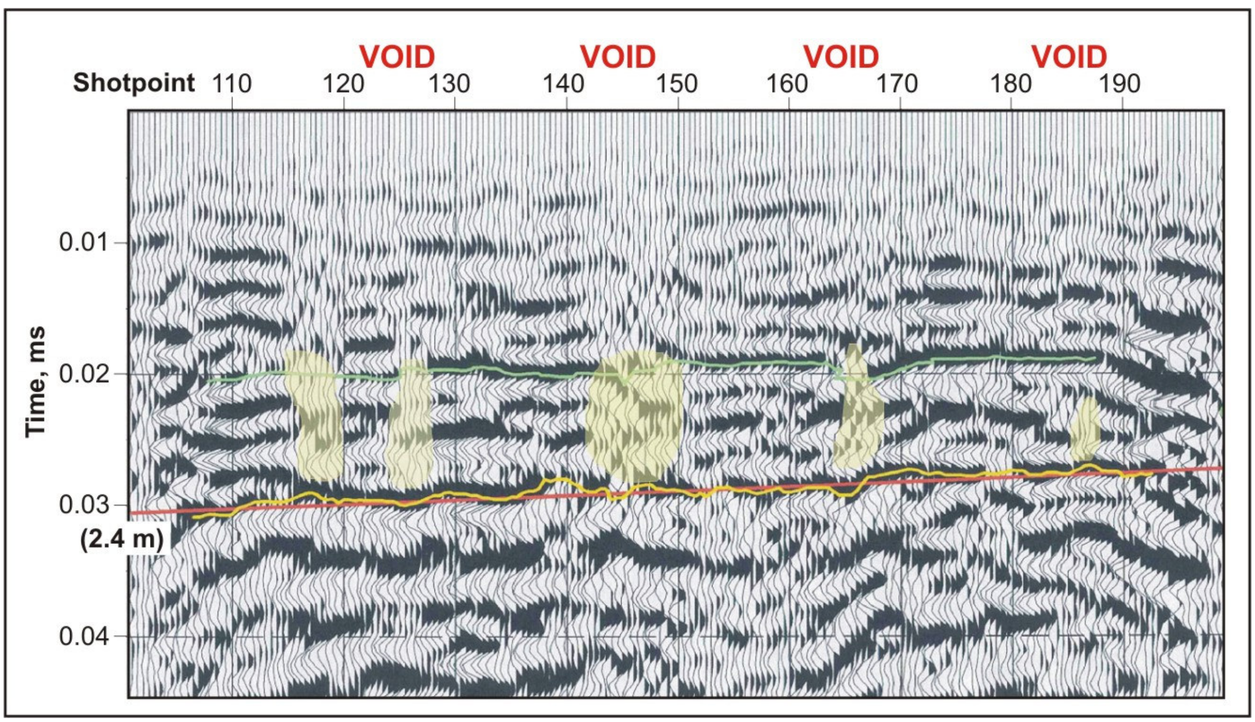

Figure 12. Cross Section. Voids interpreted from shear wave seismic data. [7]

3.6.4 Case Studies for Mapping Subsurface Voids

Shear wave reflection has proven successful in the past for locating voids. In a paper titled Double Feature at the Bijou: Shear Wave Reflection Seismic Acquired Within a Working Movie Theater [(12)], shear wave seismic data located an abandoned mine underneath a movie theater. A MicroVibrator was used as the seismic source because it is compact, portable, has controlled frequency output, and has improved ambient noise rejection. OYO 1x 40 Hz SMC-70 shear wave geophones were used. Three lines were laid out parallel to each other with a fourth line running perpendicular to the first three lines.

The geology in the area consists of 8.8 m (28.9 ft) of horizontally layered clays interlaced with layers of sands, overlaying weathered shale roughly 4.1 m (13.5 ft) thick. This sequence overlays a coal seam that is 1.7 m (5.6 ft) thick. The seismic data showed the coal seam dipping to the south and terminating against an erosional channel. A channel was also observed in each of the three parallel lines. Borings in the area confirmed the presence of a channel in the coal.

3.6.5 Application of the Seismic Reflection Method at LBNM

The high-resolution shear wave reflection method was tested at LBNM. The equipment included the MicroVibrator, a 96-channel OYO DAS-1 Seismograph, and a 96-channel Land Streamer configured with 40-Hz OYO SMC70 horizontal geophones. These particular geophones differ from classical geophones because they do not require insertion into the ground in order to record the signals. All 96 geophones are connected to a nylon strap that rests on the ground surface. The collection time with the Land Streamer is less when compared to other seismic setups. However, it is important to note that this method has a reduced signal to noise ratio due to the less effective ground coupling than with conventional geophones. The MicroVibrator and Land Streamer are shown in figure 13. HRSW was originally proposed to investigate areas where cut bank operations were to take place. In these areas, CFLHD was interested in detecting voids to depths between 10 and 20 m.

3.7 GRAVITY METHOD

3.7.1 General Background and Data Acquisition

The gravitational method measures small spatial differences in the gravitational field of the Earth. The gravitational field of an object is directly related to its mass; therefore, the more mass that an object has, the higher the gravitational pull from that object. Likewise, if a mass deficit occurs, as with a lava tube, then this will result in a decrease in the gravitation pull close to this feature. Figure 14 illustrates this concept over a void. Geophysical gravity surveys do not measure the absolute gravitational pull; rather, they measure the gravitational pull relative to that at some known location, usually some point close to the site of interest. Since the gravitational pull from an object decreases as the inverse square of its distance from the measuring point, the anomaly from a void, or lava tube, decreases rapidly with depth. In order to observe the expected small anomalies from voids, accurate gravity reading would be required. Since the pull of gravity decreases with distance from the center of the earth, the elevations

(± 1 inch) of the gravity stations would also be required. Microgravity is the name given to surveys requiring the most accurate data, such as would be needed to locate lava tubes.

