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APPLICATION OF WAVELETS IN DETECTION OF CAVITIES UNDER PAVEMENTS BY SURFACE WAVES

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ABSTRACT

A new seismic approach based on wavelet transforms of the surface response is proposed and applied to the problem of detection of shallow cavities under pavements. Seismic wave propagation is simulated by a transient response analysis on an axisymmetric finite element model. Shallow cavities in a homogeneous half-space and a pavement system of a variety of shapes and embedment depths are considered. The formulation of the continuous wavelet transform (CWT) is presented and its advantage over the traditional time or spectral analysis based methods is demonstrated through illustrative examples. The response of the medium at different surface points is presented in the wavelet based time-frequency maps. Waves reflected from the boundaries of a cavity introduce new features of specific time and frequency characteristics in the wavelet time-frequency maps. The characteristics of these features can be used to locate a cavity and estimate its size. As a case history, detection of a cavity/sinkhole under the pavement of a section of expressway I-80 in the northwestern New Jersey is presented.

INTRODUCTION

Nondestructive detection and characterization of underground cavities is an important part of many projects and applications. For example, it may be required to locate a utility conduit before an excavation or to examine pavements for the presence of subsiding sinkholes to prevent pavement collapse. There are many physical and geophysical techniques that are being tested and used for this purpose, such as ground penetrating radar (GPR), gravity gradiometry, magnetic and electromagnetic induction, ultrasonic and seismic methods, and imagery analysis. Each of theses methods has some advantages in specific situations, but also some limitations (Philips et al. 2000). These limitations point to the need for further research and development

The strength of seismic techniques lies in their ability to measure and characterize a medium in terms of its elastic properties, i.e. elastic moduli, stiffness, damping characteristics. Therefore seismic methods for anomaly detection are especially advantageous where there is a significant rigidity contrast between the sought object and the surrounding medium. Presence of a cavity in a medium introduces a discontinuity in rigidity and makes them an ideal target for seismic methods. The methods are based on either travel time or spectral analysis of elastic waves generated by different sources. Refraction and reflection methods are the most widely used travel-time based seismic techniques. The former usually fails to detect shallow cavities in a 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, 1988 ; Belesky and Hardy, 1986).

Application of surface waves in shallow cavity detection became especially attractive with the development of the Spectral Analysis of Surface Waves (SASW) technique. While the SASW method has been primarily used in evaluation of elastic moduli and layer thicknesses of layered systems, such as pavements (Nazarian and Stokoe, 1983), it has shown a good for detection of cavities in several numerical and experimental studies (Al-Shayea *et al*., 1994; Gucunski *et al*, 1996*;* Ganji *et al*., 1997). However, it has been found that the success in anomaly detection in this method, depends on the receiver spacing and location, shear wave velocity, and damping of the surrounding soil medium (Ganji *et al*., 1997).

Surface seismic techniques rely on the analysis of the surface response of a medium to an impact source. When a shallow cavity is present, waves reflected from the near and far faces of the cavity change the near-surface wave patterns. Due to damping, the reflections from cavity faces are of a limited duration. It has been also found that (Shokouhi *et al*., 2003) they have certain frequency bandwidths. In other words, the presence of a cavity influences the frequency content of a limited portion of the response. This fact suggests that a time-frequency analysis of the response could be more efficient than analyzing it in merely one domain.

Wavelet transforms are fairly recent mathematical tools, which can be used to extract both local and global time and frequency information of a signal efficiently. Wavelet transforms were used herein to study simultaneous spatial and spectral changes in the near-surface wave pattern due to a presence of a cavity. Numerical simulations were used to simulate the seismic test performed on a soil medium and a pavement system. Using a wavelet transform, the theoretical response of a medium is transformed into a time-frequency presentation. Studying the features of this time-frequency presentation of the response is the basis for the proposed method for cavity detection and characterization.

There are two major parts in this paper. The first part deals with the fundamentals of the theory of continuous wavelet transform (CWT) and the results of wavelet analysis performed on the numerical results. The second part deals with the field implementation of the method on a section of interstate I-80.

