Seismic velocity anomalies due to stress concentrations above shallow voids

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Introduction
If we were to consider the myriad of features sought by geophysical methods, we might, with some astonishment, arrive at the conclusion that the tunnel and/or void is the most ubiquitous subsurface target. Consider, for example, the wide variety of reasons for seeking to locate tunnels. The reasons may be economic, as would be the case for an enterprising coal mining company which has bought new mine lands without knowing if, or to what extent, previous, undocumented mining has taken place on the property. The abandoned workings (tunnels) could tell them the amount of reserves remaining. Another reason is national security for nations having to deal with infiltration by unfriendly forces who gain access through tunnels. A third reason would be safety. Surface mining operations may be threatened by the possibility that surface machinery, such as a large dragline, digs into, or falls into, such a void left behind by previous operations. Underground mining faces the potential of mining into such an old working which has now become filled with water and methane gas. A fourth, and certainly not a final, consideration is the environmental concern of such subsurface voids. Subsurface voids nearly always have subsidence problems associated with them. It does not really matter whether the void is due to mining of solid rock materials, extraction of fluids (water, oil, and gas), or because of natural dissolution (karst); the net result is a loss of support for overlying strata and differential settlement at the ground surface. Consider, too, that old mines and other subsurface voids are also reservoirs of water which has typically leached toxic material from the host rock, and are thus long-term environmental hazards because some day they may leak or be breached and come into contact with the biosphere (acid mine drainage). Thus, although many millions of dollars and line-kilometres of data are not spent on the void/tunnel search annually, as compared with the search for petroleum, it is a target which is sought by many for a variety of reasons. It is one of the more important economic and environmental tasks to which the geophysicist can contribute.

Unfortunately, the driving force governing the extent and sophistication of applied geophysical surveys is purely one of economics (Dobecki and Romig 1985). Whereas the potential rewards from a successful geophysical survey in a petroleum prospect are very great, the successful application of geophysical methods to environmental problems does not stand to make money. The exploration phase of such programmes has quite a limited budget, and geophysical surveys command only a small portion of these. At best, geophysical methods are used to decrease the number of boreholes which will ultimately be drilled. This is the standard void exploration programme—drill many boreholes at close spacings. It is often difficult to include a geophysical component in such an exploration programme if it costs as much as, say, four or five boreholes. It must be shown that the geophysics can eliminate the need for, say, as many as ten boreholes before management will consider its use. In this type of economic scenario, then, there exists a strong need for the geophysical investigation to be inexpensive as well as effective. Thus, while large-scale research programmes are important to determine the effectiveness of various geophysical methods and their limits of applicability, there is a practical need for data acquisition and interpretation methods which can fit into a tight budget.

A brief review of seismic tunnel detection
The purpose of this paper is to illustrate the application of surface seismic techniques to void detection. Other common methods, such as microgravity (e.g. Fajklewicz 1983, Adams 1984), resistivity (Daniels 1983), EM (Dubus et al. 1978), thermal (Moscicki 1988), and radar (Dolphin, Beatty and Tanzi 1978, Benson and Galcum 1980) have also found some success. Several reviews of geophysical applications to the tunnel detection problem are available which consider many of these techniques (e.g. Dobecki 1984). The present paper does not claim that the seismic method is the best or even least expensive method—it just seems to be the method which has met with most universal success for a wide variety of situations.

The principal seismic methods which have been employed to map voids fall into three categories: refraction, resonance (induced reverberations), and reflection techniques. Although the method described in this
paper employs facets of each of these, it is, principally, a reflection technique.

**Refraction**
As a void is a target of lower velocity than the enclosing medium, it cannot be detected directly by refraction surveying, which is only responsive to higher velocity transitions. In an indirect sense, however, refraction methods may be useful in detecting voids through the time delays these can impose upon refracted arrivals from layers deeper than the void (e.g. Fig. 1). A discussion of such an application of refraction to void detection is given by Turpening (1976).

