Basic study for propagation characteristics of elastic wave around subsurface cavities

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ABSTRACT

This study examines the detection of subsurface cavities using seismic wave propagation. Both vertical and horizontal excitation methods were employed to measure the reflection characteristics of artificially constructed cavities in a test field. The study was conducted at the Le Petau golf course in the town of Abira, Hokkaido, Japan. In this study, a new horizontal excitation technique was introduced along with conventional vertical excitation to compare its effectiveness in identifying wave reflections caused by cavities. An artificial cavity was created using rubber balloons reinforced with cardboard to simulate subsurface anomalies. The measurement used 24 geophones connected to an automatic data logger, and the acquired data underwent extensive analysis with bandpass filtering, amplitude normalization, and deconvolution to elucidate the interaction between the elastic waves and the subsurface structures. The results showed that horizontal excitation provided a clearer view of the cavity due to reflected waves. This is because only SH waves are excited and observed in the horizontal excitation mode. However, this study also recognized that it is difficult to distinguish the boundary between direct and reflected waves at shallow cavity depths, suggesting the need for excitation methods capable of generating shorter wavelengths to improve resolution. This study highlights the potential of integrating vertical and horizontal excitation methods in seismic surveys to enhance subsurface cavity exploration, and highlights future research issues, such as improving waveform analysis techniques and searching for alternative excitation sources, to advance the field of subsurface exploration.

Keywords: subsurface cavity, seismic, s-wave

1. Introduction

In recent years, ground cave-in accidents have been occurring frequently, especially in urban areas, causing significant social damage, including the destruction of road surfaces.

In many cases, the cause of ground cave-in is a subsurface cavity. The cavity expands and rises to near the ground surface as a result of the collapse of the ceiling, causing ground surface collapse. One of the most cited causes of cavity formation due to subterranean soil runoff is the release of sediment from broken sections of old buried pipes, etc. (Sato et al. 2015)

Ground penetrating radar is mainly used for cavity exploration in areas shallower than 1.5 m below ground level. Ground penetrating radar can detect cavities in the shallow ground with relatively high accuracy. The presence of significant cavities are identified in practice near the ground surface just below the road surface before settlement. On the other hand, when cavities are located at depths beyond the reach of radar (approximately 1.5 m below the ground surface), exploration methods are limited to geophysical surveys such as penetration tests. There are no established non-destructive exploration method for the cavity detections.

Seismic surveys are sometimes discussed as a geophysical exploration technique to investigate cavities deep subsurface. These techniques detect reflected waves from heterogeneous regions such as cavities in the ground by capturing them with receivers placed on the ground surface. Analysis of surface wave dispersion curves in multichannel has also been studied for detection of subsurface cavities, and there are several references that study the effect of subsurface cavities on surface wave dispersion curves (Rahnema et al. 2022, Mohamed et al. 2022). In addition, identifying natural frequencies using microtremor arrays and determining peak frequencies of standing waves have also been devised to search for cavities (Okada. 2006, Kolesnikov et al 2018, Kristekova et al 2021).

Seismic reflection surveys utilise seismic waves reflected at the geologic interface. It can be used to detect subsurface cavities because cavities cause dramatic acoustic impedance gaps in the ground (Cook 1965: Guy et al. 2003; and Engelsfeld et al. 2008.). Zhang found that unifying offsets is an effective way to suppress reflected wave losses and improve the ability to extract and magnify scattered waves (Zhang et al, 2021). A focal point in seismic survey methods that detect reflected waves is whether to use vertical or horizontal seismic sources. Since horizontal excitation excites only horizontal shear waves (SH waves), it is expected to have higher resolution and simpler theory due to its shorter wavelength than vertical excitation, which excites P and S waves (SV waves in this case).

The reflection characteristics of SH waves generated at the surface of a cavity are well known (Smerzini. et al 2009). In recent few years, our laboratory has been investigating the possibility of using SH waves as a method of seismic survey of cavities in the ground. Numerical analyses using DEM simulations in granular materials, considering the excitation method, have also suggested that SH waves perpendicular to the measurement plane are effective for cavity exploration (Nakata et al 2019, Karasaki et al 2022). However, few tests have yet been conducted on actual ground, and there was a lack of empirical evidence for detecting elastic wave propagation around cavities, especially reflected waves, depending on the direction of excitation of the elastic wave survey.

