Efficiency of MASW in detecting near-surface cavities

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SUMMARY

The purpose of this study is to evaluate the efficacy of using multichannel analysis of surface wave (MASW) to detect the near-surface cavities. The methods used in this study include interpreting dispersion curves and amplitude mapping of the multichannel analysis of surface wave technique and interpreting the delay in first arrivals of compressional waves. To test these methods, a seismic survey was conducted above a known near surface cavity in Al-Suman Area, Saudi Arabia. The cause of the cavity is carbonization in the area; there are many cavities similar to this one. The seismic data were collected using a seismograph system with 48 vertical geophones. Both techniques show a tangible result for detecting the cavity. The 2D section of shear wave velocity, which was obtained by inverting the dispersion curves from the MASW technique, leads us to determine the shape of the cavity, as described by a low-velocity zone. Frequency against relative offset is plotted and shows a significant frequency drop in the presence of the cavity, which also provides an indication to the presence of cavity underneath. This interpretation is matched by the interpretation of observed delays in first arrivals of compressional waves. The integration of both P-wave seismic refraction and MASW gives confidence in the result and matches observations of the existing cavity closely.

Key words: MASW, Seismic, Refraction, Amplitude, Dispersion

INTRODUCTION

Seismic body waves travel in the solid earth and depend on the elastic properties of the rocks obeying Snell's Law and laws of reflection and refraction. Greater compaction of earth material will generally yield faster-traveling waves and vice versa. Surface waves, on the other hand, travel along the surface of the earth, obeying the property known as dispersion. The detection of underground cavities is still problematic, despite recent advancements in near-surface geophysical methods. These cavities, such as karstic cavities or mine-crown pillars, can be the cause of severe damage. In order to prevent the damage caused by cavities, special attention has been devoted to the detection of underground cavities during the construction of dams, buildings, roads and other engineering purposes. Many geophysical techniques have been developed to study near surface cavities, but generally, seismic reflection, surface-wave analysis, seismic refraction and ground-penetrating radar methods are used. Seismic reflection methods rely on seismic waves reflected back from geological interfaces. Because the cavities cause strong acoustic impedance contrasts, the method is widely used in detecting underground cavities (Guy *et al.* 2003; Grandjean *et al*. 2002; Leparoux *et al.* 2000; Baker *et al*. 1997; Piwakowski *et al.* 1997; Miller and Steeples 1991; Cook 1965).

For surface waves analysis, the system must be dispersive, i.e. non-homogeneous. Phase velocity of surface waves depends on the frequency of the wave. Jones (1962) describes the theoretical development of surface waves usage in the near surface, which was later enhanced by Nazarian *et al.* (1983) using a technique named spectral analysis of surface waves (SASW). SASW has been used for site investigation for several decades (Ganji *et al.* 1997; Nazarian and Stokoe 1984). SASW uses the spectral analysis of ground roll generated by an impulsive source and recorded by a pair of receivers. Park *et al*. (1999) improved upon the SASW method through the application of multichannel analysis of surface waves (MASW). The MASW approach allows more effective noise removal, due to multi-channel coverage, faster acquisition and easier methods of identifying higher modes of Rayleigh waves. The MASW method has shown potential for the detection of underground cavities at shallow depths (Xu and Butt 2006; Gelis *et al*. 2005; Phillips *et al.* 2000). Nasseri-Moghaddam *et al*. (2007) showed numerically that incident energy is trapped within the void, and this energy is seen as a concentration of energy over the void region in the frequency domain. The application of MASW is limited to a depth of <30 m; it is a reliable technique to detect underground cavities for shallow studies. MASW has been successfully applied in desert areas for subsurface studies (Cheng *et al.* 2007; Cheng *et al*. 2005; Zeng *et al*. 2001).

In this paper, we describe the comparison of multichannel analysis of surface waves (Rayleigh waves) with seismic refraction (P-waves) over a known cavity in Al-Suman, Riyadh. The chosen cavity is 3 meters deep, irregular shape and of 25 meters in lateral extension. This particular cavity has been selected to test the efficiency of multichannel analysis of surface waves and the P-wave seismic refraction technique in the detection of subsurface voids. The low-velocity zone is identified by MASW (by shear velocity section and amplitude mapping) and also with P-wave first arrivals. Markiewicz and Rodriguez, (1985) explained that the first breaks over the cavity area are more delayed in time than would be normally expected from increasing offset.

METHOD AND RESULTS

Multichannel Analysis of Surface Wave (MASW)

MASW involves three steps: extraction of dispersion curve, inversion of dispersion curve and mapping of inversion results. The dispersive nature of different types of waves is imaged through a 2D wavefield transformation into a dispersion image, Xia *et al*. (2004). Certain noise wavefields, such as back- and side-scattered surface waves, and several types of body waves are automatically filtered out during the wavefield transformation explained by Park *et al*. (2007). Xia *et al.* (1999) showed that from the dispersion image, a dispersion curve of the fundamental mode of Rayleigh waves is picked, which is subsequently inverted for a 1D shear-wave velocity profile. A 2D velocity section is obtained from the inversion of each 1D S-wave velocity with interpolation between each survey point. The amplitude mapping technique is enacted by plotting frequency versus relative offset. The amplitudes are affected by the presence of cavities and the crests changes to troughs in the cavity. The P-wave first breaks are muted such that only Rayleigh wave are considered in this mapping.