![Delayed Traces](image)

**Resonance**
Seismic energy interacts with a void such that the void itself resonates, or rings, with a characteristic frequency. The frequency of resonance depends, principally, upon the radius of the void, its fill material (water or air), and the shear-wave velocity of the medium enclosing it (Watkins, Godson and Watson 1967). Thus, depending upon the frequency of resonance, the strength of the resonant signal, and the frequency response of the recording system, it may be possible to detect voids by the presence of a long train of monofrequency waves when conducting seismic reflection or refraction surveys in the vicinity of a void.

**Reflection**
Seismic energy will be scattered back to the ground surface by a void because of the great contrast in acoustic impedance represented by a water- or air-filled void within a rock mass. Whether such energy is detectable is, generally, dependent upon the relative size of the void as compared with the wavelength of the impinging seismic wave. For very large voids (as compared to the seismic wavelength), the reflection from the surface of the void should be quite pronounced and traceable (e.g. Steeples and Miller 1987). In most cases, however, the void can be much smaller than the wavelength dimension and, therefore, appears as a diffraction on the reflection record (e.g. Dobecki and Balch 1987). In most circumstances, common midpoint (CMP) reflection methods have been the only means to observe such reflections and locate the voids. These methods, however, are inherently quite expensive in terms of manpower during acquisition and computer time for processing, and so do not constitute a rapid and inexpensive methodology.

In the process of trying to acquire optimum-offset reflection data (Hunter et al. 1984), which is a rapid and inexpensive method, I was impressed by the consistency of anomalous features which appeared on the reflection records at positions of known voids. It then became a matter of explaining why these anomalies occurred in conjunction with voids.

**Acquisition procedure**
The optimum-offset seismic reflection procedure was devised (Hunter et al. 1984) so that seismic reflection data could be acquired rapidly by a small number of people using relatively unsophisticated equipment and minimal data processing. In fact, the data example cited later in this paper utilized a crew of, typically, two or three people, a twelve-channel ‘engineering’ seismograph, and interpretable records were produced in real time in the field (i.e. no processing other than re-plotting field records).

The key procedures in this acquisition method are:

- Determine the optimum shot to geophone offset such that the reflection of interest lies within a clear (optimum) time window (i.e. not confused by earlier refractions/reflections or later airblast or groundroll).
- Acquire data by maintaining this constant offset and recording only the geophone having that shot offset for each shotpoint (Fig. 2).

![Shotpoint](image)

**Fig. 1.** Schematic diagram showing delay of refracted ray paths which travel through a lower velocity void from below.

**Fig. 2.** Field procedure for acquiring common-offset reflection data. Shot S1 is recorded by geophone R1, S2 by R2, etc.
The optimum offset can be predicted by some rudimentary seismic modelling such as described by Knapp and Steeples (1986), and must be checked in the field by shooting a ‘walk-away’ spread and determining the correct window. Test shooting, then, verifies the modelling exercise and also determines the optimum values of other parameters (e.g. analogue filtering, single geophones versus arrays, source) to yield the best field data. This latter point is emphasized because the goal is to acquire interpretable data in the field without relying on subsequent processing.

Once the offset and other acquisition parameters have been determined, data are acquired in a routine fashion, as described by Hunter et al. (1984).

The optimum-offset method is not without its pitfalls or detractors. Some (e.g. Lankston and Lankston 1988) point to the advantages of multi-channel processing available with CMP data which are impossible to apply to optimum-offset data. When it does work, however, the optimum-offset method fulfills the need for a rapid and inexpensive method. What makes it particularly useful for void detection is that the method itself enhances the appearance of certain anomalies over a void, which might be lost if CMP processing were employed. This will be explained in the next section.

