DETECTION OF SHALLOW CAVITIES BY WAVELET TRANSFORM ANALYSIS OF SURFACE WAVES

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Abstract

The ability to locate and characterize shallow underground cavities, such as utility lines and sinkholes is required in many projects and applications. Various physical and geophysical techniques are currently being tested and used for this purpose. A new seismic method based on wavelet time-frequency analysis of surface waves for detection of shallow cavities in soil medium or under the pavement is investigated in this study.

Wave propagation is simulated through a transient response analysis on an axisymmetric finite element model. Cavities of different shapes and embedment depths in a homogeneous half-space and a pavement system are considered. The continuous wavelet transform (CWT) is introduced as a new tool for studying wave propagation patterns. Response of the medium at different surface points is presented in a wavelet time-frequency plane. Effects of different types of cavities on surface response time-frequency maps (wavelet transform coefficients versus time and frequency) are studied. Time and frequency signatures of waves reflected from near and far faces of the cavity can be clearly observed in the wavelet time-frequency maps. Based on these observations, a practical step-by-step procedure for detection and characterization of shallow cavities is proposed. Finally, experimental test results verifying the validity of this method in detection of cavities are presented.

Introduction

There are many circumstances that necessitate nondestructive detection and characterization of underground cavities. For example, it may be required to locate a utility conduit before an excavation or to examine the presence of subsiding sinkholes to prevent pavement collapse. A number of different physical and geophysical techniques are being tested and used for cavity detection, such as ground penetrating radar (GPR), gravity gradiometer, magnetic and electromagnetic induction, seismic methods, and imagery analysis. Each of theses methods has shown limited success in certain circumstances, but none of them has been unconditionally successful.

Seismic techniques are usually advantageous where there is a significant rigidity contrast between the sought object and the medium. Therefore, seismic methods are expected to be successful in cavity detection applications. These methods are based on either travel time or spectral analysis of elastic waves generated in a medium due to an impact. Refraction and reflection methods are the most widely used travel-time based seismic techniques. The former usually fails to detect shallow cavities in stratified medium. The latter is quite successful in detection of deep cavities. However, it is difficult to be utilized in near-surface cavity detection applications (Cooper and Ballard & Belesky and Hardy). Spectral analysis of surface waves (SASW) is the most widely known spectral based nondestructive seismic techniques. It has been primarily used in evaluation of elastic moduli and layer thicknesses of layered systems (Nazarian *et al*.). SASW technique has been used for detection of cavities in several studies (Al-Shayea *et al*., Gucunski *et al*., & Ganji *et al*.). However, it

has been found that the success in anomaly detection in this method, depends on receiver spacing and location, shear wave velocity and damping of the surrounding soil medium (Ganji *et al*.).

Surface seismic techniques rely on the analysis of surface response of the medium to an impact source. When a shallow cavity is present, reflected waves from near and far faces of the cavity change the near-surface wave patterns. Studying these changes led to seismic cavity detection techniques. The reflections from cavity faces are of limited duration. It has been found that (Shokouhi *et al*.) they have certain frequency bandwidths. These facts suggest time-frequency analysis of the response could be more efficient than analyzing it in merely one domain. Wavelet transform are recently developed mathematical tools, which can extract local and global time and frequency information of a signal efficiently. Therefore, they can be advantageous in studying the changes in the near-surface wave patterns due to the presence of a cavity. Consequently, they can be used efficiently in cavity detection and characterization applications.

Numerical simulations are used in this study to investigate the effects of shallow cavities on surface wave patterns in soil medium. The basic theory of continuous wavelet transform (CWT) is discussed through a number of illustrative examples. The response of the medium at a number of surface points is presented in wavelet time-frequency plane. The time and frequency signature of the cavity in these maps are studied and used to propose a practical scheme for detection of cavity and estimation of its size. Finally application of this technique in detection of underground cavity is demonstrated using experimental results.

Continuous Wavelet Transform (CWT)

The travel-time based techniques for cavity detection do not provide any information on the change in frequency content of the response due to the presence of the cavity. On the other hand, spectral analysis based methods rely on the analysis of the response in the frequency domain. However, using Fourier transform, the time location of the changes in the spectrum cannot be taken in to account. Reflections from the cavity boundaries change both the time history and the spectrum of the response recorded at surface points. Therefore, time-frequency analysis of the surface response can be advantageous over analyzing it in merely one domain.