CONTINUOUS WAVELET TRANSFORMS (CWT)

Travel-time based techniques for cavity detection do not take into account changes in the spectrum of the response due to a presence of a cavity. On the other hand, spectral analysis based methods rely only on the changes in the frequency domain. However, using Fourier transforms, the duration of occurrence of the changes in the frequency content can not be identified. Waves reflected from the cavity boundaries influence both the spatial and spectral characteristics of the near-surface wave patterns. Therefore, a time-frequency study of the surface response can be advantageous over analyzing it in merely one domain.

Wavelet transforms are a new class of transformations, which can be used to present the changing spectrum of a nonstationary signal in a time-frequency plane. 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 t is obtained through scaling and translating of the mother wavelet function according to the following equation

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

At finer scales, wavelets are shorter in the time domain, but have a broader frequency bandwidth, and vice versa. This fact implies a reciprocal relationship between the scale and frequency. A wavelet transform is a convolution between a signal $x(\tau)$ and a set of wavelets over a finite range of scales. The continuous wavelet transform (CWT) is defined as,

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

where $W_\psi x_{a,t}$ is the wavelet coefficient at scale a and time t using wavelet function $\psi(\tau)$, and * indicates the complex conjugate. If a signal correlates well with the analyzing wavelet, the wavelet coefficient will be large; otherwise, it will be small. Plotting the wavelet coefficients $W_\psi x_{a,t}$ for a range of scales (scale is a reciprocal function of frequency) and time produces a time-frequency representation of the signal.

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 offset in the frequency domain. Therefore, many different wavelet functions have been developed for different analysis purposes. Among all types of wavelets examined, Gaussian real wavelets have shown to be the most appropriate wavelets for this study.

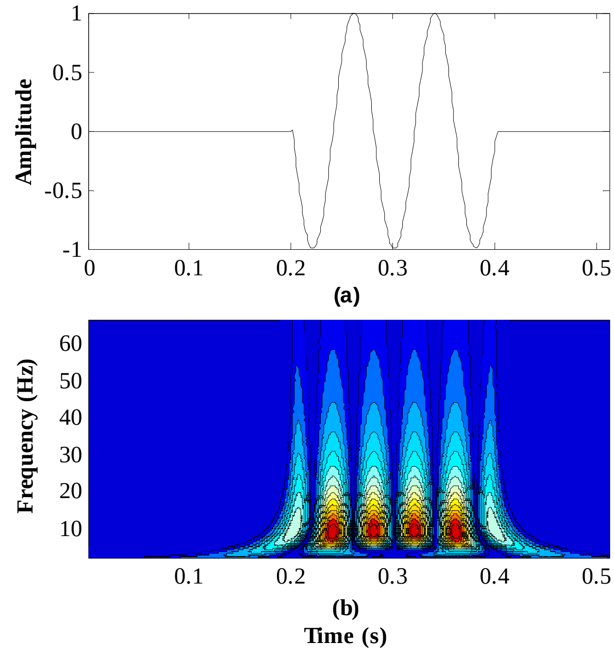


Fig. 1- Illustration of continuous wavelet transform (a) a synthetic signal, (b) Gaussian wavelet time-frequency map.

Wavelet transforms by virtue of their varying bandwidth basis (wavelets) can capture local and global time and frequency characteristics of a signal very efficiently It is useful to illustrate characteristics of the CWT through an analysis of a signal of known time and frequency properties. A synthetic signal is obtained from 512 evenly spaced samples of the function $\sin(25\pi)$. The sine function is windowed using a unit square window of width 0.2s extended from 0.2s to 0.4s, and is shown in Fig. 1(a). The signal is analyzed using Gaussian wavelets and the resulting time-frequency map is presented in Fig. 1(b). As it can be clearly observed, the CWT map provides not only the fundamental frequency of 12.5 Hz, but also the time extent of the occurrence of this frequency component.