P-wave Seismic Refraction

The MASW method records not only surface waves of different modes but also refracted waves. Low and high cut filters were applied for all traces to make the first breaks more clean to observe the delay if any. Velocities obtained by differential method, considering slopes of constant velocity. It deals with the first breaks recorded in the seismic data. Conventional interpretation of refraction study fails to determine the hidden layer in depth model case but it is achievable from the first breaks which might possess the sufficient information. Engelsfeld *et al.* (2008) derived expressions for determining both position and size of circular cavity from the observed delays in the first arrivals of seismic wave by using seismic refraction technique.

Examples

The MASW test was performed along the side of the open cavity such that the midpoint of the coverage coincides with the cavity. A continuous shooting approach was adopted for the survey (Figure 1).

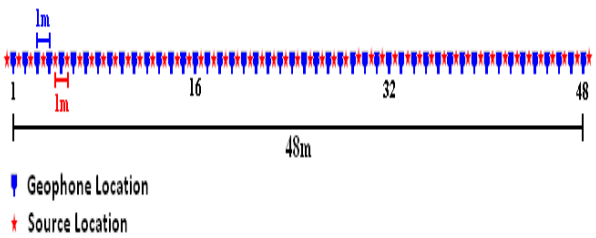

Figure 1. Geometry of the MASW line. Red Stars representing shot locations, while blue shapes are representing geophones. A continuous common midpoint shooting approach was adopted. Both shot and geophone intervals were 1 m and total spread length was 48 m.

The 2D velocity section of MASW shows the low-velocity zone encountered at depth 7 m, and it laterally extends from 10 m to 35 m (Figure 2). This finding indicates that the low-velocity zone extends for approximately 25 m laterally. The section shows two layers: one is up to 5 m depth, and a second is below where cavity starts. This shear velocity section helps in determining the shape of the cavity. The amplitude mapping shows a few other amplitude drops other than the known cavity (Figure 3). These anomalies may be an indication of other sideline cavities that are unknown. However, considering the reliable results for the known cavity, we have sufficient confidence to mark these as cavities (Figure 4). This approach also helps in defining the lateral extension of the cavity. The P-wave first arrivals are interpreted to be delayed in time between geophones 12 to 34 (Figure 5). Normal delay times are observed with increasing offset up to geophone 12. However the delay times of first breaks are greater at geophones 12 to 34 and it shifted back to normal delay with offset after geophone 34. The average velocity for first layer is 1217 m/sec, while for the second layer it is approximately 2619 m/sec. This zone is defining a lateral extension of 22 m and cavity depth of 3 m. The thickness of cavity is observed to be 8 m.

Field measurements were taken for cavity (Figure 6). The MASW 2D section shows the cavity depth as 5 m and with a lateral extension of 25 m. This result nearly matches field measurements. The amplitude mapping defines the lateral extension of cavity and surface position. The seismic refraction delay time analysis shows a 22-m lateral extension of cavity and an upper layer of 3 m, which indicates an accurate depth of the cavity and lateral extension with acceptable error.

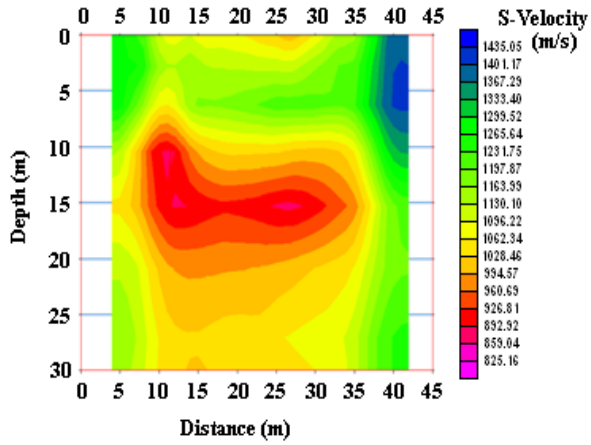

Figure 2. MASW 2D velocity-depth section.

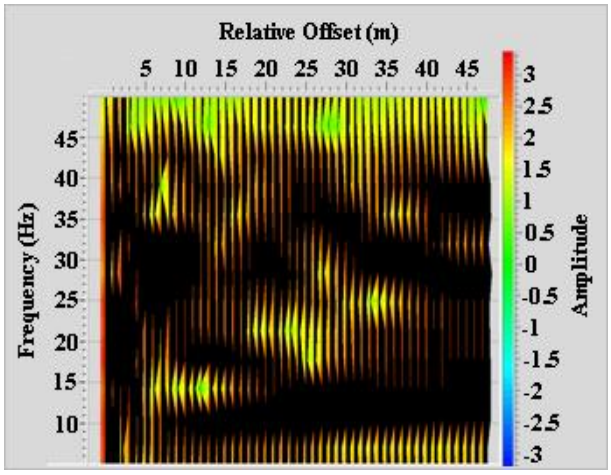

Figure 3. Amplitude mapping in variable density mode and wiggles displayed over it to see the amplitude drop in the cavities. The amplitudes are marking the presence of known cavity so clear and also indicating the presence of few more small cavities in the surroundings of known cavity.