In this study, two types of excitation methods, vertical and horizontal excitation, were employed to measure the reflection characteristics of cavities in the ground, and seismic surveys were conducted at test sites where artificial cavities were constructed. For horizontal excitation, an artificial excitation method was developed to investigate the change in seismic wave propagation with and without the cavity.

2. The site and models

2.1. Test site

The test was a 40 m square field constructed on a site within the Le Petau Golf Course in the town of Abira, Hokkaido, Japan (Fig. 1). It is known that the field was artificially filled with sandy soil. The field is located far from the city area, and there is almost no influence of traffic vibrations from cars and other vehicles with respect to measurements. The surface ground covered with grass, and the influence of noise from the surrounding environment is lower than typical environment.

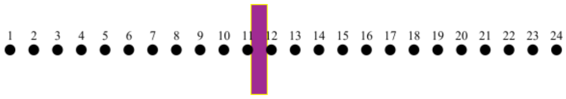
2.2. Test models

In the field test, 2 model case lines were prepared (Fig. 1): a case in which a disturbed layer was placed in the middle of the line, and a case which an artificial cavity was placed whose size was 0.9m high, 0.5m wide, under 1.3m below from the surface. An overview of the test and the direction of excitation is shown in Fig. 2. The depth of excavation by heavy machinery was limited to about 2.4 m. The two cases are shown in the Fig. 2.

The way to place artificial cavity in the test field is as follows: the test field was excavated to 2.4 m deep, the cavity was placed at the bottom, the trench was backfilled,

Figure. 1 The test site: Le Petau Golf Course in the town of Abira, Hokkaido, Japan.

a) Sensor place



b) Cross

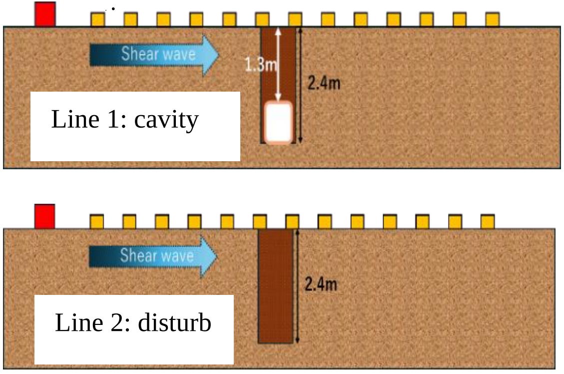


Figure. 2 (a) Sensor place (disturbance zone/ artificial cavity was located at purple area) and (b)Model Cases of the field test.

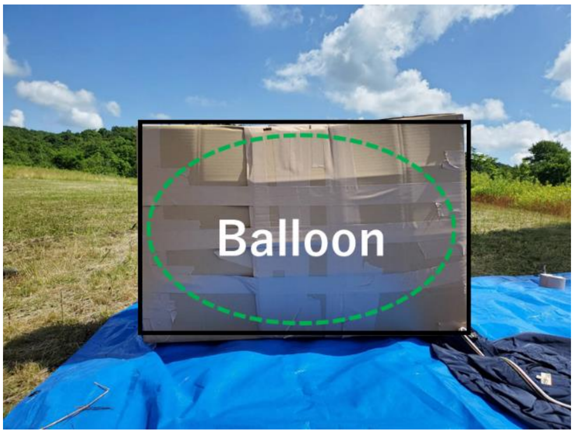


Figure. 3 The artificial cavity. The balloon is filled with air and the surrounding area is protected with reinforced cardboard.

and the surface was compacted. For artificial cavity, rubber balloons packed with reinforced cardboard were used (Fig. 3).

The purpose of this experiment was to compare changes in the observed locations of seismic wave propagation with and without cavities in the ground, as well as the direction of excitation in which changes are more likely to be observed. In addition to the conventional method of vertical excitation, the test case of horizontal excitation direction was conducted (SH wave propagation) as shown in Fig. 4.