FINITE ELEMENT MODEL

A surface seismic test is simulated by a transient analysis of the response of a finite element model. Assuming that the wave propagation occurs in the vertical plane only, the soil medium is modeled as an axisymmetric model with an impact source at its origin. Certain criteria are imposed to ensure that the finite element analysis simulates accurately the surface wave propagation (Ganji *et al*.,1997; Zerwer *et al*.,2002; and, Shokouhi *et al*.,2003). 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. The mesh is very fine between the source and the first receiver location. The element size gradually increases towards the boundaries. The soil is assumed to be linearly elastic with a shear wave velocity of 50 m/s. The impact is described as an impulse of a trapezoidal shape of 1-KN amplitude and 6-ms duration. A time step of 1 ms is chosen for the analysis. The finite element mesh is shown in Fig. 2.

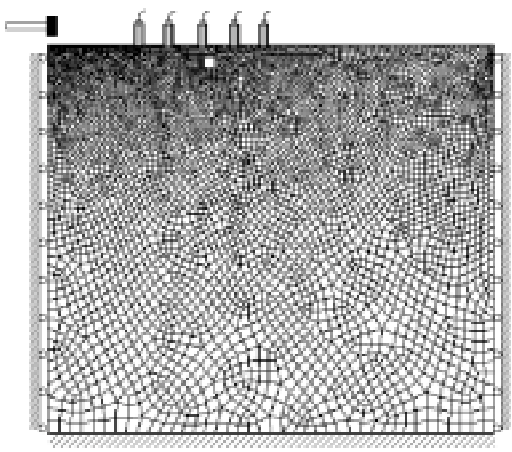
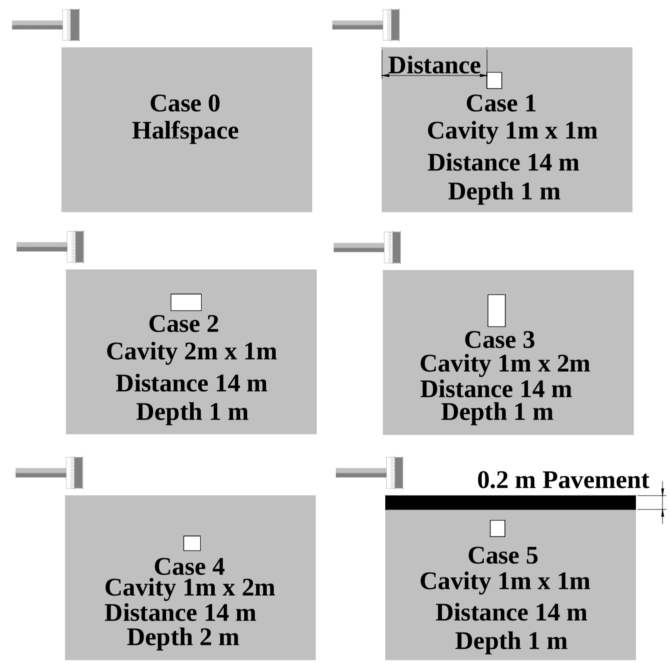


Fig. 2. Finite element mesh.

WAVELET TRANSFORM ANALYSIS OF NUMERICAL RESULTS

To investigate changes in the time-frequency characteristics of the surface response caused by the presence of a cavity, the theoretical response of the medium at different surface points was transformed using Gaussian wavelets. Effects of the width, height, and embedment depth of the cavity were studied by considering cavities of different shapes and depth in a half-space and a pavement system (Fig. 3). The wavelet time-frequency maps of the response at a single receiver location (distance 11.7m from the source) for all the cases are presented in Fig. 4. Peaks I, II and, III in Fig. 4(a) correspond to the arrivals of different components of incident waves, namely, compression, shear and surface waves. Comparing Figs. 4(b)-4(f) to Fig.4(a) clearly demonstrates the influence of the presence of a cavity on the response. Although the peaks of incident wave components (I, II, and III) are still present in these figures, a new sets of peaks (IV, and V) appear in Figs. 4(b) to 4(f). Peak IV in all these three figures marks the arrival of reflected waves from the boundaries of each of the cavities.



