A study on the potential size of subsurface cavities in sandy soil

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ABSTRACT

An old deteriorated sewer pipe, when it is damaged, may eventually cause local subside or a cave-in in the road. Recently, the number of pipes which are older than the service life time of 50 years, has been rapidly increasing. Accordingly, incidents of a road cave-in are found to be more frequent in urban areas. In spite of the significance, full investigation of the road cave-in is often skipped as the urgent road restoration is usually priotised. It is difficult to clearly identify the real cause by the fact that eventual cave-in is likely to occur long after the initial formation of a cavity in soil. In this study, considering the underground situation in urban area, the typical process of cavity formation/expansion in sand was evaluated and the potential size of cavity was roughly quantified.

Keywords: subsurface cavity; model test; ground cave-in; soil arching

1 INTRODUCTION

Local subsidence, sinkholes or cave-in's of the ground often occur in urban roads. The complicated under-ground situation as well as the necessity of urgent restoration do not usually allow full investigation of the real cause. The detailed mechanism and process of the phenomenon has not been, therefore, well understood. A cave-in is usually initiated by the formation of a cavity in the ground. Then it is possible that the hidden cavity expands to eventually cause apparently sudden collapse.

Kuwano et al. (2006) conducted a survey to obtain basic information on how the damaged sewer pipes were related to the collapses of road, which occurred from 2001 to 2003. The survey was performed by sending questionnaires and interviewing local government officers in seven cities where the sewerage system had started more than 30 years ago and the management and maintenance of old sewer pipes are likely to be the concerned issues. It was found that even small gaps or cracks could lead to road cave-in and the rainfall appears to be one of the most important factors. Based on the survey results, Mukunoki et al. (2009) and Kuwano et al. (2010a, 2010b) performed a series of model tests to investigate how a cavity initially forms in soil and how it progresses up to the ground surface.

In this study, the typical process of cavity formation/expansion in sand and the potential size of cavity was evaluated. The risk of surface collapse was also roughly assessed.

2 APPARATUS AND TEST PROCEDURE

2.1 Apparatus

A test apparatus used in this study is schematically shown in Figure 1. Model ground of 300 mm wide, 80 mm long and 200 mm high was made in a small soil chamber having an opening of 5 mm in a base plate. Water was supplied to the model ground from a water tank connected to sides or bottom of the ground. Water level in the model ground was controlled by the height of the water tank. Soil flowed out of the opening with water. Pore water pressure transducers were placed at the bottom of both sides to monitor ground water level. Surface ground settlements were measured using non-contact displacement transducers.

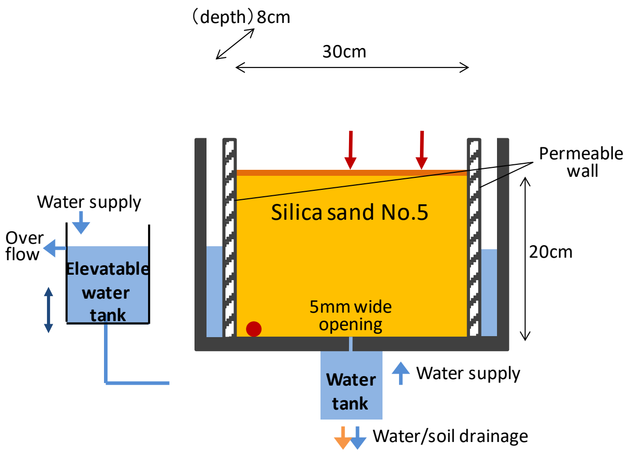

Fig. 1. Schematic figure of test apparatus.

2.2 Tested materials and model ground

Uniform silica sand having mean grain size of 0.4 mm was mainly used for the model ground. The maximum and minimum void ratios were 1.04 and 0.66 respectively. Dry sand was gently placed by a scoop in the soil chamber and colored sand layer was put in front at intervals of 2.5 cm. Relative density of the model ground was about 50% ($\rho_d \fallingdotseq 1.4$ g/cm^3).

