Experimental observation of ground cave-ins induced by a damaged sewer pipe

L'observation expérimentale des déblais du sol induits par un tuyau d'égout endommagé

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ABSTRACT: Ground cave-ins occur frequently in metropolitan areas and cause severe socioeconomic losses. A damaged underground sewer pipe is regarded as one of the primary causes of ground cave-ins. In this study, a series of model experiments was conducted to fully understand how ground cave-ins develop from a damaged sewer pipe. The experiment conditions were determined based on previous researches, the criteria for burying sewer pipe, and practical site conditions. Additionally, the influence of the soil type, the amount of fine particles, and the degree of compaction on the occurrence of ground cave-ins was investigated. During the tests, the response of the model ground was continuously measured at multiple locations. Particle image velocimetry was also adopted to evaluate the displacement and monitor the internal behavior.

RÉSUMÉ : Les débris terrestres se produisent fréquemment dans les régions métropolitaines et causent de graves pertes socioéconomiques. Un tuyau d'égout souterrain endommagé est considéré comme l'une des principales causes des déblais au sol. Dans cette étude, une série d'expériences modèles ont été menées afin de comprendre comment les débris terrestres se développent par un tuyau d'égout endommagé. Les conditions expérimentales ont été déterminées à partir des recherches antérieures, des critères d'enfouissement des conduites d'égout et des conditions pratiques du site. De plus, on a étudié l'influence du type de sol, la quantité de particules fines et le degré de compactage lors de l'apparition de déblais. Au cours des essais, la réponse du sol du modèle, telle que le règlement, a été mesurée en continu à plusieurs endroits. La vélocimétrie de l'image de particules a également été adoptée pour évaluer le déplacement et surveiller le comportement interne.

KEYWORDS: ground cave-in, damaged sewer pipe, model experiment, digital image analysis.

1 INTRODUCTION

A large number of ground cave-ins, which include ground collapse and subsidence, have been reported in metropolitan areas, which can result in severe socioeconomic losses (Japan National Institute for Land Infrastructure Management, 2012; Galloway, 1999; Guarino, 2012). In the case of Seoul, a total of 3,626 cases of ground cave-ins were reported from 2011 to 2015. Ground cave-ins can be triggered by several causes, such as a damaged sewer pipe, careless excavation, groundwater lowering, and frost heaving. Approximately 77% of the ground cave-ins that have occurred in Seoul were due to defective underground sewer pipes (Seoul Metropolitan Government, 2016).

The development of ground cave-ins induced by damaged sewer pipes was first presented by WRC (Water Research Center) in England (Rogers, 1986), as follows: (1) when the quantity of water in a sewer pipe becomes larger during a rainfall, a damaged sewer pipe will cause the water to leak into the soil through the crack or hole in the pipe; (2) leakage of water from a damaged sewer pipe into the soil will result in the rise of the groundwater level; (3) after the rainfall, the groundwater will flow back into the damaged sewer pipe accompanying soil erosion and cavity formation; and (4) the repeated occurrence of these phenomena will expand the cavity as well as the loosened soil area, and will eventually lead to the collapse or subsidence of the upper ground.

Based on the phenomena that were introduced in the report of WRC, several researchers reproduced the development of a cavity and of subsidence by performing model experiments to investigate the mechanism of ground cave-ins induced by damaged sewer pipes (Higashi et al., 2003; Mukunoki et al., 2009; Kuwano et al., 2010). A series of ground cave-in model experiments was performed to investigate the effect of the fine content, soil compaction, and hole size. During the model experiments, the cavity development was monitored with the naked eyes and with X-ray computed tomography (CT), which can scan the density variation (Mukunoki et al., 2009; Kuwano et al., 2010).

The previous researches, however, focused on observing the aforementioned phenomena during the model experiments. Moreover, several experiment conditions, such as the soil type, degree of compaction, and hydraulic pressure, were determined arbitrarily. The ground cave-in and subsidence susceptibility evaluated from the model experiments can be either overestimated or underestimated if the experiment conditions were not determined based on the practical site conditions.

This study focused on simulating the development of ground cave-in due to a damaged sewer pipe considering the criteria (e.g., specifications, guidelines, codes) and soil types widely used for burying sewer pipes in South Korea. A model experiment system that can reproduce soil erosion during and after a heavy rainfall was designed and manufactured. The experiment conditions were determined based on previous researches, the criteria for burying sewer pipes, and the practical site conditions. Four model experiments were performed to investigate the effects of the particle size distribution, amount of fine content, and degree of compaction on the internal behavior and occurrence of ground cave-in.