Wavelet transforms are fairly new mathematical tools, which can be used to present the changing spectrum of a nonstationary signal in a time-frequency plane. Wavelet transform is a convolution between the signal and a set of analyzing wavelets. Wavelets are the scaled and translated versions of a single function called mother wavelet. A mother wavelet $\psi\ (\tau)$ is a well-localized function in both time and frequency domains. A Wavelet $\psi_{a,t}(\tau)$ at scale a and time location t is obtained through scaling and translating the mother wavelet function $\psi\ (\tau)$ according to the following equation

$$\psi_{a,t}(\tau) = \frac{1}{\sqrt{a}}\psi\ (\frac{t-\tau}{a}) \qquad (1)$$

The continuous wavelet transform (CWT) of a signal $x(\tau)$ using wavelet function $\psi\ (\tau)$, $W_\psi x$, is defined through the convolution between $x(\tau)$ and analyzing wavelets over a finite range of scales as,

$$W_\psi x_{a,t} = \int_{-\infty}^{\infty} x(\tau)\psi_{a,t}^{*}(\tau)d\tau \qquad (2)$$

where $\psi_{a,t}^{*}(\tau)$ indicates the complex conjugate of $\psi_{a,t}(\tau)$.If a signal correlates well with the analyzing wavelet, wavelet coefficient $W_\psi x_{a,t}$ will be large, otherwise, it will be small. Plotting wavelet

coefficients $W_{\psi} x_{a,t}$ for different scale (scale is a reciprocal function of frequency) and time produces a representation of the signal in a time-frequency plane.

Having varying bandwidth basis, wavelet transform can capture both local and global time and frequency information of a signal efficiently. The only constraint imposed on an integrable function to be a wavelet is having a zero mean in the time domain or a zero DC (direct current) offset in the frequency domain. Therefore, a variety of different types of wavelets have been developed for different analysis purposes. From all families of wavelets examined, Gaussian real wavelets have shown to be the most appropriate wavelets for this study and have been used for the analysis.

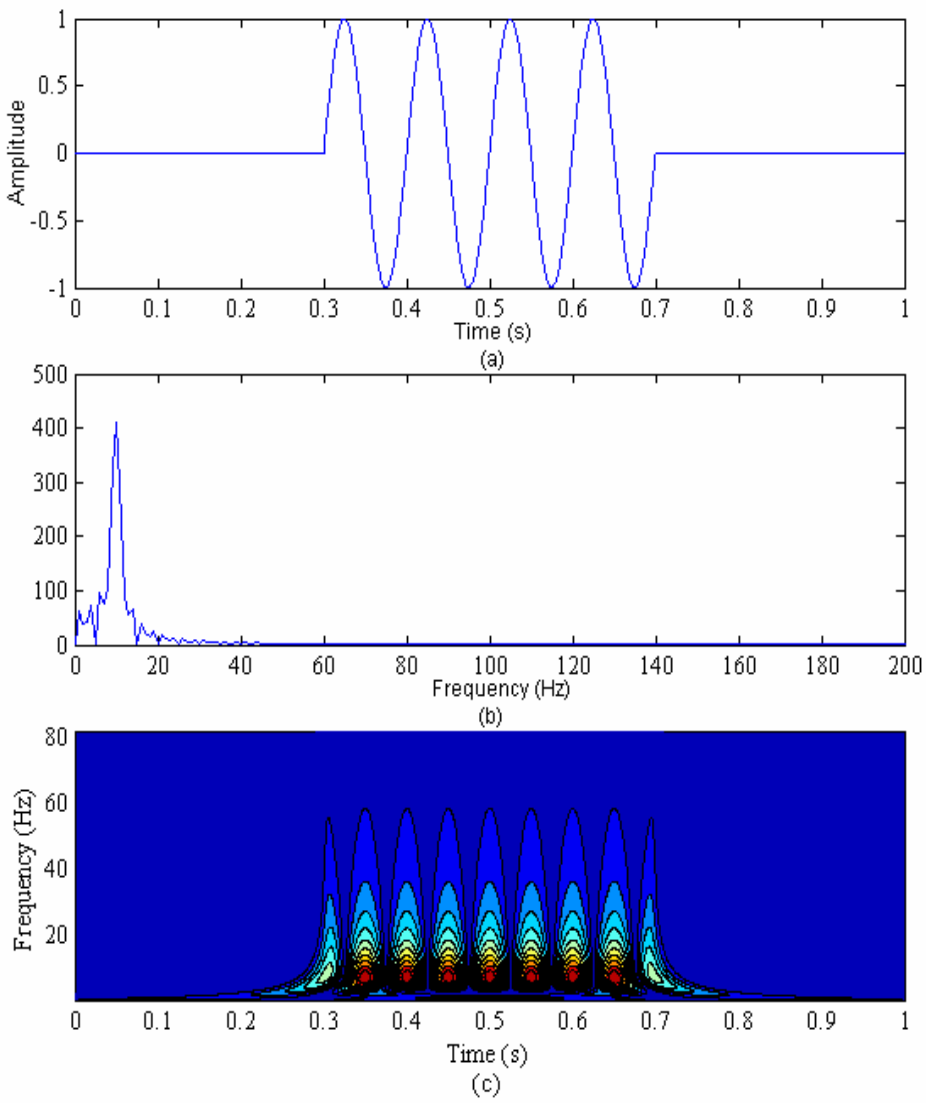


Figure 1- Illustration of continuous wavelet transform (a) Analyzed signal, (b) Spectrum and, (c) Signal Gaussian wavelet time-frequency map.