Fig, 3. Cavity cases considered in the numerical analysis.

Effect of Width

Since the near face of the cavity in case 2 is at the same distance of 14m, peak IV starts at about the same time in this figure. However, the time bandwidth of the reflection peak is increased. The wider the cavity, the larger is the time delay between the arrivals of reflected waves from near and far sides of the cavity. When the cavity is wide enough, the reflection peak will have two separate “hats”; each marking the arrival of the wave packet from one of the faces of the cavity. The two separate hats can be noticed for case 2 in Fig. 4(c). On the other hand, as the width of the cavity increases, the frequency of the reflection peaks decreases. Therefore, wider cavities cause two well-separated reflection hats of a lower frequency. Knowing the surface wave velocity of the medium, the time difference between these two hats (or equally the time bandwidth of the reflection peak) can be used easily to estimate the width of the cavity. Peak V marks the end of the transient response and does not have any physical significance.

Effect of Height

To study effects of the height of the cavity on wavelet time-frequency maps, the surface response at receiver location 11.7 m for Case 3 is analyzed and presented in Fig. 4(d). Other than the three incident wave peaks (I, II and, III), two other peaks (IV, and V) are also present in this figure. Peak IV correspond to the arrival of reflected waves from the cavity faces. Since, the width

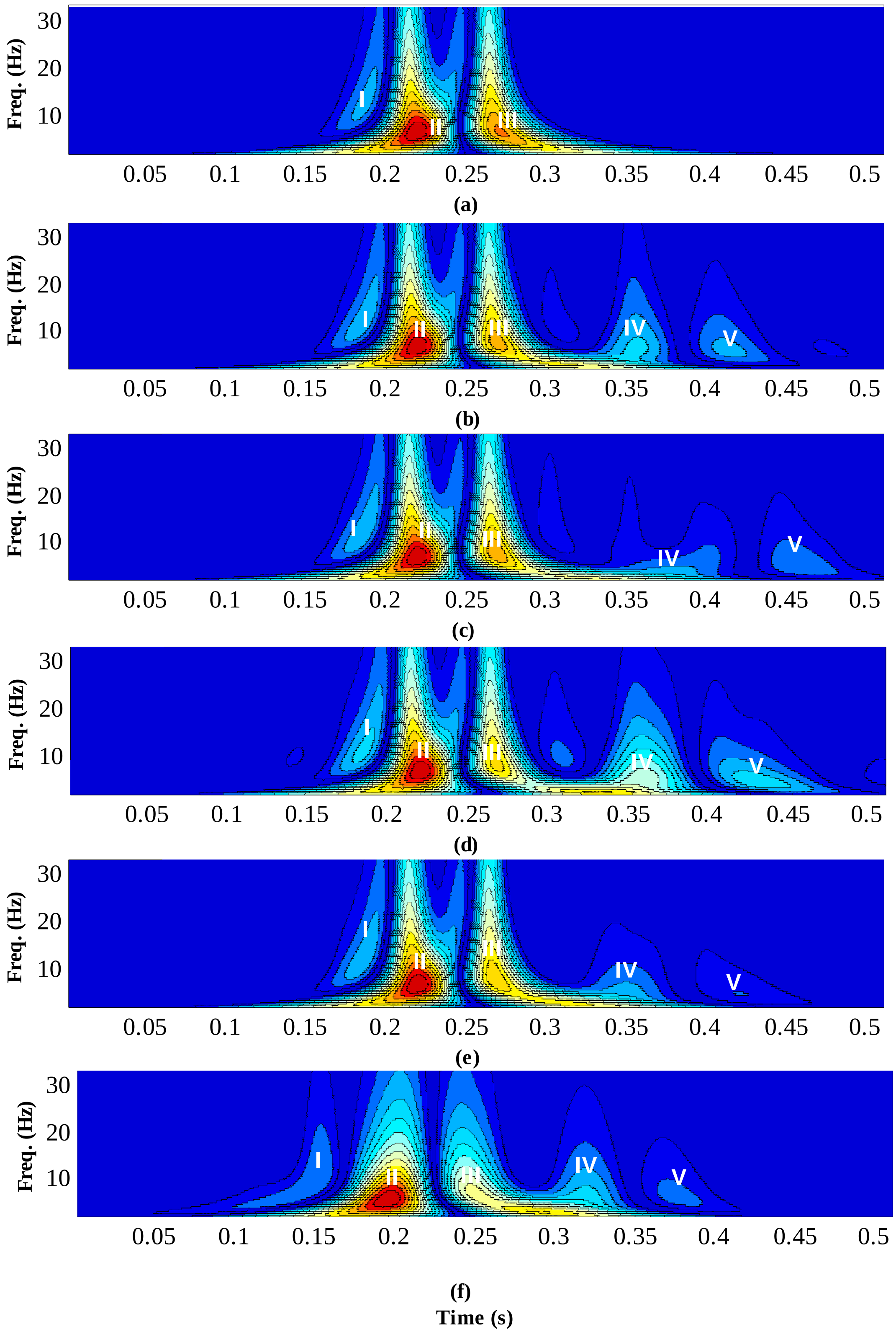


Fig. 4 Guassian wavelet time frequency map at 11.7 m for (a) case 0, (b) case 1, (c) case 2, (d) case 3, (e) case 4 and (f) case 5