Preliminary tests of elastic wave propagation were conducted on undisturbed original ground to observe the wave velocity and to ensure that the signal frequency was within an appropriately measurable range. The main frequency of the exciter was in a frequency range between 30 and 80 Hz, and the velocity of the elastic wave (S-wave) propagation was approximately 190~220 m/s, using two-dimensional Fourier analysis in the time and space domains (Fig. 5).

In horizontal excitation case, a device capable of exciting in the horizontal direction was developed and introduced (Fig. 6). A rectangular wooden board 20 cm wide, 20 cm high, and 50 cm long, with metal spikes placed on the ground connection surface for better engagement with the ground. The vibration method used was to strike the end face of the board horizontally with a hammer to generate horizontal excitatory waves. The source device was carefully tested prior to the experiment to ensure that the signal frequency within an appropriately measurable range.

3. Data acquisition and analysis

3.1. Data acquisition

For the measurement, 24 geophones capable of measuring the three components of the xyz axis were used. The natural frequency of the geophones was 4.5 Hz, connected to a Geoseis data logger. The exciter's hammer had a trigger to detect acceleration changes, starting the measurement automatically upon striking. The source was placed 1 m from the first geophone, with each geophone spaced 1 m apart, making the model sideline length 23 m.

3.2. Analysis

For waveform analysis, a 10Hz-100Hz bandpass filter was first applied to the traces measured at a sampling frequency of 10 kHz to remove noise. Amplitude normalization was then applied to the traces to correct for time and offset energy decay.

In the artificial excitation of the elastic wave, the conditions were aligned as much as possible to minimize the variation in the excitation waveform. However, there were still variations from one data set to another. To make the reflected waves clear, a deconvolution process was applied in the frequency domain using the excitation pulse of each data as a wavelet operator. In addition, the estimated arrival time was calculated from the estimated elastic wave velocity and distance, and waveforms prior to the calculated arrival time were removed.

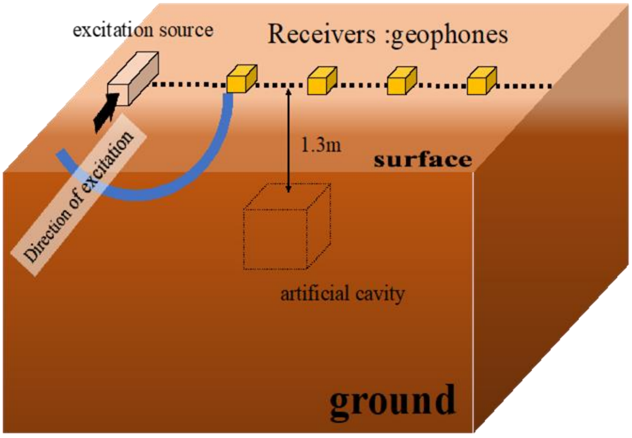


Figure. 4 Excitation direction of the SH wave propagation test.

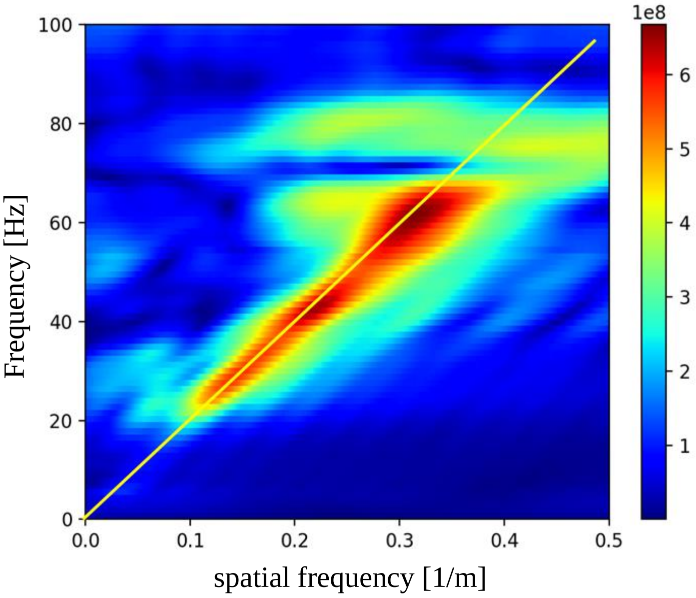


Figure. 5 SH wave velocity by 2-dimensional Fourier transformation. Yellow line is estimated SH wave velocity, 190m/s

Figure. 6 Right: Artificial Vibration Exciters for SH Waves
Left: Vibration excitation. Right: Structure of the exciter. A spike attached to a piece of wood is placed on the ground.

