Smart detection of limestone cavities in dense urban cities

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ABSTRACT: Undetected cavities pose a great threat to underground construction in the limestone formations. In dense urban areas, additional challenges exist, such as fast and unnoisy field operations. Here we reported a new method to extract the characteristic energy of scattered and reflected signals for detection of limestone cavities. Comparing to the traditional seismic methods, this method does not require the seismic inversion and can thus achieve nearly real-time detection. The scattered and reflected signals are used to derive an anomaly score based on a signal processing framework, including multi-scale division and selection as well as enhanced low-rank feature extraction, to quantify possible locations of limestone cavities. We conducted a cavity detection test and demonstrated accurate detection of the horizontal location of a limestone cavity, but the accuracy of vertical location relies on the P-wave velocities of geologic layers.

Keywords: Seismic imaging, limestone cavities, urban environment, field validation.

1 INTRODUCTION

Limestone cavities are formed due to acidic groundwater dissolving carbonate minerals and grow to sizes ranging from millimeters to kilometers over hundreds of years. The existence of undetected cavities is a major threat to underground construction in the limestone formations, particularly disrupting ground traffic and underground utility in dense urban cities. The detection of limestone cavities in the dense urban areas also requires convenient field operation and timely data analysis to minimize the disturbance of urban environment as well as high detection resolution at a depth of 10-60 m where most of the underground facilities are located.

Numerous non-destructive methods have been developed to detect subsurface structures, such as seismic reflection survey, surface wave survey, and ground penetrating radar. Seismic reflection survey is suitable to map deep structures and may be difficult to obtain the details of shallow structures using low-frequency and long-wavelength seismic waves (Feroci et al., 2000). Also, the use of explosive materials may be prohibited in urban cities. Surface wave survey can be more sensitive to ambient noise and available space to place geophone streamers in urban areas (Sechwenk et al., 2016). Ground penetrating radar detects electromagnetic pulses reflected from shallow underground and scans subsurface features with high resolution at a few meters below the ground surface, but the high-frequency and short-wavelength pulses can be greatly attenuated beyond the depth, especially under high water content conditions (Leucci, 2008).

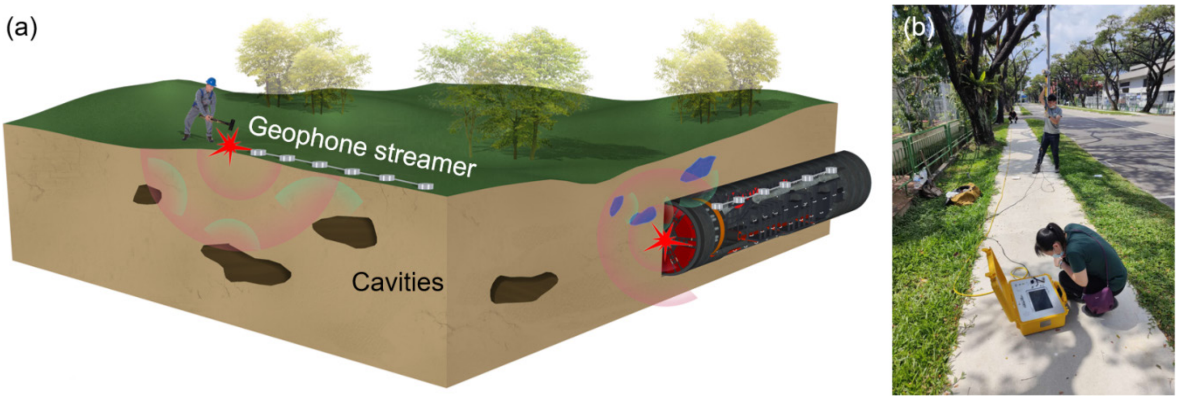

Figure 1. (a) Detection of underground cavities and future application on TBM and (b) cavity detection test setup, including data logger, land streamer, and hammering impact.

To overcome the limitations of the current non-destructive methods, we developed a new method to extract the characteristic energy of scattered and reflected signals for detection of limestone cavities (Figure 1a). We considered seismic wave propagating through heterogeneous media with cavities and exhibiting strong wave scattering, and these cavities can be considered as new wave sources (Shapiro & Kneib, 1993; Tahemura & Yoshimoto, 2014). In this case, the possible existence of limestone cavities can be quantified using an anomaly score derived from the scattered and reflected signals. A larger anomaly score indicates a higher possibility of limestone cavities. We also performed a field test to verify the accuracy of this method to assess the horizontal and vertical locations of a known cavity according to the borehole data.