2.3 Test procedure and test case

After setting up of the model ground, water was supplied. Two conditions were considered for the flow of water; i) water flows in and out of the base opening, ii) water was supplied through side walls and drained out of the opening. Considering the real situation, when the soil outlet exists above the ground water level the condition can be the former and when the soil outlet is below the ground water level, it is similar to the latter condition.

Non-woven cloth was put in the opening as a plug to prevent soil grains from flowing out in the preparation stage. When the water level was stabilized in the model ground, the plug was removed to start testing. Deformation of the ground was observed, with the measurement of surface displacement, amount of drained water and soil. Water was supplied/drained several times from the bottom opening for Test B. Tests were continued until the surface collapsed for Test A, B, D and F, while the penetration resistance was measured above the cavity formed in the Test C. Test cases are presented in Table 1.

Table 1. Test condition.

Test case	Initial water level	Water supply/drain cycle	Surface collapse	Penetration test
A	200 mm	-	yes	-
B	100 mm	4 times	yes	-
C	100 mm	-	-	done
D	100 mm	-	yes	-
E*	150 mm	-	-	-
F*	150 mm	-	yes	-

* tests with a model ground of 500 mm wide, 100 mm long and 300 mm high with 15mm opening at the base

3 CAVITY FORMATION IN THE GROUND

3.1 Soil loss below the ground water level

Deformation of the ground for Test A is presented in Figure 2. As soon as the plug was taken out, soil started to flow out of the opening. Deformation of the soil immediately spread to the above without forming a clear cavity and reached the surface. Area of significant deformation was limited to a band of approximately 5 cm. Almost all the soil of deformed area flowed out in a short period to form a hole.

3.2 Cavity formation in/under unsaturated layer

Surface settlements, ground water levels and amount of drained water and soil for Test B are shown in Figure 3 with some photos in Figure 4. Water was supplied from bottom and initially ground water level was set to 100mm from the bottom. As soon as the plug was taken out, water quickly drained and soil below the ground water level was dragged down with water/soil drainage. A cavity of about 5cm wide emerged at height of 10cm as a result. A surface settlement of about 1 mm was observed at the center. After the 1st soil/water drainage was completed, the 2nd cycle of water supply started. Water penetrated into the cavity. Inside the cavity, soil under the water slid down towards the center along the slope formed in both sides. Angle of the slope was 37° and seemed to approach to the angle of repose of the material. The width of the cavity of fan-like shape became larger and when it became about 10cm, the soil above lost the stability. Then during 3rd and 4th water supply/drain cycle, the deformation of the ground expanded to the ground surface. Finally, a hole of 15cm wide appeared.

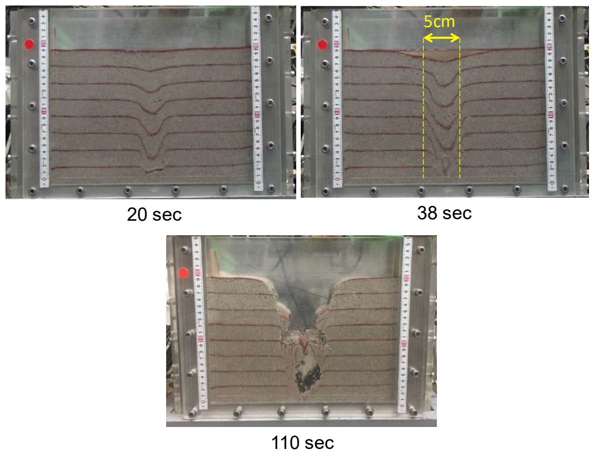

Fig. 2. Deformation of the ground in Test A.