of the cavity is the same as that of Case 1, the waves reflected from the near and far faces of the cavity are not well-separated, but form a single peak. However, the reflection peak in this figure is of a considerably higher energy. It can be concluded that increasing the height of the cavity results in reflection peaks of a broad frequency bandwidth and a higher energy level. However, the fundamental frequency of the reflections does not show a noticeable change.

Effect of Embedment Depth

To study the effect of the embedment depth of the cavity on the wavelet transform maps, the response for Case 4 at distance of 11.7 m is analyzed and presented in Fig. 4(e). As expected, the reflection peak for a deeper cavity is of a much lower energy level. Consequently, it was found that a cavity of an embedment depth larger than its height is hard to detect by this method.

Cavity Under a Paving Layer

In Case 5, the cavity is present under a 20 cm thick paving layer of a shear wave velocity of 250 m/s (five times the shear wave velocity of the soil). The response at a distance of 11.7 m is analyzed and presented in Fig. 4(f). Despite the high velocity layer on the top, the reflections from the cavity boundaries (peak IV) can still be clearly observed. The other characteristic of the reflection peak, such as the time width and peak frequency are the same as those for 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.

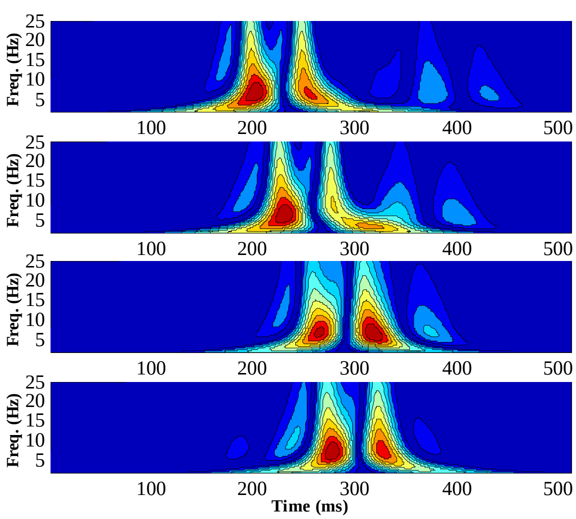


Fig. 5. Gaussian wavelet transform for case 1 at receiver locations 10.6, 12.3, 13 and 14,8 m (top to bottom).