2 METHOD

The test setup of cavity detection, as shown in Figure 1b, is similar to the seismic reflection survey, using a hammer impact as a seismic source and a land streamer to receive seismic signals. A three-dimensional dataset, including time, offset, and source number, is recorded during the test. The signal processing framework includes multi-scale division and selection and enhanced low-rank feature extraction.

For the multi-scale division and selection, the average frequency spectrum of each 2D record is calculated to obtain the general frequency range of effective signals (Figure 2a). A scale window corresponding to a fixed frequency range then moves along the average frequency spectrum at a regular interval. The goal of multi-scale division and selection is to find the optimal scale on which the largest difference exists. After obtaining the optimal scale, a band-pass filter with corresponding cut-off frequencies is applied to collect the seismic data to realize the scale extraction.

After the multi-scale division and selection, less noise exists in each 2D record. The correlated events from the selected scale are extracted using a low-rank approximation method (Ding et al., 2008; Rousset et al., 2018). Before running the low-rank extraction, an auto-correlation operation is conducted for each record to enhance the low-rank characteristics. The effective signals in the 2D record can be presented as the form of horizontal correlated events in the extracted low-rank component.

Finally, an anomaly score (S_i) for a seismic record is calculated using the p-norm of final extracted low-rank components by:

$$S_i = \frac{\| \mathbf{L}_i \|_p^p}{\sum_{i=1}^{N} \| \mathbf{L}_i \|_p^p}, \tag{1}$$

where $\|\cdot\|_p$ denotes the p-norm, $\mathbf{L}_i$ represents the extracted low-rank component with an index i, i is the source number, and N is the total number of sources. The anomaly score S_i is between 0 and 1. A larger value indicates a higher possibility of encountering cavities.

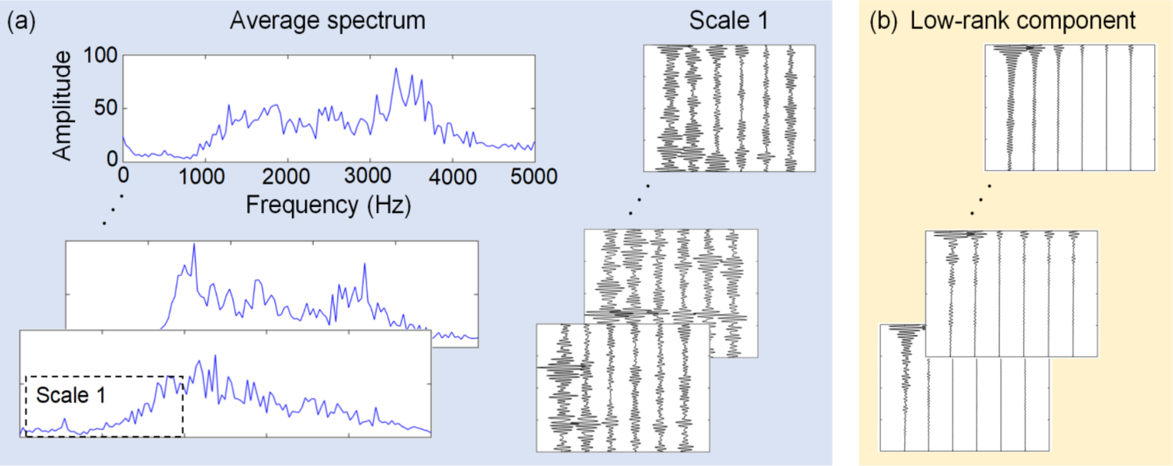

Figure 2. Signal processing framework, including (a) multi-scale division and selection and (b) enhanced low-rank feature extraction.

3 RESULTS AND DISCUSSION

We conducted a cavity detection test on a concrete pavement in the Tuas industrial area, which is situated on the Jurong sedimentary formations in southwest Singapore. A vertical borehole was drilled next to the pavement, showing a limestone formation with a hollow section at a depth of 21-35 m covered by a layer of sandy silt with a thickness of 15 m (Figure 3a). We thus chose this area to verify the proposed method.

During the test (Figure 1b), a land streamer with 32 geophones and 0.5 m spacing was placed on the pavement. A steel hammer with a weight of 9 kg was used to impact a polyethylene plate as the seismic source. The impact event was started next to one end of the land streamer initially located 3 m away from one side of the borehole. After each impact event, both the hammering point and the land streamer were shifted by 0.5 m towards the borehole and subsequently across the borehole until located 3 m away from the opposite side of the borehole. Totally 13 impact events were performed, and the collected signals were processed by the proposed method.

The test results demonstrate that the anomaly scores in the horizontal direction are given in 13 scale windows, each corresponding to a source number. The anomaly score at the source number 7 is notably higher than those at the other source numbers (Figure 3b). The horizontal location of the source number 7 coincides with the location of the borehole (Figure 3c), verifying accurate detection of the horizontal location of a limestone cavity using this method.