To illustrate the characteristics of CWT, a synthetic signal of known characteristics is analyzed and the presentation of the signal in time, frequency and wavelet time-frequency domain is

shown in Figure 1. This signal obtained from 2048 evenly spaced samples of the truncated sine function $\sin(20\pi)$ over the interval $0 < t < 1$s. The sine function is windowed using a unit square window of width 0.4s (0.3s-0.7s) (Figure 1(a)). The spectrum of the resulting signal is presented in Figure 1(b). Although the fundamental frequency of 10 Hz appears as a single peak in the signal spectrum, it doesn't provide any information about the extension of the signal with the corresponding frequency content. The Gaussian wavelet time-frequency map for this signal is presented in Figure 1(c). As it can be clearly seen, the wavelet time-frequency map provides not only the frequency information of the signal but also the time bandwidth of the occurrence of each frequency component.

Finite Element Model and Cavity Cases

Assuming that the wave propagation occurs in a vertical plane and no lateral reflected waves are present, the medium can be described as an axisymmetric model with an impact force applied at the origin of the system. Because of a very low strain level induced in the medium, the soil is assumed to be linearly elastic with a shear wave velocity of 50 m/s. The impact is described by an impulse of a trapezoidal shape of 1-KN amplitude and 6-ms duration. Certain criteria are imposed to ensure that the finite element analysis simulates accurately the surface wave propagation (Ganji *et al*., Zerwer *et al*. and, Shokouhi *et al*.). The soil medium is described as a 40-m wide and 32-m deep model discretized by axisymmetric quadratic elements. The smallest element size is 0.25 m (one forth of the smallest dimension of the cavity). The mesh is very fine between the source and the first receiver location. The element size gradually increases towards the boundaries in both directions. For the maximum frequency of interest of about 50 Hz, a time step of 1 ms is chosen for the analysis. The finite element mesh is shown in Figure 2.

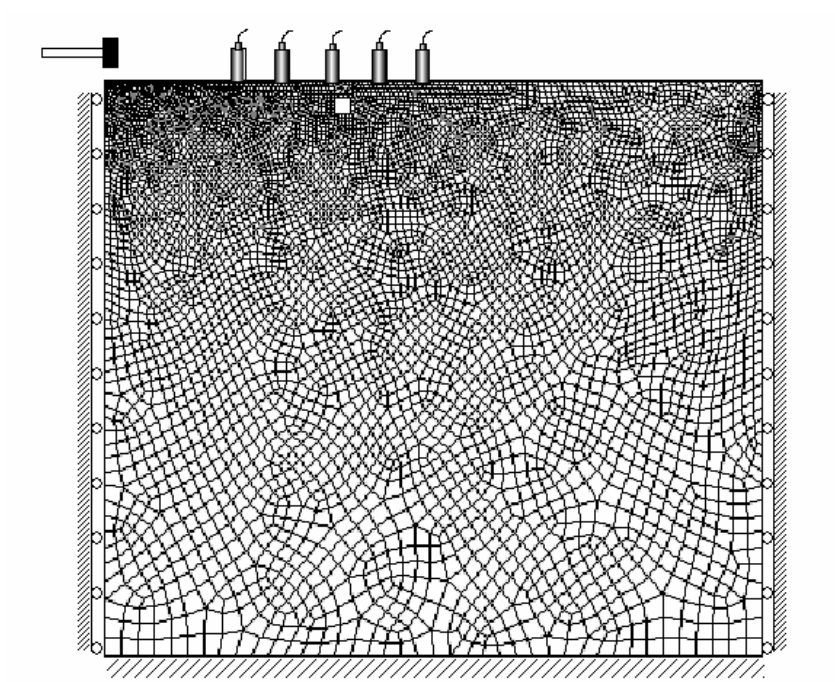
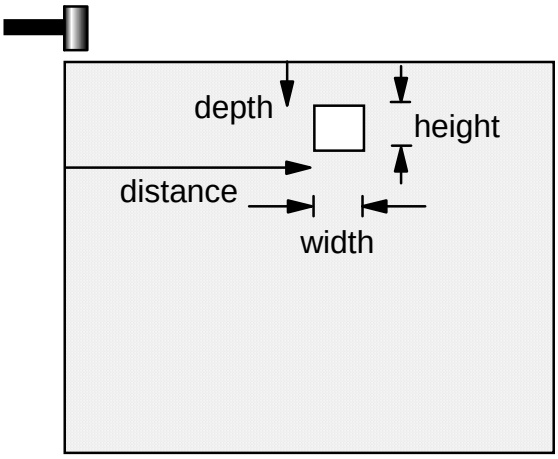


Figure 2- Finite element mesh.

