Investigation on Elastic Wave Propagation Characteristics in Small Scale Model Ground with a Cavity

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ABSTRACT: Ground sinkholes in urban areas pose a significant risk, necessitating technology for early cavity detection. This study aims to establish an effective in-tunnel exploration method using SH-waves. A two-step experimental investigation was conducted. Step 1 (Small-Scale Model Test): A laboratory-scale model test under simplified conditions confirmed the basic principle that SH-waves are reflected from a cavity's surface. Step 2 (Large-Scale Test): A large-scale field experiment was conducted, simulating a concrete tunnel structure over sandy silt ground with two embedded polystyrene foam cavities (one large, one small). The results from the large-scale test varied by source location; reflections were recorded from the larger cavity when sourced nearby, while diffracted waves from the large cavity were observed when sourcing over the small cavity. These combined results suggest the effectiveness of using in-tunnel SH-wave surveys, highlighting the utility of both reflected and diffracted waves.

1 INTRODUCTION

Ground sinkholes, often caused by tunnel construction or aging infrastructure, pose a significant risk to urban life. The 2020 ground subsidence accident in Chofu, Tokyo, highlighted that even deep-seated cavities (approx. 40m deep) can trigger failures. Detecting such deep cavities from the surface is difficult in complex urban areas. This necessitates exploration methods deployed from within the tunnel structure itself. While Ground Penetrating Radar (GPR) is a conventional method, its detection depth is shallow (typically <1.5m) and it is less effective below the groundwater level. In such cases seismic surveys offer a promising alternative.

Karasaki (2022) demonstrated the effectiveness of utilizing reflected waves from cavities using surface sources through DEM simulations. However, the propagation mechanisms of elastic waves associated with deep cavities, particularly their relationship with the tunnel structure itself, remain to be fully clarified. Therefore, this study aims to establish an early detection method for cavities near tunnels using in-tunnel surveys.

2 METHODOLOGY

2.1 Step 1: Small-Scale Model Test

The first step confirmed the basic reflection principle under simplified conditions (i.e., a uniform medium). The experiment was conducted in a soil tank (L 0.93m, D 0.53m, H 0.40m) made of steel and acrylic plates. A uniform model ground (silica No.6) was prepared. Tests were conducted for two cases: a homogeneous ground without a cavity and a ground with a cavity. In the latter case, a rectangular polystyrene foam (10cm x 10cm x 44cm) was embedded as a simulated cavity at a depth of 10cm. The cavity was oriented with its longitudinal axis perpendicular to the survey line. Measurements were conducted along the centerline of the tank. The SH-waves source was located 2 cm from the end of the survey line, generated by horizontally striking a metal plate partially embedded in the surface with a linear solenoid. For seismic wave reception , 12 accelerometers were aligned on the surface at 4 cm intervals along the survey line.

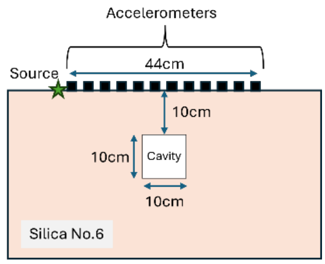

Figure 1. The dimensions of model tests (Cross-sectional view)

2.2 Step 2: Large-Scale Model Test

Based on Step 1, this phase evaluated the method's applicability in a realistic setting. A large-scale test field (6m L x 14.5m W x 2.5m D) was prepared using sandy silt mixed with gravel. Two polystyrene foam blocks (Cavity A: 2.0x2.0x1.0m (Large); Cavity B:

1.0x1.0x0.5m (Small)) were embedded. A simulated tunnel structure (0.3m concrete layer, 0.2m grout layer) was constructed on the surface. The survey was conducted on the concrete surface along a survey line. The source signal was generated by horizontally striking rebar embedded within the concrete to produce predominantly SH-waves. Reception was performed using a total of 66 horizontal geophones installed at 0.15 m intervals along the line.

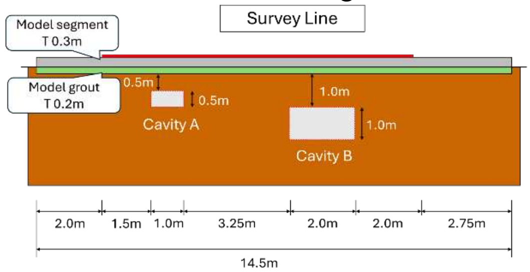

Figure 2. The dimensions of large-scale model tests (Cross-sectional view)

3 RESULTS AND DISCUSSION

3.1 Small-Scale Model Test (Step 1)

Figure 3 shows the seismic shot records in each accelerometers. In the conditon with cavity, it was observed that other waves propagated from the cavity toward the source after the direct waves. This is considered to be the reflected wave from the cavity arriving with a delay. This result confirmed the effectiveness of the polystyrene foam as a reflector.

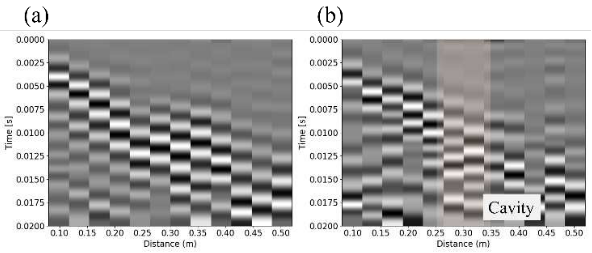

Figure 3. Shot records of small-scale model test: (a) homogeneous ground, (b) ground with a cavity

3.2 Large-Scale Model Test (Step 2)

Figure 4 illustrates representative seismic shot records (Step 2) with theoretical travel times (red lines).

(a) Source over Cavity A; (b) Source over Cavity B. The theoretical travel times (hyperbolas) of the first-arriving reflected and diffracted waves were calculated based on the S-wave velocity estimated from the results and are plotted as red lines in the figures. When the source was activated directly above the large cavity (Cavity A), the first arrival of the reflected wave was difficult to identify as it overlapped with the direct wave. However, reflected waves, presumed to have been generated due to the low damping of the source wave, were observed in the subsequent phase (Fig. 4a).

In contrast, when sourcing above the small cavity (Cavity B), corresponding reflections were not identified. This result indicates that the size of Cavity B (1.0 m) was insufficient relative to the wavelength, demonstrating that cavity dimensions influence detectability. However, for the diffracted wave originating from the edge of the large cavity (Cavity A), its first arrival was observed at a position consistent with the calculated travel time (Fig. 4b).

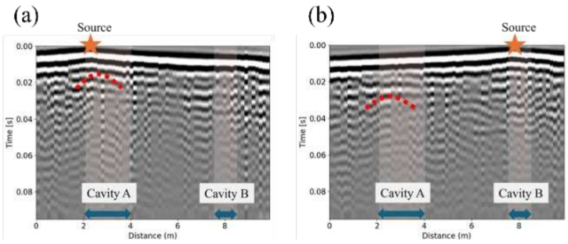

Figure 4. Shot records of large-scale-model test: (a) Source over Cavity A, (b) Source over Cavity B

4 CONCLUSIONS

This study validated the effectiveness of in-tunnel SH-wave exploration through a two-step approach. The small-scale (laboratory) test first confirmed under simplified conditions that SH-waves are reflected by a cavity. The large-scale (field) test then demonstrated that large cavities (Cavity A) can be detected by reflected waves when sourced nearby. Furthermore, diffracted waves from the edges of large cavities were also observed, aiding in identification. These findings suggest that in-tunnel SH-wave surveys are effective for detecting cavities, particularly larger ones, and that both reflected and diffracted waves provide crucial information.

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