In the vertical direction, the anomaly scores are given in 5 scale windows over a travel duration of 0.15 s. The use of travel time as the vertical axis is because the P-wave velocity is not constant over these geologic layers. Figure 3b presents the anomaly scores with high values over a travel time ranging from 0.03 to 0.12 s, which cover a larger depth range than the vertical range of hollow section along the borehole. If the P-wave velocities of different geologic layers are derived from the collected signals, the vertical location of the cavity can be accurately determined, which is the next step for the development of the method.

The horizontal resolution of this method is associated with the interval of source points. The vertical resolution is related to the number and size of scale windows used in the data analysis and can be improved by an increasing number of scale windows. However, a larger number of scale windows corresponding to a smaller time duration may affect the geometry of effective signals. A reasonable balance between the number and size of scale windows should be considered to include a relatively complete geometry in a scale window.

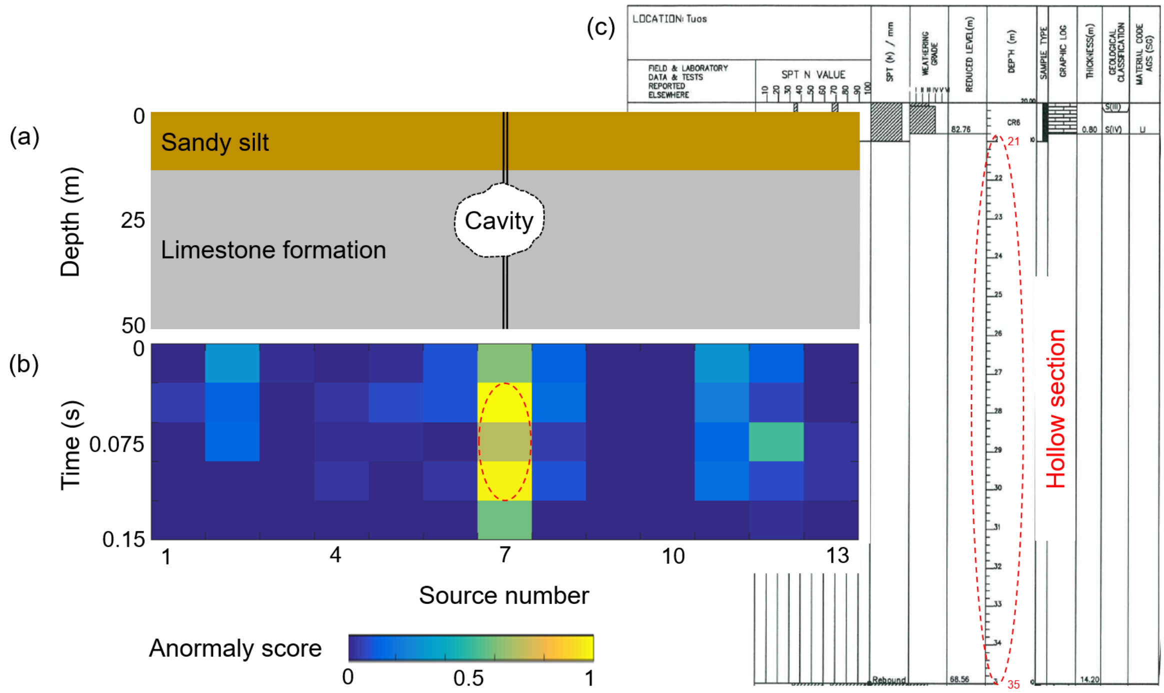

Figure 3. Cavity detection test results, (a) schematic diagram of a sedimentary formation with a vertical borehole and a limestone cavity, (b) anomaly score as functions of travel time and source number, and (3) borehole data showing a hollow section at a depth of 21-35 m.

4 CONCLUSIONS

This study reports a new method for fast and efficient detection of limestone cavities based on changes in characteristic energy of scattered and reflected signals. Limestone cavities are detected based on the anomaly score, which is proportional to the characteristic energy of effective signals. Unlike the traditional seismic methods (e.g., seismic reflection survey and ground penetrating radar), this method does not require time-consuming inversion and can directly diagnose limestone cavities from the features of collected data, making it more efficient for scanning over a large-scale area. A cavity detection test shows that accurate detection of the horizontal location of a limestone cavity, but the accuracy of vertical location relies on the P-wave velocities of different geologic layers. Given the achievement of nearly real-time detection, this method is possibly applied during bored tunneling (Figure 1a) to provide early warning of the initiation and development of cavities above and in front of tunnel boring machine and sinkholes on the ground surface.

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