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Experimental study on cavity formation and collapse in fine-grained soils triggered by sewer damage

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ABSTRACT: In January 2025, a tragic road collapse occurred in Yashio City, Saitama Prefecture, caused by soil outflow due to damaged sewer infrastructure. Such incidents, often associated with aging structures, pose serious risks to urban safety. Ground subsidence generally begins with the formation of an underground cavity that propagates upward, eventually leading to collapse when the loosened zone reaches the ground surface. Therefore, understanding the initiation and expansion of cavities is essential for effective prevention.Previous studies have mainly examined collapse behavior in sandy soils through model experiments, whereas research on fine-grained soils remains limited. The soil at the Yashio site was characterized by a high fine particle content. In sandy ground, collapse hazards can be evaluated based on cavity width and overburden thickness. To clarify the mechanism behind the Yashio event, model experiments simulating cavity formation and ground subsidence were conducted using soil with a high fine particle content. Soil outflow was triggered through a slit representing sewer pipe damage, and the processes of cavity initiation, expansion, and collapse were observed. The results indicate that collapse behavior in fine-grained soil differs from that in sandy soil, and hazard assessment cannot rely solely on cavity width and overburden thickness. These findings contribute to improving infrastructure maintenance and disaster prevention strategies.

1 INTRODUCTION

Last January, a tragic large-scale sinkhole accident occurred in Yashio City, Saitama, resulting in the loss of a precious life. Given the critical nature of this issue, identifying the causes of this incident and developing preventative measures is an urgent priority.

Ground subsidence typically proceeds from the formation of an underground cavity (often due to damaged sewer pipes or tunnelling), its upward enlargement, and final collapse when the loosened zone reaches the ground surface. Therefore, understanding the mechanism of cavity formation—the early stage of collapse—is essential.

Previous research has predominantly utilized sandy soil, where the collapse hazard of cavities is generally evaluated based on their width and overburden thickness (depth) (Ohara and Kuwano, 2021). However, the Yashio site soil contains a high proportion of fine particles, suggesting that these conventional collapse risk assessments may not be directly applicable. Consequently, this study aims to clarify the mechanism of cavity formation and expansion specifically for fine-grained ground.

2 METHODOLOGY

Model soils simulating the field conditions in Yashio were used in the experiments. The particle size distributions of the field soil and the model soil (fine content, FC = 40%) are shown in Figure 1. The model soil was prepared by mixing Silica sand No. 6, 7, and 8 with non-plastic silt to achieve a fine content ratio of 40%, corresponding to the field soil.

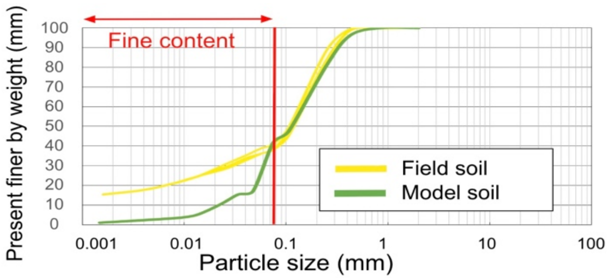

Figure 1. Particle size distributions of the field soil and the model soil

The dry density of the model ground was adjusted to 1.337 g/cm³, matching the reported field condition at the Yashio site. The initial water content was controlled to achieve a degree of saturation of approximately 10%, ensuring consistent and reproducible initial conditions.

The experimental apparatus is schematically illustrated in Figure 2. The model ground (H = 25 cm) was constructed within an acrylic container, and a slit located at the bottom of the container was opened to simulate soil outflow caused by sewer pipe damage. Upon opening the slit, soil near the opening was gradually drawn out, leading to the formation of an initial cavity. Subsequently, repeated cycles of water drainage and supply were conducted to observe cavity expansion and eventual ground collapse (subsidence). Three distinct groundwater levels (GWLs) were established at 20 cm, 15 cm, and 10 cm. The water levels in the external tank and the side tank were maintained at the same elevation to provide stable groundwater conditions during the tests.

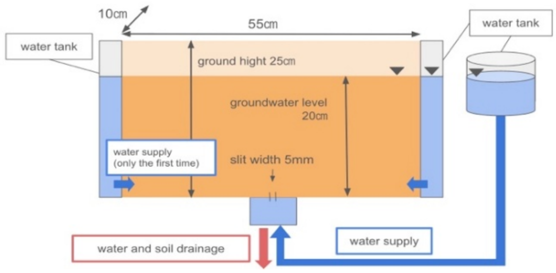

Figure 2. Schematic illustration of the soil tank

3 RESULTS AND DISCUSSION

Figures 2 and 3 illustrate the cavity development and collapse process in the fine-grained soil under different GWLs, with Figure 2 also presenting comparative results for sandy soil (Ohara and Kuwano, 2021). In these figures, the progression of time is shown sequentially from the top to the bottom photograph in each set.

Figure 3. Comparison of cavity collapse process. (Left: Sandy soil; Right: Fine-grained soil, GWL = 20 cm)

A chimney-shaped initial cavity formed in both soil types upon opening the slit. However, subsequent water cycles revealed contrasting processes (Figure. 2). The high permeability of sandy soil resulted in significant horizontal expansion, whereas the low permeability of fine-grained soil led to enlargement primarily via localized collapse of the cavity surface. Consequently, the fine-grained soil failed with a smaller cavity width than the sandy soil.

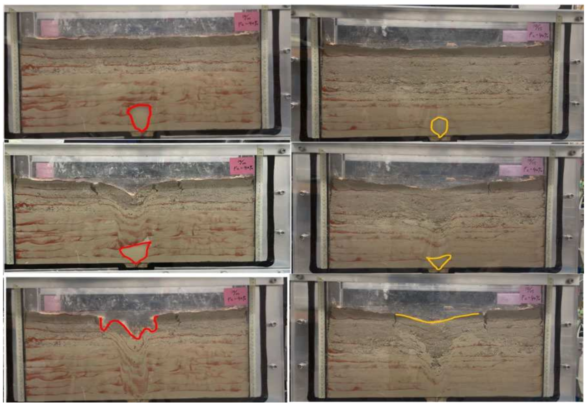

Figure 4. Progression of cavity collapse under lower groundwater levels. (Left: GWL = 15 cm; Right: GWL = 10 cm)

The initial cavity's crown generally formed at the GWL (Figure. 3). A higher GWL promoted a larger initial cavity, and the mass of discharged soil and the collapse scale tended to increase with GWL. Crucially, a comparison of the terminal cavity shapes immediately prior to collapse revealed that while the cavity width was nearly identical across all GWL conditions, the depth of cavity occurrence was smaller at higher GWLs. This indicates that the conventional hazard assessment method used for sandy ground—relying solely on cavity width and overburden thickness—is insufficient for fine-grained ground, implying that the groundwater level significantly influences collapse occurrence.

4 CONCLUSION

Model tests confirmed that the collapse process in fine-grained soil is distinct from that in sandy soil, being characterized by limited horizontal expansion and increased collapse scale with a higher groundwater level (GWL). Consequently, the conventional hazard assessment method based solely on cavity width and overburden thickness is insufficient for fine-grained ground. Future work will investigate key parameters and establish a new methodology for evaluating collapse hazard in fine-grained ground.

REFERENCES

Ohara, Y.& Kuwano R.(2021). Mechanism of Underground Cavity Formation and Enlargement, and Evaluation of Collapse Hazard (in Japanese). Japanese Geotechnical Journal, Vol. 16, No. 3, pp. 307–319. https://doi.org/10.3208/jgs.16.307