Observations

In the course of planning optimum-offset reflection surveys for void detection, I felt confident that if I could clearly see the reflection from the horizon containing the void, then lateral disruptions in the character of this reflection would indicate a void. This, of course, assumes that the void, or void plus associated collapse zone, is large enough to satisfy lateral resolution criteria (e.g. radius of first Fresnel zone). However, when observing real data (e.g. Fig. 3) over a known void, I was struck by three anomalous observations. Firstly, over the void, I did observe the expected break-up, or disruption of the reflection (Fig. 3a). Secondly, almost without exception, I observed that the first breaks above the void came in early (also Fig. 3a). For common-offset surveying, as the offset distance does not vary from trace to trace, the first breaks should arrive at the same time unless (a) there is significant surface topographic variation; (b) the thickness of the surficial (low velocity) layer varies laterally; and/or (c) the subsurface velocity structure varies laterally. These are commonly referred to as ‘static’ problems. In general, static variations on optimum-offset sections are the rule rather than the exception, and these are usually removed from the data to provide a clearer image of deeper reflections. Such static adjustments were not applied to the data presented in this study. As the data acquired were taken on as level ground as possible, surface topography was not a factor; therefore, any observed statics are due to either thickness variations or lateral velocity variations within the overburden. A model to explain this static shift in terms of its association with a void will be offered in a later section of this paper.

The third anomalous observation (Fig. 3b) was not observed for every void. When observed, it was as a monofrequency, ringy trace or sequence of ringy traces which occurred when a void was crossed. Not every void can be expected to produce this resonance effect. The natural frequency of void resonance is inversely dependent upon void diameter and dependent upon the shear velocity of the rock mass. A combination of void geometry and geology may be such that the resonant frequency is outside the frequency band of the seismic wave which excites the phenomenon. The void may also be so deep that the amount of energy coupling into the void from the seismic wave is insufficient to stimulate the void resonance effectively.

![Fig. 3. Field data examples of anomalous seismic observations over voids. (a) Example showing early first breaks (scallop) and reflection splitting. (b) Example showing induced resonance.](image)

To this point, what has been shown is that three anomalous, empirical characteristics can be associated with the presence of a subsurface void. The disruption of the reflection fits the model of a lateral transition from solid rock to void and back to solid rock. The resonance
does not always occur (the resonant frequency may be outside the system response, the void may be so deep as to ignore the stimulation, etc.), but, when it does, it is a clear indication of a void—especially if it is associated with a disruption of the reflection. The only observation which does not fit the model is the early first breaks above the void. I might add that this observation is not limited to the datasets reported within this paper but has also been noted, although not published, by others in coal-mining areas (D.W. Steeples, Kansas Geological Survey, personal communication) and over shallow tunnels discovered in Vietnam (T.E. Owen, Southwest Research Institute, San Antonio, Texas, personal communication). The Vietnam example is especially intriguing in that, while in the field, investigators located a tunnel using the same, early first-break criterion. They then proceeded to enter the tunnel and, using joists, supported (lifted) the tunnel roof. Doing this caused the first break anomaly to disappear, verifying the relationship between the static shift and the tunnel's presence. This anomalous seismic observation requires a rational explanation which is supported by rock mechanics arguments.

**Stress localization—velocity effects**

In considering the observed surface effects due to a subsidence zone over a void, we are impressed by the fact that the ground has moved downwards and that tension cracks are often seen surrounding the surface depression. The immediate supposition would be that the subsided block is heavily fractured and should be a zone of lowered seismic velocity. If this were indeed the case, then the first break static shifts, whether direct waves or refractions through this zone, should be delayed and not advanced, as reported here. This suggests that something is basically incorrect regarding our supposed model of the subsided block. Fortunately, this problem has been researched and monitored by rock mechanists (e.g. Schoemaker 1949, Rellensmann 1957, Livingston 1961, Savin 1961, Obert and Duvall 1967, Shadbolt 1977). Their findings offer a model which is, indeed, consistent with field seismic observations.