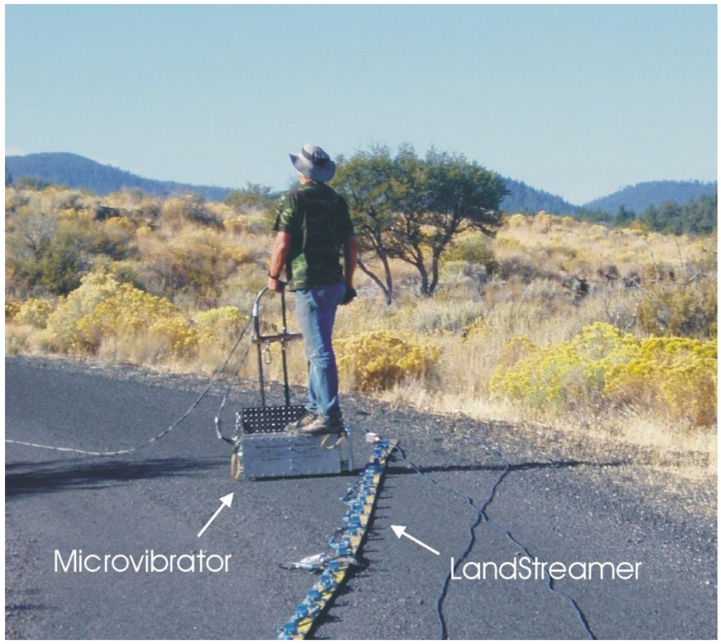

Figure 13. Photo. Data collection with the MicroVibrator and the Land Streamer at LBNM.

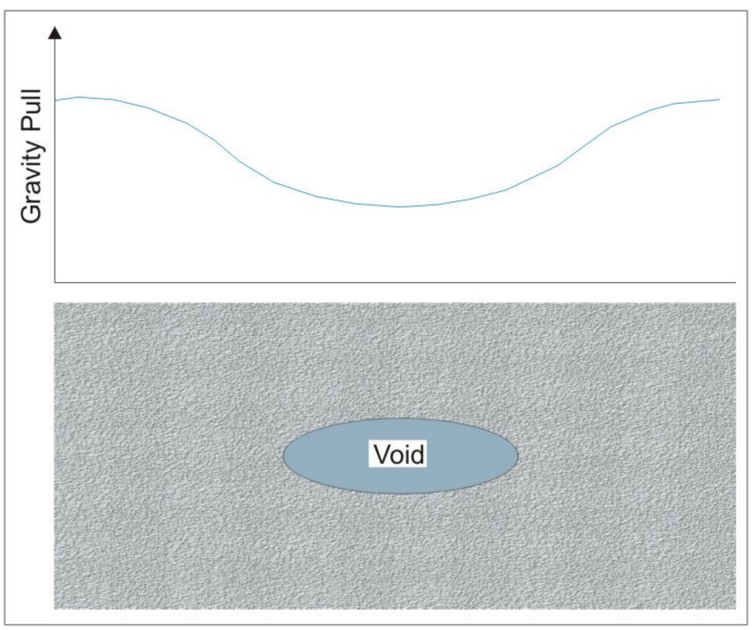

Figure 14. Drawing. Gravity field over a void. [(7)]

3.7.2 Advantages for Mapping Subsurface Voids

The gravity method may be useful in that well defined "negative" anomalies are likely to be caused by some kind of local mass deficit, which in this area will probably be a near surface lava tube. Gravity is a good method at locating larger tubes, which should provide a significant mass deficit, thus producing a significant anomaly.

3.7.3 Limitations for Mapping Subsurface Voids

Since precise gravitational readings are required, gravitational data collection is tedious and time consuming. Field crews must level the instrument and accurate elevation and spatial control is essential. Also, interpretation of gravity data, like magnetic data, can be ambiguous. A larger, deeper anomaly may have the same signature in the gravity data as a smaller shallower anomaly. In addition, cultural noise such as traffic and wind can negatively affect the data.

3.7.4 Case Studies for Mapping Subsurface Voids

In a paper titled *Microgravity and Magnetic Investigations for Dikes, Fissures, and Lava Tubes* [(15)], microgravity data were acquired over the Kings Bowl lava field and other lava flows on the Eastern Snake River Plain (ESRP), Idaho. This location was chosen because it is a Holocene field with exposed eruptive and non-eruptive fissures. After collection and processing, maps were created showing both the magnetic and microgravity data. The microgravity data showed many anomalies that did not relate to lava tubes, dikes, or fissures. "This indicates that basalt flows along the ESRP display rapid horizontal changes in density and magnetization, that are in part likely related to near-surface basalt porosity variations." It was determined that variances in the data collected over all but the larger fissures could be attributed to near surface density variations. In addition, gravitational data does not clearly show fissures. This is not surprising since fissures are not usually associated with significant mass changes. The microgravity data collected over Bear Trap Cave, however, showed a distinct anomaly, which decreased in amplitude as the cave depth increased.

3.7.5 Application of the Gravity Method at LBNM

Gravity data were not collected at LBNM. Because data acquisition with this method is slow, along with the need to record accurate elevations at each station, the method is quite expensive. Therefore, in view of the fact that several other methods were available, most of which were expected to be as effective as the gravity method, provide more rapid data acquisition and may be less costly, the gravity method was not used.