Wavelet Maps at Different Receiver Locations

The results presented in Fig. 4 were for the analysis of the surface response for different cases for a single receiver location (11.7m). Wavelet time-frequency maps for Case 1 and at different receiver locations in front of the cavity (10.6m, 12.3m, 14m and, 14.8m) are presented in Fig. 6. As it can be 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 the receiver location 14m. Therefore, having the surface response at different points, the cavity can be located as being near receiver locations where the reflection peaks vanish. Afterwards, 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 Fig. 5. 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 will be hard to detect. In general, increasing the depth will result in reflection peaks of lower energy and narrower frequency bandwidths.

CASE HISTORY: INTERSTATE I-80 TESTING

The proposed technique was implemented in an effort to detect a cavity/sinkhole under the pavement on a section of expressway I-

80 in northwestern New Jersey. The suspicion about the sinkhole presence was triggered by the observed excessive settlements of the embankment under the shoulder. The surface waves for obstacle detection technique (SWOD) was deployed to investigate the presence of the cavity. The test setup is shown in Fig. 7. The test was conducted using a pair of geophones 0.5 m apart. A 10 kg sledgehammer, placed 3m away from the near geophone, was used as the impact source. The SWOD technique utilizes the phenomenon of fluctuations in the dispersion curve in the detection of buried objects (Gucunski *et al.*, 1996;Ganji *et al.*, 1997). The results of SWOD pointed to a possible presence of the cavity at the location of the observed embankment depression, but also of another one at about 8m point (Gucunski *et al.*, 2000). The same set of recorded data was used herein to evaluate the potential of the newly proposed method as an alternative approach for cavity detection.

Fig. 6. Testing on I-80 (from Gucunski et al.*, 2000)*

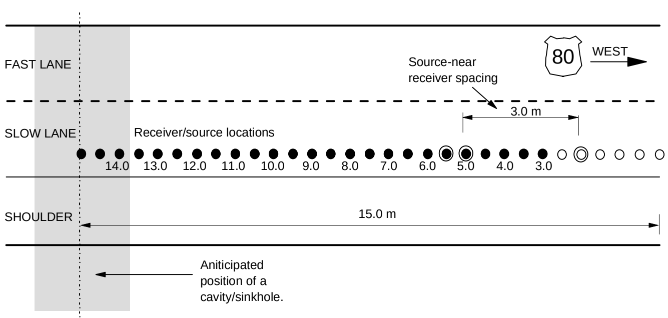


Fig. 7. Schematic of the test setup on I-80 (from Gucunski et al.,*2000)*

FIELD IMPLEMENTATION RESULTS

The recorded surface response in the near geophone at every point is transformed using Gaussian wavelets. The resulting wavelet time-frequency maps at near receiver locations of 3m to 14m are presented in Figs 8 and 9. Peaks I and II in all figures mark the incident wave arrivals. Peak III is a result of the interaction of incident and reflected waves. The reflections are a part of peak III at all receiver locations from 5m to 10m, but vanish in the subsequent locations. Furthermore, the frequency of peak III increases as the reflections disappear, indicating that reflections have a considerably lower fundamental frequency. Considering the setup of the problem, this observation points to a probable existence of a sinkhole or loosened soil lenses under the pavement at about 10m, the anticipated cavity position. This observation confirms the findings of the implementation of the SWOD technique (Gucunski *et al.*, 2000). Since the test setup is different from what was considered in the numerical model, the discussions on the size estimation and characterization as it was described in the proposed scheme cannot be applied to this set of data.

CONCLUSIONS

Application of the continuous wavelet transform (CWT) for detection and characterization of underground shallow was investigated. Results of the conducted numerical studies were utilized to develop a proposed cavity detection scheme. The method was implemented in the field and shows potential for detection of cavities and other anomalies in layered systems, such as soils and pavements.