Figure 4, after Rellensmann (1957), shows that when a subsurface excavation is completed, there is elastic deformation as well as mass movement of the geological materials overlying the void. The primary importance of this model is that material movement has two components: movement is downward (subsidence) but also movement is towards the centre-line of the excavation. This movement causes the periphery of the subsided block to be in a state of tension, as the simple model suggests, but it also causes the central portion of this same block to be a zone of horizontal compression, peaking at the midpoint above the void. This is a quite simple model; actual stress configurations depend upon, among other things, the total number of voids present and depth of the voids relative to their lateral dimen-

![Fig. 4. Effect of a subsurface excavation on overburden movement and lateral strain development (after Rellensmann 1957).](image)

sions (Shadbolt 1977). The study by Rellensmann (1957) includes actual field measurements using extensometers which validate the model by providing in situ verification of this compressive zone.

The relationship between confining stress and seismic velocity and attenuation has been researched by many. The net conclusions of these studies are that as confining stress is increased, seismic velocities of both P- and S-waves also increase, while attenuation decreases. The opposite is true for a tensional environment. Considering the case of a single void whose depth of burial is substantially greater than its diameter, we would then anticipate the simplified overburden velocity model shown in Fig. 5. The zone above the void would be

![Fig. 5. Schematic depiction of the effect of strained overburden (as per Fig. 4) on velocity distribution above an excavation. (a) Velocity distribution prior to excavation of void. (b) Velocity distribution after excavation.](image)
predominantly one of increased seismic velocity with narrow, flanking zones where velocity is locally decreased. Such lateral velocity variations can lead to static anomalies of the type described; that is, waves traversing the zone above a void would arrive early relative to waves traversing normal overburden materials. Depth to the void is mentioned as a key factor, and indeed it is. One might imagine that for a shallow depth of burial movement would be predominantly vertical, and the entire zone above a void would be dominated by fracturing and tensile horizontal stresses. In this case, lowered velocity and increased attenuation would be expected.

As a means of assessing how such a velocity distribution (Fig. 5) might affect the first break arrivals in a common-offset geometry, the reader is referred to the model of Fig. 6. Here, a geometric model of single-layer overburden of 3-m thickness is situated above a half space. Both layers show lateral velocity variations which we suppose are due to subsidence. Every ‘zone’ (constant velocity segment) in the upper layer has exactly half the velocity of the half-space zone immediately beneath it. This ensures that the critical angle of refraction will remain constant across the section. Refraction at vertical boundaries is ignored in this simple model. Lateral velocity changes of -20% (with respect to undisturbed velocity) for the tensional zones (each 3 m wide) and +20% for the compressional zone above the void (9 m wide) have been ascribed to both the surface layer and the half space. Traveltimes for the critically refracted wave (first break) were calculated for common-offset geometries for two offsets. The first offset was chosen to be 9 m, or three times the thickness of the upper layer and equal to the width of the compression zone (Fig. 7a). The second offset was chosen to be 18 m, which is six times the upper layer thickness and twice the width of the compression zone (Fig. 7b). In each case, the shot-point interval is taken as 3 m. The plots of mod-}

eled first breaks for these two offsets are quite different and are reminiscent of the response of normal electric logs in a bedded, borehole environment. For the case where the offset is comparable to the width of the compression zone (Fig. 7a), we observe a pair of flanking delayed first break zones and a central area where the first breaks come in early. For the case where the offset is larger than this width (Fig. 7b), we still see the flanking delayed zones, but the central, early feature has been disrupted by a narrow, central delayed zone. Some of the complexity of these results is due to the sharp boundaries of the model; if the actual velocity effects are transitional, the static effects themselves might appear more transitional (smooth) as well. The net impression to be gained from this simple model exercise is that if the ±20% imposed velocity change is reasonable, then we can expect to observe static effects of ±1.5–2.0 ms, or roughly ±10–20% variation around the average first break times. Given the typical sample rates (0.02–0.1 ms) of engineering seismographs, such disruptions should easily be visible.