To investigate the effect of cavities of different width, height, embedment depth, seven different cases of cavity in a soil medium (half-space) and a pavement system was considered for this study. The characteristics of all theses cases are listed in Figure 3.

Case	Distance (m)	Depth (m)	Height (m)	Width (m)



* Case 0 refers to medium without a cavity.

** In Case 7, a pavement layer of thickness 20 cm and shear wave velocity of 250 m/s is considered on top of the half-space.

Case	Distance (m)	Depth (m)	Height (m)	Width (m)
0*	NA	NA	NA	NA
1	14	1	1	1
2	14	1	1	2
3	14	1	1	3
4	14	1	2	1
5	14	1	3	1
6	14	2	1	1
7**	14	1	1	1

Figure 3- Cavity cases for numerical study.

Wavelet Transform Analysis Results

To study the changes in the near-surface wave pattern due to the presence of a cavity, surface response at different surface points (receiver locations) have been analyzed using Gaussian wavelet transform. To compare the effects of different types of cavity Cases (Figure 3), the wavelet time-frequency maps for a single receiver location (at distance 12.5 m from the source) for Cases 0,1,2 and, 3 are presented in Figure 4. The changes in the signal appear as peaks in the wavelet time-frequency maps. Peaks I, II and, III in Figure 4(a) mark the arrival of different component of waves generated in the medium namely, compression, shear and surface waves. Comparing Figures 4(b), (c) and, (d) to Figure 4(a) demonstrates the changes in the response due to the presence of the cavity Cases 1,2 and, 3. Although the peaks of incident wave components (I,II and, III) are still present in all these figures, a new sets of peaks (IV,V and, VI) appear in these Figures, which could not be seen in Figure 4(a). Peaks IV and V in all these three Figures mark the arrival of reflected waves from two faces of each Case of cavity. Since the near face of the cavity is at the same location distance of 14m, peak IV has the same time location in all theses three cases. However, the time difference between peaks IV and V is controlled by the width the cavity. The wider the cavity, the time difference is larger and the peaks are better separated. This is obviously because of the increasing time delay between the arrivals of reflected waves from two faces of the cavity. On the other hand, as the width of the cavity increases, the frequency of the reflection peaks decreases. Therefore, wider cavities result in two well-separated reflection peaks of low frequency. Knowing the surface wave velocity of the medium, the time difference between these two peaks can be easily used to estimate the width of the cavity. Peak VI marks the end of the transient response and does not have any physical significance.

Effect of height and embedment depth

To study the effect of height of the cavity on wavelet time-frequency maps, the surface responses at receiver location 12.2 m for Cases 4 and 5 (Figure 3) are analyzed and presented in Figures 5(a) and (b). Other than the incident wave peaks (I, II and, III), three other peaks (IV, V and, VI) are also present in both Figures. Peaks IV and V correspond to the arrival of reflected waves from the cavity boundaries. Since, the width of the cavity as the same as that of Case 1, the reflected waves from near and far faces of cavity are not well-separated rather form a single peak. However, the peak IV in Figures 5(a) and (b) is of considerably higher energy. Therefore it can be concluded

that increasing the height of the cavity results in reflection peaks of broad frequency bandwidth and much higher energy level. However, the frequency of the reflection peaks does not show a noticeable change.