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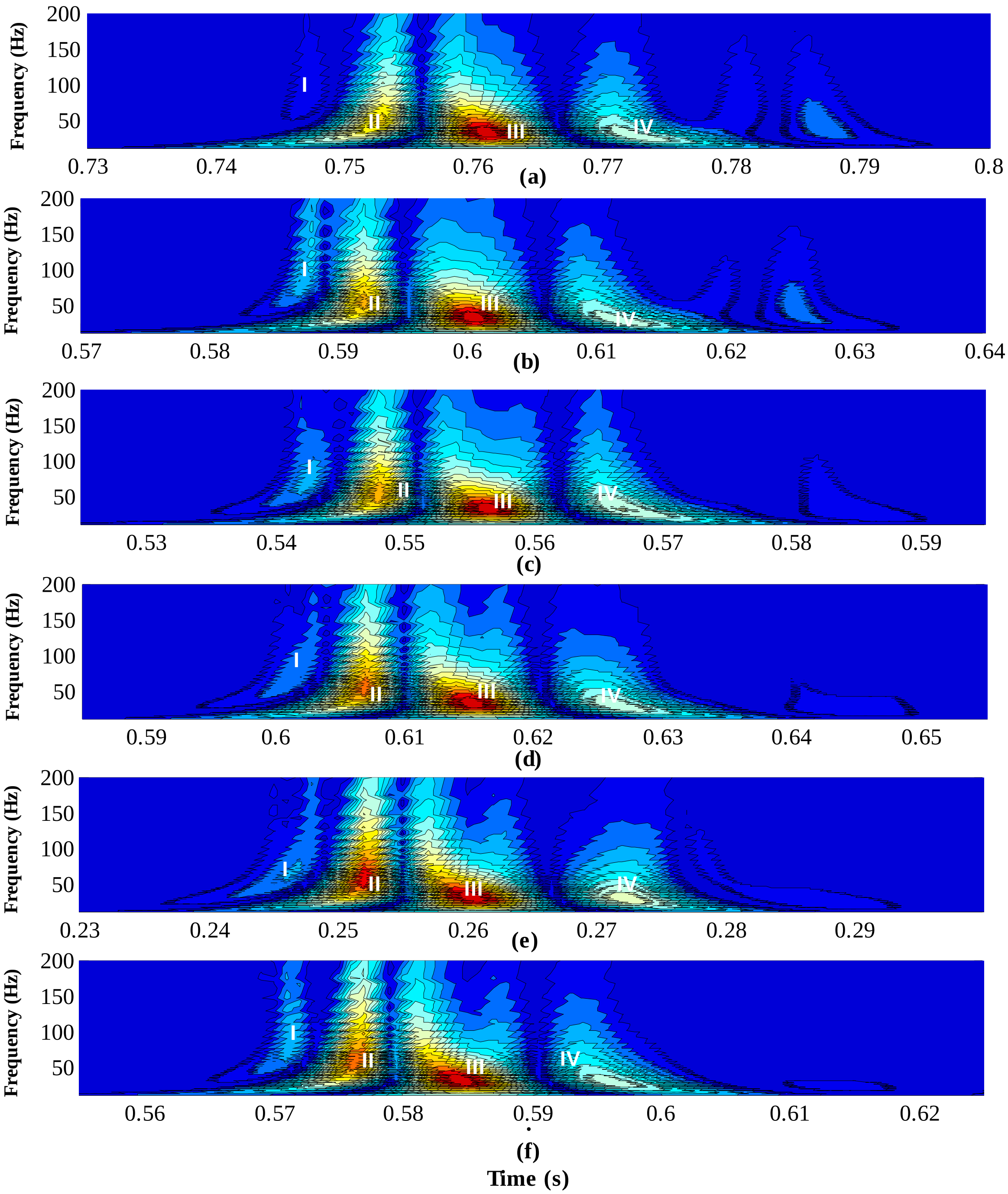

Fig. 8. Gausian wavelet time frequency maps for near receiver location at (a) 3 m, (b) 4 m, (c) 5 m, (d) 6 m, (e) 7 m, and (f) 8.