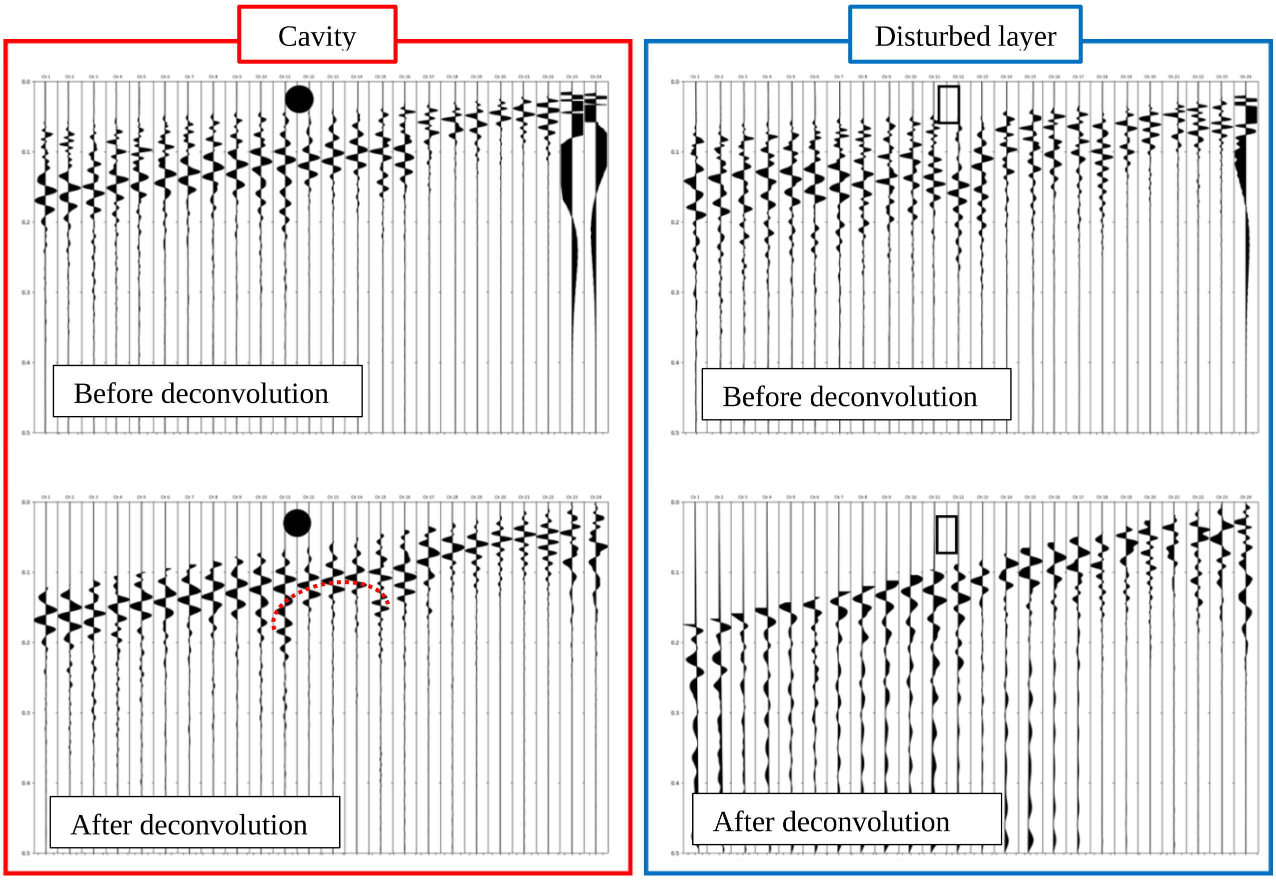


Figure. 7 Raw trace data from vertical excitation and deconvolution processed data. The black circles in the left panel indicate the location of population cavities, and the rectangular area in the right panel indicates the location of the disturbed layer.