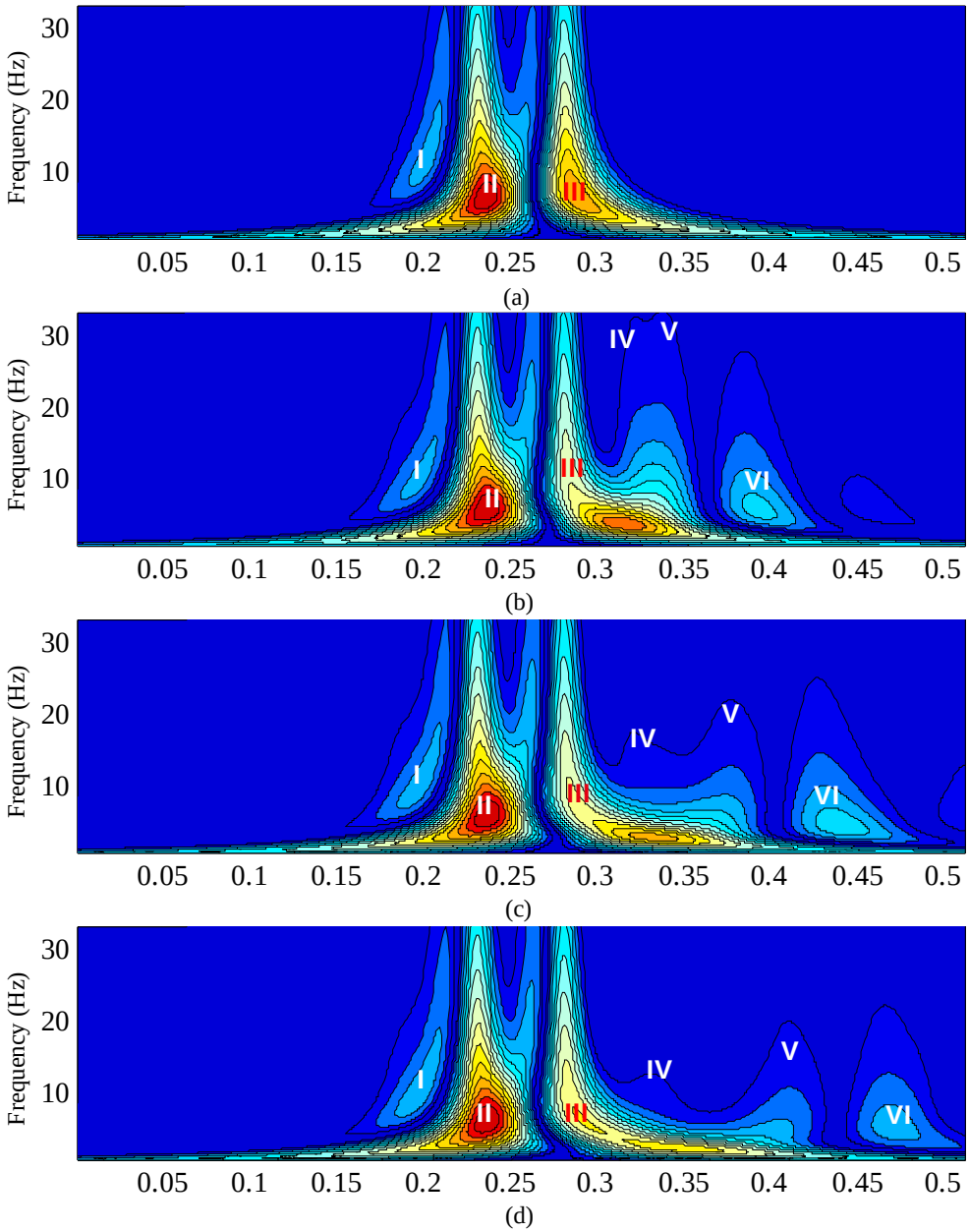


Figure 4- CWT maps for (a) Case 0, (b) Case 1, (c) Case 2 and, (d) Case3

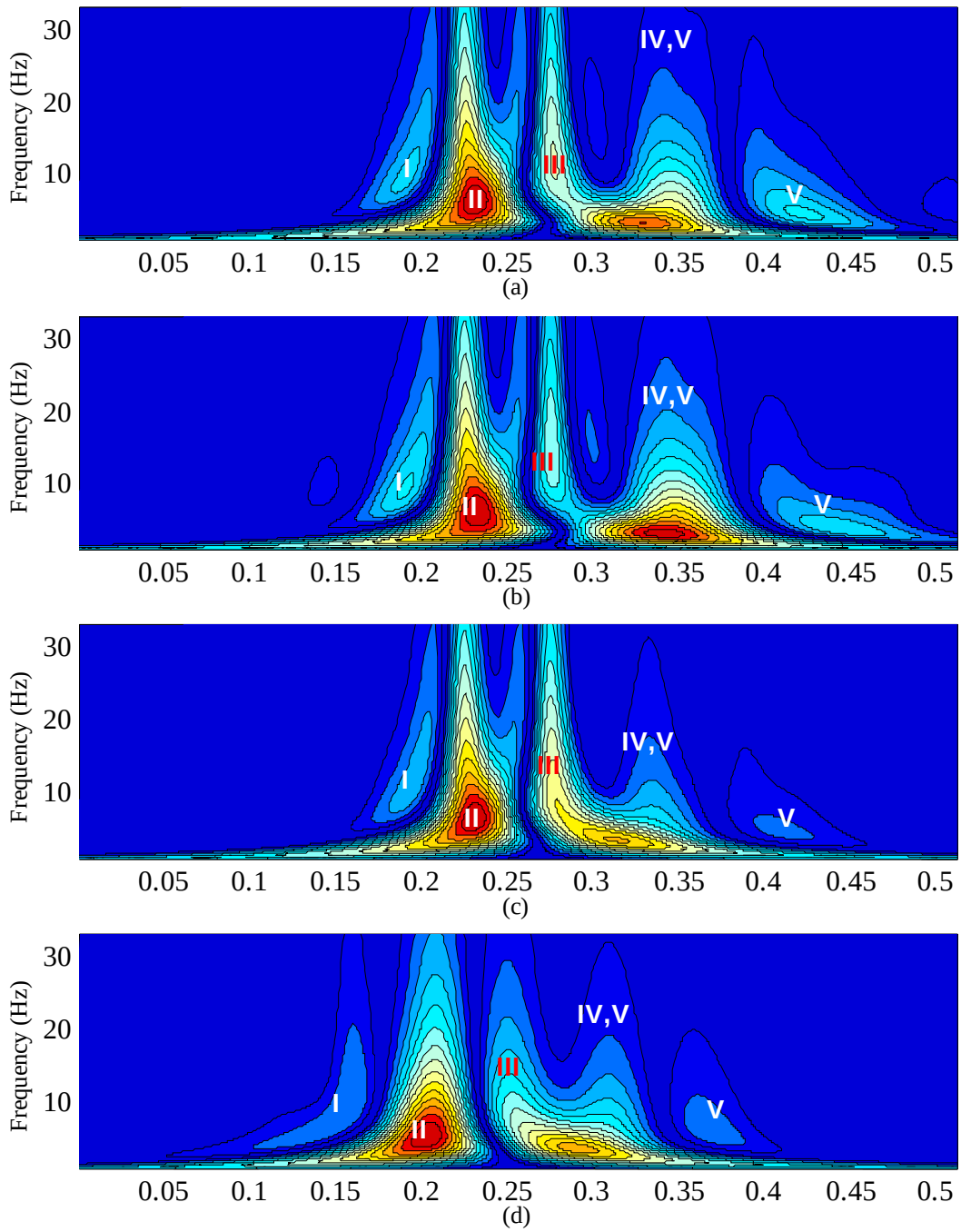


Figure 5- CWT maps for (a) Case 4, (b) Case 5, (c) Case 6 and, (d) Case7

To study the effect of increasing the embedment depth of the cavity on the wavelet transform maps, the response for Case 6 at distance of 12 m is analyzed and presented in Figure 4(c). As expected,

increasing the depth results in a reflection peak of much lower energy level. Consequently, a cavity of embedment depth of more than its height is hard to detect by this method.

Cavity under the pavement layer

In Case 7, the cavity is located under a 20 cm thick pavement layer of shear wave velocity of 250 m/s (five times the shear wave velocity of the soil). The response at distance of 12.2 m is analyzed and presented in Figure 5(d). Despite the high velocity layer on top, the reflections from the cavity boundaries (peaks IV, V) can still be clearly observed in this Case. The other characteristic of the reflection peak is similar to those of Case 1. It can be concluded that shallow cavities in a pavement system (e.g. sinkholes and conduits) can be easily detected by this method.

Wavelet maps at different receiver locations

The results presented in Figures 4 and 5 were the analysis of the surface response for different cases for a single receiver location (12.5m and 12.2m). Wavelet time-frequency maps for Case 1 at different receiver locations in front of the cavity (10.6m, 12.3m, 14m and, 14.8m) are presented in Figure 6. As it can be easily observed, reflections from the cavity boundaries can be easily identified for the receiver locations in front of the cavity. On the other hand there is no noticeable signature of the cavity in the wavelet maps at receiver location 14m. Therefore, having the surface response at different points, the cavity can be located as being near to the receiver locations where the reflection peaks vanish. After locating the cavity, its size and shape can be approximated by studying the time and frequency characteristics of the reflection peak according to the discussion above.