3.3 Penetration resistance of soil above the cavity

Water was supplied from both sides and ground water level at side was kept at 100 mm in Test C. Ground deformation and cavity formation was observed as shown in Figure 5. Similar behavior to the 1st cycle of Test B was observed in Test C. A cavity of 4.5 cm wide was formed within 40 seconds below the initial ground water level. Although the water was continuously supplied from both sides, it drained from the opening at the center without seeping into the cavity. The cavity was never filled with water and the water level at the center was zero. The cavity was not expanded and soil was not drained any more.

Penetration resistance was measured at three locations as shown in Figure 6, using a rod of 3mm diameter having a cone shape head. Penetration resistances at left, right and center showed similar trend up to 4 cm from the surface, while that at the center significantly reduced below.

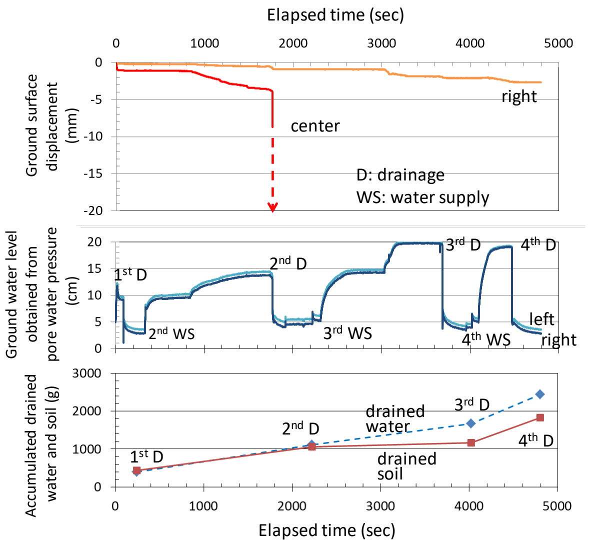

Fig. 3. Surface settlements, ground water levels and amount of drained water/soil in Test B.