4. Result

4.1. Waveform analysis

The results of the exploration oscillated in a direction perpendicular to the ground surface (P-SV wave), are shown in Fig. 7, for the case with artificial cavities and disturbed layers and for the case with disturbed layers only disturbed layers and for the case with disturbed layers only.

Waveform processing by deconvolution makes it easier to see wave propagation. In particular, the propagation of P-waves and S-waves can be seen. Focusing on the direct arrival of the S-wave, the arrival of the s-wave was delayed in the presence of cavities and disturbed layers. This phenomenon appeared as if it

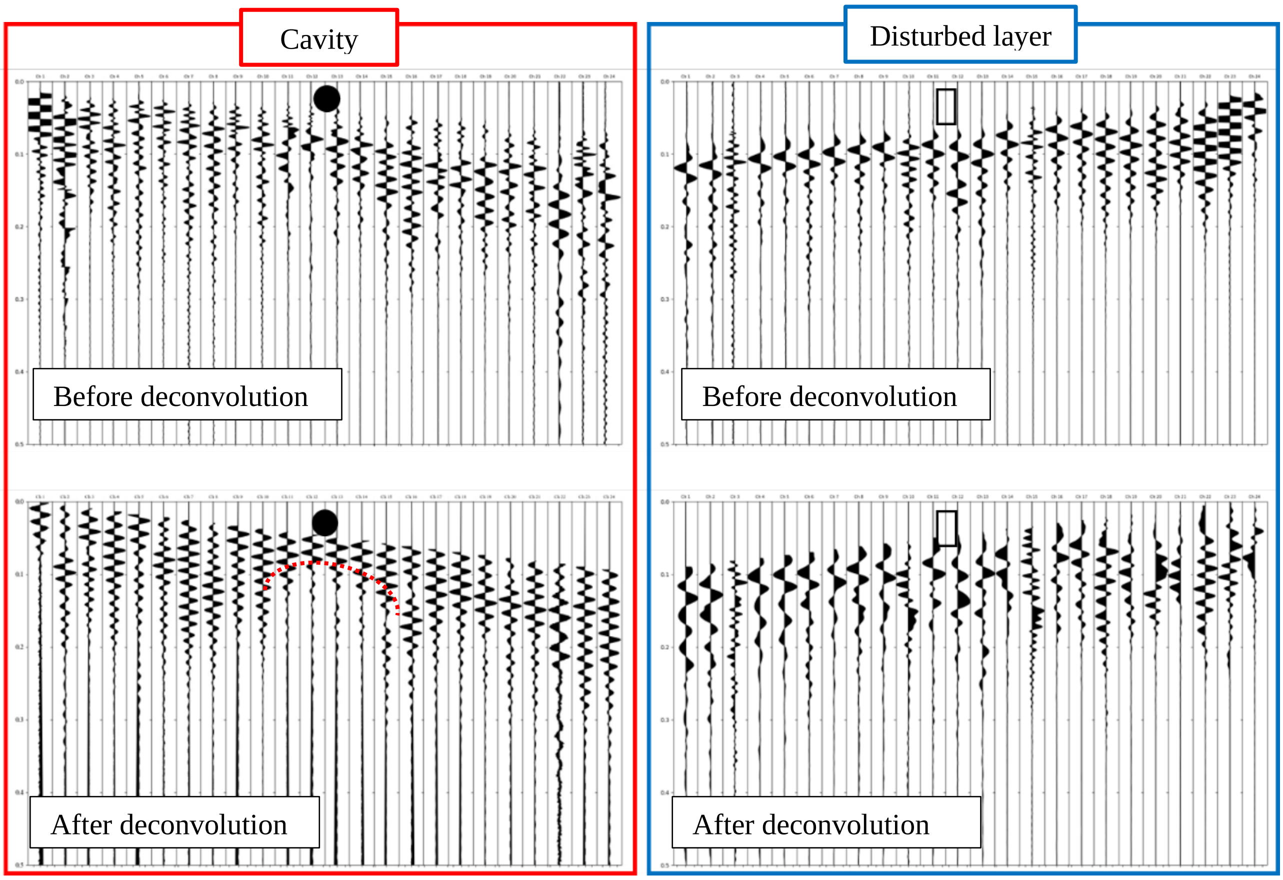


Figure. 8 Raw trace data from horizontal excitation and deconvolution processed data. The black circles in the left panel indicate the location of population cavities, and the rectangular area in the right panel indicates the location of the disturbed layer.

overlaps with the P-wave that arrives immediately before the S-wave, so after waveform processing by deconvolution, the P-wave is not visible due to the coordination of the P-wave. Phase shifts were observed outside the near-offset region, and areas of localized vibration remained around the cavity. However, compared to the case of propagation by horizontal excitation described below, the observation of residual vibration around the cavity was ambiguous.