Cavity Detection Scheme

Based on the wavelet analysis results, the following scheme for cavity detection is proposed:

1. Obtain and analyze the surface response for different radial directions and a number of receiver positions along each direction and present the results in the form of time-frequency maps.
2. Compare the pattern of changes in the time-frequency maps for each direction to those shown in Figure 6. Choose the direction for which the changes in the maps resemble the most those in the presented pattern. If necessary, obtain the surface response in the selected direction at smaller receiver distances.
3. Approximate the location of the cavity based on the pattern of changes of time-frequency maps. The cavity is located near the receiver position where the reflection peaks vanish.
4. Calculate the distance of the near side of the cavity from the time position of the reflection peak in each time-frequency map (for each receiver position). The accuracy will increase if calculated for different locations and averaged.
5. Calculate the width of the cavity from the time bandwidth of the reflection peak. The accuracy will increase by averaging the time bandwidth for different receiver locations.
6. Determine the shape of the cavity from the time and frequency characteristics of the reflection peak. If the cavity is wide enough, the reflection peak will be recognized by two distinguished hats, a low peak frequency and a narrow frequency bandwidth. The vertical elongation results in peaks of significantly higher energy levels and broader frequency ranges.
7. Cavities with an embedment depth of more than two times their size can be hardly detected. In general, increasing depth will result in reflection peaks of lower energy and narrower frequency bandwidths.

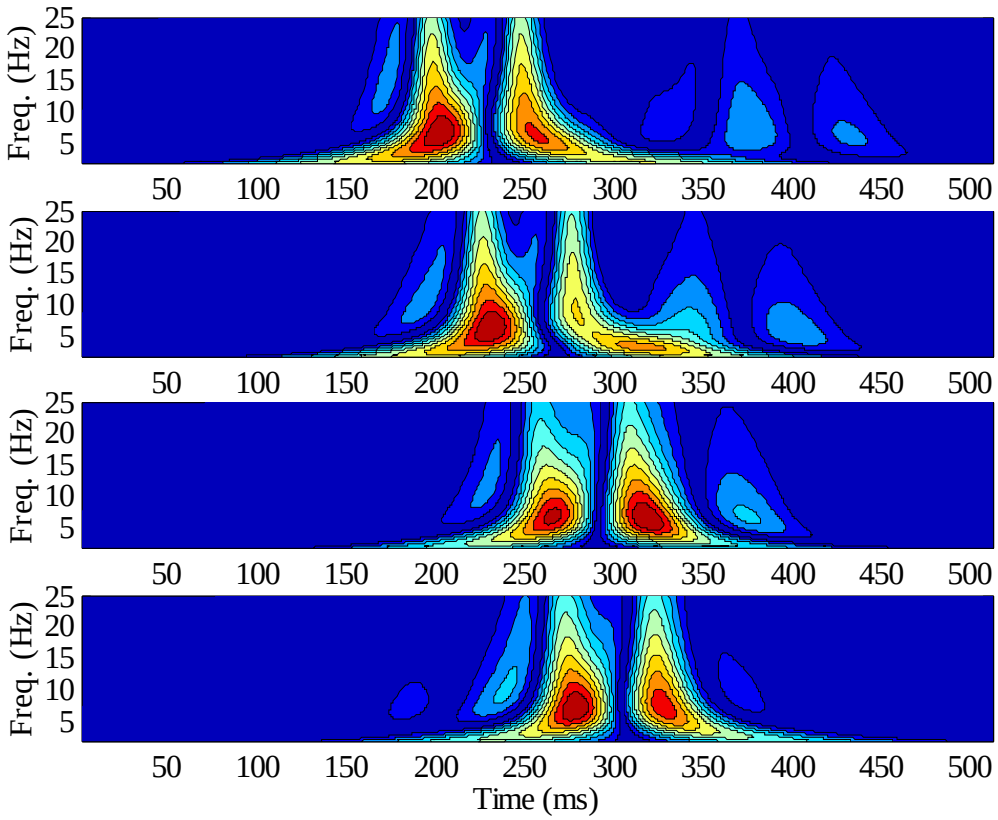


Figure 6- CWT maps for Case 1 at receiver locations 10.6m, 12.3m, 14 m and, 14.8m (top to bottom)

Field Testing

A preliminary test setup was designed to evaluate the applicability of this analysis procedure in the filed. An underground pipe of 40 cm diameter buried at about 15 cm under pavement perpendicular to the travel direction was selected as the detection target. Data collection was carried out using Seismic Pavement Analyzer (SPA) trailer (Nazarain et al.). SPA is a device designed for evaluation of pavement and bridges using seismic techniques. The device is capable of performing an array of seismic tests such is Impact Echo (IE), Impulse Response (IR), Ultrasonic Surface Waves (USW) and Spectral Analysis of Surface Waves (SASW). SPA trailer basically collects time history response of testing media at different offsets from source, which is one low frequency and one high frequency hammer used separately. These time histories along with the described analysis procedure using wavelet transform were used in detection of the underground obstacle (i.e. pipe).