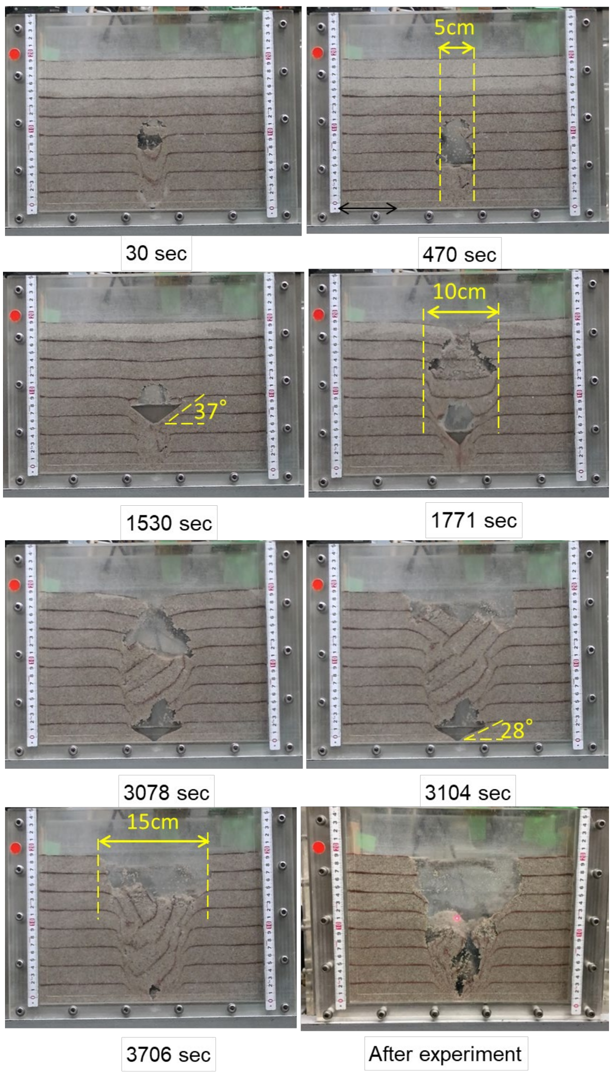

Fig. 4. Deformation of the ground and cavity formation in Test B

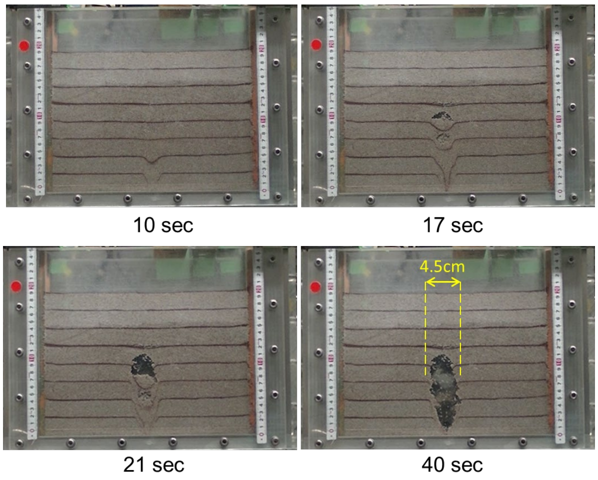

Fig. 5. Deformation of the ground and cavity formation in Test C

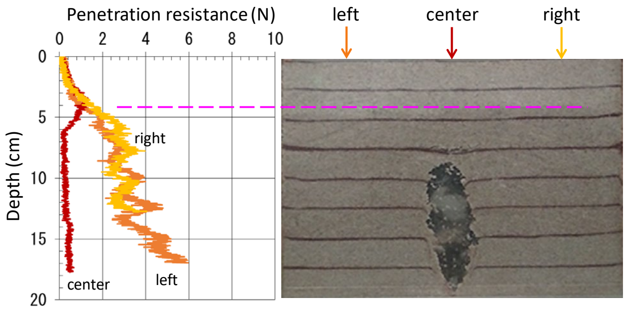

Fig. 6. Penetration resistance above the cavity in Test C.

3.4 Size and shape of initial cavity

At the start of tests, when water/soil quickly drains, a chimney-like vertically elongated cavity developed. Widths and heights of the initially developed cavities are plotted against initial water level in Figure 7, in which in addition to Tests A to F, tests using silica sand No.3 (D_{50}=1.2 mm) are also included.

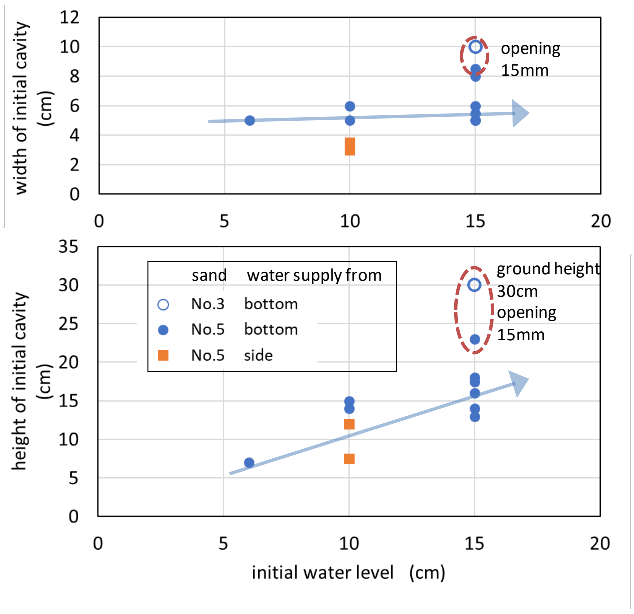

Fig. 7. Size and shape of initially developed cavities.

The heights of initial cavities are nearly the same as the water levels. When water starts to drain from the opening, soil particles are also dragged down with water. The widths of initial cavities seemed to be less sensitive to the water level. Values of width are around 5cm when the opening size was 5 mm wide. In case the opening size was 15mm, larger width was observed.