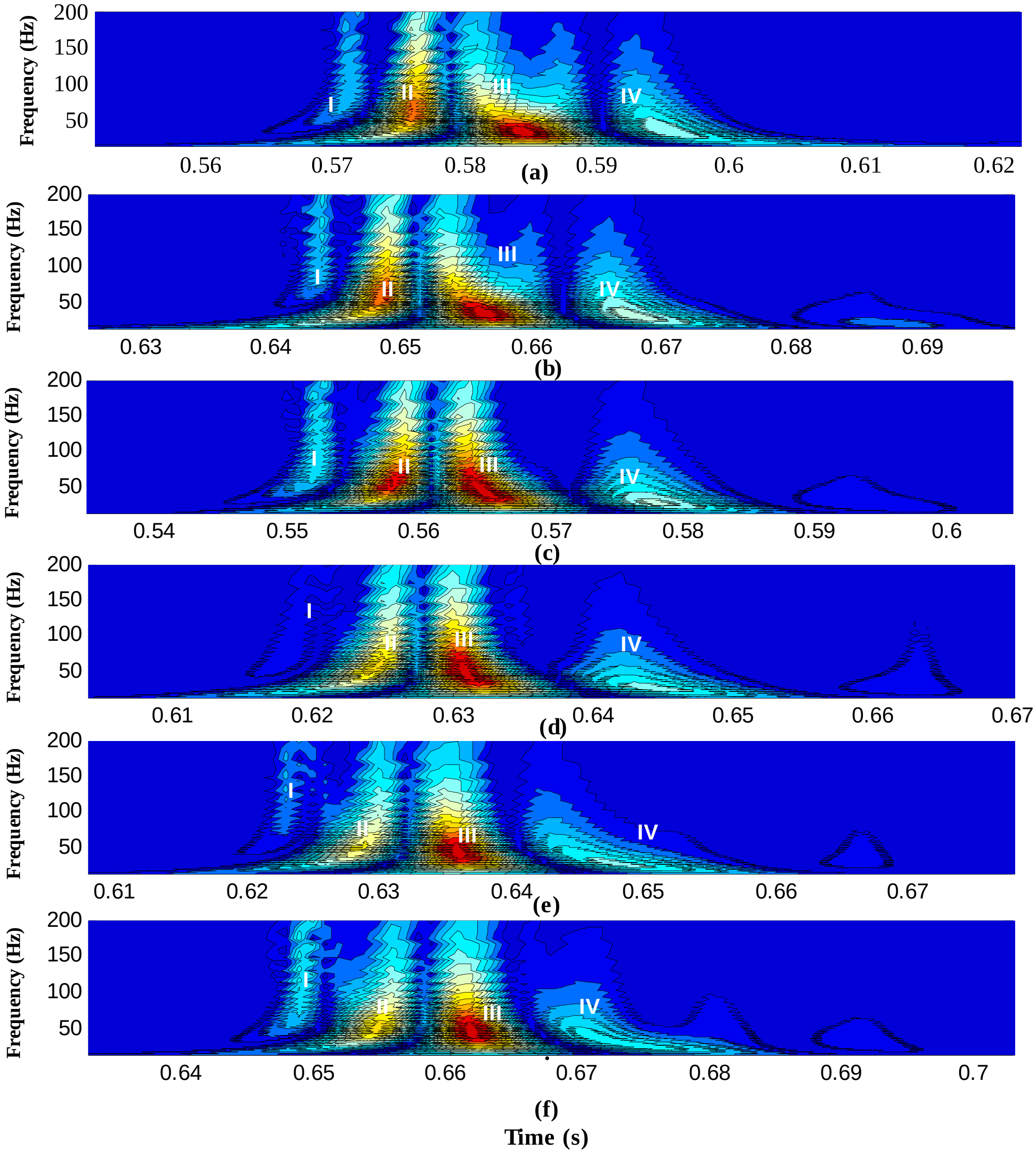

Fig. 9. Gausian wavelet time frequency maps for near receiver location at (a) 9 m, (b) 10 m, (c) 11 m, (d) 12 m, (e) 13 m, and (f) 14.