The CWT analysis of the response at 0.3m, 0.6m and, 1.2m from the impact source is shown in Figure 7 (Figure 8 shows the trailer during the testing over the selected pipe). In this particular case, the buried pipe was located between 0.5 and 0.9m from the source at about 15 cm below the pavement surface. Since the receiver at 0.3m is relatively far from the pipe and very close to the source, only the incident waves are observed at this location. However, the reflections from the pipe are clearly visible in the CWT of the receiver at 0.6m. The position and characterization of the reflection peak is in conjunction with the results of the numerical analysis. The receiver at 1.2m is located after the pipe. It is believed that due to the shallow depth of the pipe, most of the energy of the incident wave is reflected. Therefore, this receiver has a much quite CWT.

This preliminary testing confirms the numerical simulation results. However, a much more comprehensive experimental is being carried out to quantify the advantages and limitations of this method in practice.

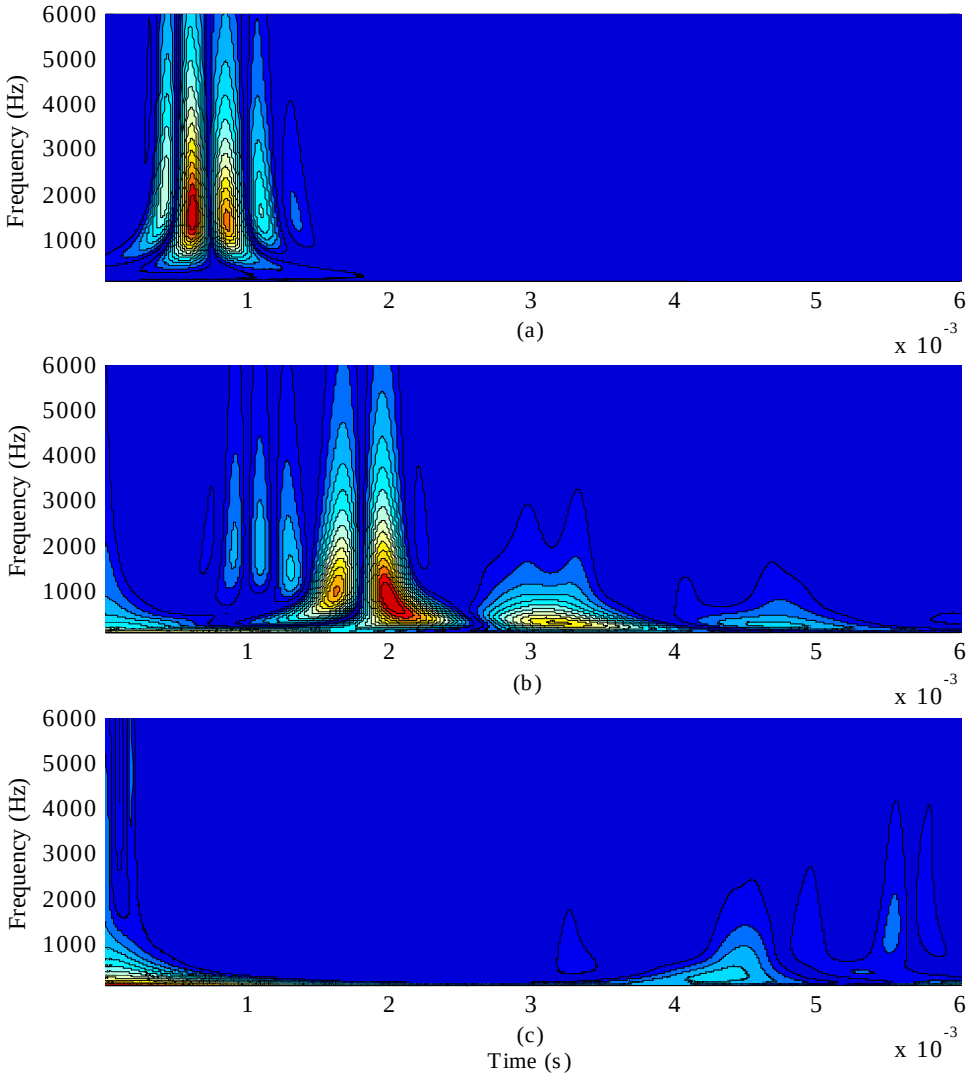


Figure 7- CWT maps for the response at (a) 0.3m, (b) 0.6m and, (c) 1.2m from the source.

Figure 8- SPA trailer during testing

Conclusion

A new technique in detection of underground cavities using wavelet transform of the surface seismic response of the medium is proposed in this study. The technique is verified numerically using extensive finite element analysis. A pilot field-testing was conducted to demonstrate the potential of this technique to be applied in real situations. The test results are promising and confirming the observations in numerical study.

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