The arguments presented here are not to dispute that static effects are due to the presence of significant low-velocity layers. What we are trying to establish is why the particular type of static (a pull-up) appears to be associated with the presence of voids.

**Case history example**

To demonstrate the utility of the described method of data acquisition and interpretation for void detection, I present a case history example. This represents a typical situation in terms of host rock type, void depth and fill, as well as cultural setting.

This test attempted to locate water-filled abandoned coalmine workings, typically 3×3 m in section, near the top of a 15-m thick coal seam at 30 m depth. At the ground surface, there are grass-covered sands, with
the depth to weathered rock (carbonaceous shales) being less than 3 m. The subject mines were large-scale commercial operations which were reasonably well documented. Common-offset seismic lines were laid out normal to the direction of mine tunnels and data acquired with an 18-m offset and a 3-m geophone station spacing. Data were acquired with a 12-channel engineering seismograph, a shotgun-type source (Pullan and MacAulay 1987), and single 50 Hz geophones.

Figure 8 is one common-offset record for this site. On this section, we can see two of the seismic diagnostics described earlier: the coal zone reflection splits notably and the first breaks have a scalloped, not horizontal, appearance. The total static shift (from earliest arrival to latest arrival) is approximately 7 ms. The three borings on the right-hand portion were drilled on the basis of the seismic data, and each encountered a void. That is, two of the three boreholes were sited at the crests of first break arches where there also was a corresponding splitting of the coal composite reflection. We thought that the central borehole might hit a coal pillar as it is on the flank of one of the arches and where the reflection split is minimal, but it also hit a void. If there was a pillar, it was simply missed. Or, perhaps, this is the response of a particularly large void, and the first break anomaly might show a local reversal as demonstrated by the model in Fig. 7(b). Judging by the correlation of located voids with the seismic features, we would suggest that a similar feature on the left would also indicate a void.

We note at this site no observable resonance traces. This may be due to the depth and/or the water-fill of these particular voids. As mentioned earlier, this is the least consistent diagnostic feature.

Summary and conclusions
In the course of acquiring optimum-offset reflection data in the search for subsurface voids, three prominent seismic indicators were observed to be associated with these voids:

- Distortion of reflected arrivals from the void and the layer containing the void.
- Ringy (resonance) traces sometimes when the source was over the void.
- Early first breaks over the void.

The first two indicators were anticipated and have been described elsewhere. The third indicator was not anticipated and actually ran counter to preconceived expectations. By considering a rock mechanics argument which states that the overburden materials above a void should dominantly be subject to, lateral compression flanked by tensional zones, we can explain these early first breaks as a result of a local velocity increase due to lateral compression in the overburden. That is, as the overburden materials move downwards and towards the midpoint of the void excavation, the zone above the void becomes compressed. Compression, especially in poorly consolidated materials, causes an increase in seismic velocity. The presence of a localized zone of increased overburden velocity, as shown by a simple model, can cause the type of static anomaly which has been observed to be associated with voids. Certainly, in areas where surficial conditions are such that large static anomalies due to topography or weathering thicknesses are to be expected, this stress-related effect might be difficult to observe. If the effect is readily apparent, this stress-induced effect adds to the diagnostic tools available for void detection.

Most of our failed predictions (i.e. predicted void but coal found by drilling) have encountered subsurface features which, themselves, are anomalous but have not been voids (e.g. large clay splits in a coal seam). Therefore, a word of caution regarding the influence of geological noise is offered along with encouragement.

The technique, as described, has turned out to be rapid and inexpensive. A crew of three people (observer, source operator and labourer) has no trouble flagging, laying out, shooting, and picking up over 300 m...
of seismic line with 3 m reflection point spacing in an eight-hour working day. At the end of the day, the common-offset record sections are actually available for near-real time interpretation.

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References