The results of the waveform analysis of the horizontal oscillation case are shown in the Fig. 8. The results of the experiment conducted with horizontal excitation were compared between the case with only a disturbance layer and the case with a cavity in the disturbance layer.

In the case of the disturbed layer, the vibration is observed to remain at the disturbed layer. This is thought that the disturbance reduces the stiffness of the soil, resulting in a layer where the propagation velocity of elastic waves is reduced. In the presence of the low-wave velocity layer, the elastic waves that penetrate into the interior repeatedly undergo total reflection within the low velocity layer, and in some cases the vibration is amplified due to the effect of natural frequencies, and the vibration is often observed for a long time.

On the other hand, in the case of the internal cavity, the vibration just above the cavity decayed relatively quickly even though it was in the disturbed layer. In contrast, in some cases, the vibrations around the cavity remained for a long period of time and were considered to be reflected waves from the cavity. These reflected waves were observed for both P-SV and SH waves, but in the former case, P-SV waves, as well as Rayleigh waves, were confused, whereas in horizontal excitation, theoretically, SH waves and accompanying Love waves are mainly observed, so the observation is considered to be clearer.

The main frequencies of the excitatory waves were 30Hz~70Hz, with wavelengths ranging from λ = 2.85~6.67m. In contrast, the cavity depth was 1.3m, and the wavenumber was 0.20~0.46, which is less than 1.0 This depth was shallow enough to obscure the boundary plane between direct and reflected waves from the viewpoint of resolution, making separation difficult. This implies that shorter-than-constant wave excitation is necessary to capture reflected waves from subsurface cavities.

5. Conclusion

This study was initiated to provide an empirical study of seismic wave propagation around an subsurface cavity. The experiment was conducted in a test field at the Le Petau golf course in the town of Abira, Hokkaido, Japan. An artificial cavity was constructed in the test field to compare the changes in seismic wave propagation with and without the cavity in the ground, as well as with vertical or horizontal excitation. A novel aspect of this study is that both vertical and horizontal excitation methods were applied to generate the elastic waves, allowing for a comparative analysis of the effectiveness in detecting wave reflections due to the cavities. Rubber balloons filled with reinforced cardboard to withstand the burial process were used to create the artificial cavities. New equipment for horizontal excitation was also installed to observe changes in seismic wave propagation in the presence of the cavities. Twenty-four geophones were used for data collection, connected to a data logger designed to automatically initiate measurements when waves were generated. The captured data were subjected to bandpass filtering, amplitude normalization, and deconvolution to clarify the reflected wave signals and gain insight into the interaction between elastic waves and subsurface structures.

As a result, important findings were obtained. In particular, the presence of cavities was more clearly indicated by horizontal excitation through the observation of reflected waves. This is due to the peculiar behavior of SH waves under horizontal excitation, which seems to make the detection of cavities more obvious compared to vertical excitation. However, this study also highlighted the challenge of resolving the boundary plane between direct and reflected waves at shallow cavity depths, highlighting the need for excitation methods that can generate higher frequencies and shorter wavelengths to improve detection accuracy. Waveform analysis techniques such as CMP polymerization and NMO correction, as well as noise processing, are also issues for this study. In addition to solving these issues, vibrators and other exciters will be reconsidered, and methods such as microtremor arrays and full-waveform inversion will be used to establish a method for cavity exploration.

In conclusion, this study provided an advance in understanding elastic wave propagation around subsurface cavities, but also highlighted the need for further research. Future work includes improving excitation techniques to increase detection capabilities, investigating a wider range of cavity sizes and depths, and extending the study to different soil types. This endeavor will not only contribute to the fields of geophysics and civil engineering but will also lead to a more sophisticated approach to subsurface exploration and monitoring.

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