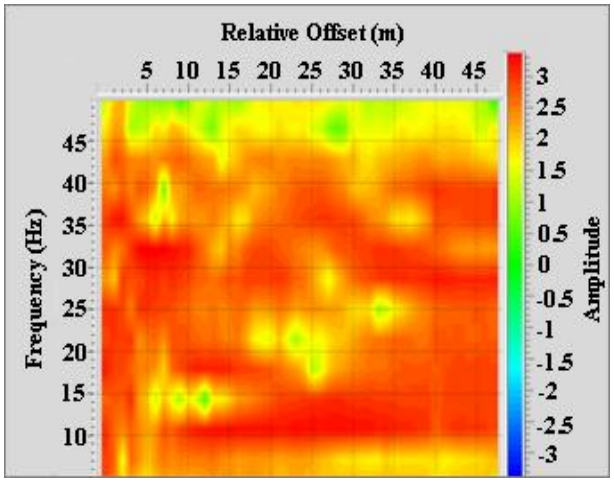

Figure 4. Amplitude mapping in variable density mode only. Green dots are indicating the presence of cavities.

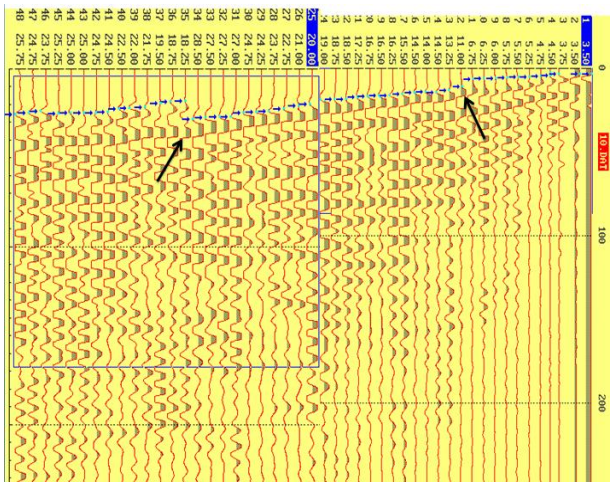

Figure 5. Shot record with interpreted delay-time in first arrival of refracted P wave.

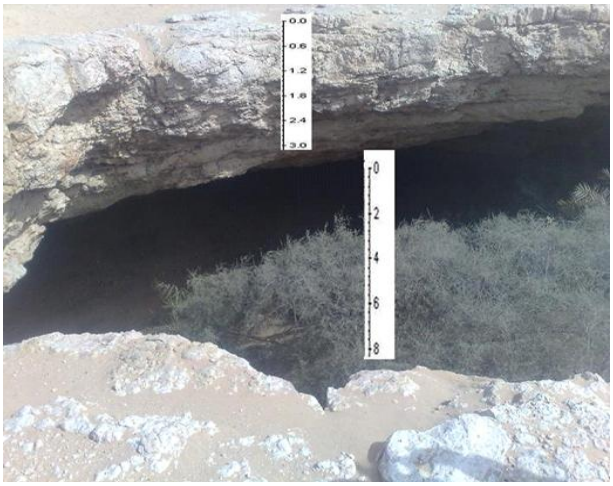

Figure 6. A Field measurement taken on known cavity and scale is in meters. Cavity thickness is 8m and upper layer thickness is 3m.

CONCLUSIONS

Depending on the analysis used for the MASW data, the results obtained in this study confirm the low velocity zone (i.e., cavity) from both surface-wave analysis and P-wave seismic refraction. From surface-wave analysis, the 2D shear velocity section shows the cavity presence and the shape in both lateral and vertical dimensions. The amplitude mapping also shows the cavity presence and gives more minor details of the cavity surroundings (i.e., fractures under the profile and a second cavity in addition to the known cavity, which is not identified from conventional 2D shear velocity section). Including this amplitude mapping in the MASW analysis can thus provide greater near-surface detail. Integrating these findings with field measurements yielded precise calculated thickness, depth and lateral extension of the cavity.

In the P-wave seismic refraction data, normal delay times in first arrivals are observed, whereas the cavity shows greater delay times than would normally be expected. P-wave seismic refraction also provides the thickness, depth and lateral extension. Therefore, from one recorded dataset of surface waves, the combination of these three results (i.e. 2D shear velocity section, amplitude mapping and P-wave seismic refraction) provides enough confidence for studying the near surface. This approach can be undertaken solely without the inclusion of ground-penetrating radar. One of the limitations of ground penetrating radar is in shaly environments, where it may fail to record reflections. In these environmental conditions, focusing on MASW data can give better results. The usage of MASW is cost-effective and time-efficient, as well, because from one dataset, we can apply three different studies, which can be combined for cavity detection.

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