3.5 Expansion of cavity and collapse of surface

Ground arching can be developed when the width of the cavity is small enough compared to the length of covered soil above the cavity as schematically shown in Figure 8. In such a case, the cavity can sustain without surface collapse due to apparent cohesion and ground arching effect. Assuming 5cm wide fan-shape for initial cavity, estimated soil loss is 280g.

In the later stage of Test B and Test D, when the water penetrated into the cavity by the cycle of water supply or the rise of surrounding water level, angle of fan-shape becomes wider as the soil starts to slide down to the opening along the slope formed both sides above the opening. If sufficient amount of water was supplied and the cavity was filled with water, the angle of slope would be the angle of repose of the tested material. Assuming that the angle of repose of the tested sand is 30°, the maximum width of the cavity developed above the opening can be about 35 cm, as indicated in Figure 8. Soil mass above the cavity cannot be sustained and it would collapse, since arching effect is not developed under such condition. Total amount of drained soil can be 1940 g or more, as compared to the measured value in Figure 9.

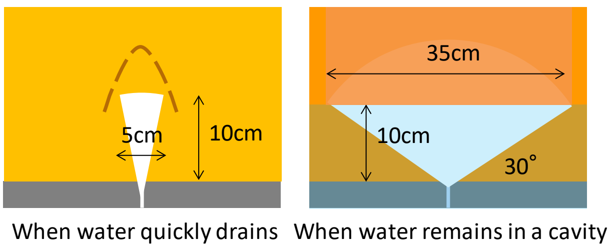

Fig. 8. Estimation of initial and expanded cavities.

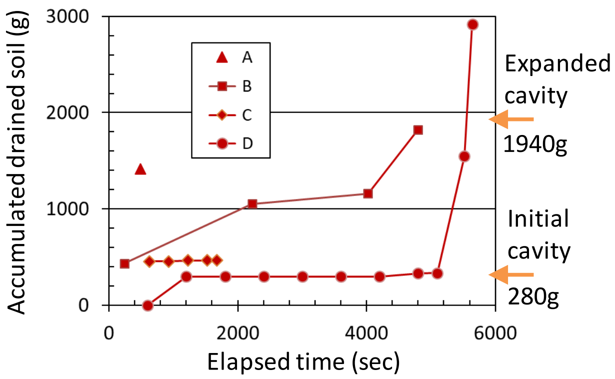

Fig. 9. Accumulated soil loss (measured and estimated).

4 SUMMARY AND CONCLUSIONS

The sinkhole or cave-in phenomenon was simulated in a sand model ground and the fundamental mechanism of subsurface cavity formation and development was investigated. In case the outlet of soil leakage exists in uniform sand, followings were observed.

Soil under the ground water level can be the potential area of cavity. Soil flowed out with water and when the water drained quickly, vertically elongated shape of cavity developed, while when the water level maintained in the cavity, the cavity developed wider and bigger.

The shape of the cavity was roughly fan-shape. If the cavity was filled with water, the angle of slope developed above the opening could be angle of re-pose of tested sand. Estimated values of cavity size approximately agreed with the measured values of drained amount of soil.

When the width of cavity was small enough compared to the covered soil length, a cavity was stable as the ground arching effect seemed to work, while when the cavity became wider and the ceiling of the cavity became shallow, the soil mass above the cavity lost the stability and the surface collapse eventually occurred.

Surface settlements above the cavity were not significant until the moment of surface collapse, since the soil above the cavity seemed to be supported by the ground arching.

It is implied that the subsurface cavity can be initiated from the soil outflow and the ground water level is the location of cavity ceiling. If the water remains in the cavity, it would grow wider. The maximum width and height of the potential cavity are estimated from angle of repose of sand and the distance between soil outlet and ground water level. When the cavity becomes wide and shallow, ground arching effect is lost and surface collapse would happen.

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