2 EXPERIMENTAL PROGRAM

2 .1 *Model experiment*

A series of ground cave-in model experiments was performed in a soil chamber of 140 cm in length, 10 cm in width (with vertical partition), and 100 cm in height as illustrated in Figure 1. The soil chamber was made relatively large length to reduce the boundary effect, and was made high enough to satisfy the burial depth requirement of a sewer pipe (100 cm, including the pavement), as stated in Standard Specifications for Sewer Pipes in South Korea (2010). The vertical partition reduced the width of the soil chamber so that a plane strain condition could be assumed. By removing the vertical partition, model experiments under three-dimensional conditions can also be conducted. A slit was made at the mid-bottom part of the chamber to represent a crack or hole on the sewer pipe. It was closed during the model ground preparation and could be opened at various widths during the experiments. A water tank was connected to the bottom of the chamber for supplying the water through the slit. The water tank contained a weir to supply water to the model ground under constant hydraulic pressure. The water level of the model ground was adjusted to 70 cm based on the experimental research on the groundwater level above a 100-cm-diameter sewer pipe under 50 mm/hour rainfall intensity (National Disaster Management Research Institute, 2014). Through the front wall, which was made of transparent acrylic, cameras could capture images and record videos during the model experiments

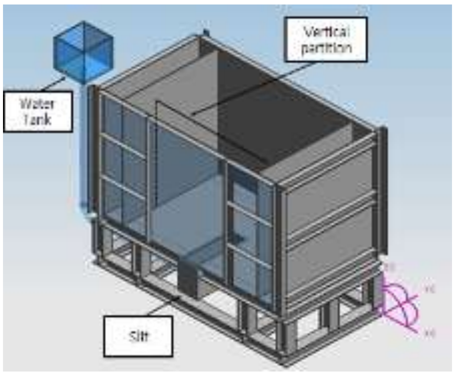

Figure 1. Model ground cave-in experiment chamber

The model experiment consisted of two stages: (1) the water supply stage; and (2) the drainage stage, which represented the time during and after a heavy rainfall. During the water supply stage, the water tank supplied water to the model ground until the groundwater level reached 70 cm. After the stabilization of the groundwater level, the applied hydraulic pressure was removed to drain the model ground. These stages were repeated several cycles until significant soil erosion or subsidence was achieved.

During the model experiment, a linear variable differential transformer (LVDT) measured the surface settlement at three locations: 10 cm, 40 cm, and 70 cm from the boundary. Digital images were captured every two seconds to evaluate the internal deformation behavior of the model ground using image analysis.

2 .2 *Soils*

In South Korea, weathered residual soils are created from the weathering of granite, gneiss, and schist, and are distributed meters thick in the subsurface. Figure 2 shows the particle size distribution of weathered soil in several regions of South Korea (Park et al., 1999; Lee et al., 2009; Kwon, 1998). It can be seen that most of the weathered soils have well-graded particles that are easily distinguishable from poorly graded sand.

This study used Jumunjin sand and Gwanak soil, which are classified as poorly graded sand (SP) and well-graded sand (SW) in the Unified Soil Classification System (USCS), respectively, for the model ground, and compared the deformation behavior during the experiments. Gwanak soil, which is residual soil produced by weathering granite, shows a particle distribution similar to those of the various weathered residual soils in South Korea, as shown in Figure 2. The geotechnical properties of Jumunjin sand and Gwanak soil are summarized in Table 2. When preparing the model ground, particles larger than 4.75 mm (no. 4 sieve size) were eliminated to exclude the undesired effect of large particles (e.g., blocking the slit). The water contents of Jumunjin sand and Gwanak soil were controlled and kept at 5.0% and 8.3%, respectively, which satisfied the water content criteria (optimum water content ± 2%) of Standard Specifications for Sewer Pipes in South Korea (2010).

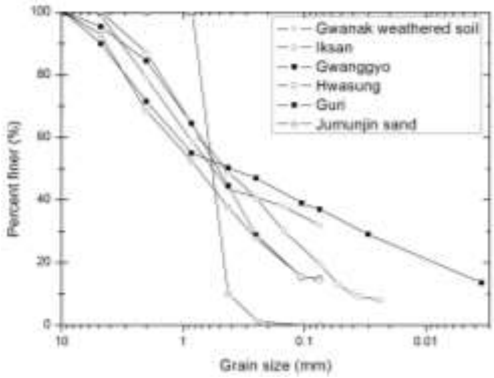

Figure 2. Particle size distribution of the Jumunjin sand and weathered soils in South Korea

Table 2. Geotechnical properties of Gwanak soil and Jumunjin sand

Description	Gwanak soil	Jumunjin sand
USCS	SW-SM	SP
Maximum dry unit weight (t/m^3)	1.88	1.63
D_{50} (mm)	0.324	0.610
C_U	29.4	1.70

2 .3 *Experimental program*

In this study, four ground cave-in model experiments were performed, one with Jumunjin sand and three with Gwanak soil, to compare the internal behaviors according to the soil type, as summarized in Table 2. The experiment conditions were determined based on the criteria of the backfill material for the burial of sewer pipes in South Korea and Japan, as summarized in Table 3. When the residual soil at the site satisfies the requirements, it is usually used in backfilling after burying the sewer pipes. The criteria commonly require the fine content to be less than 15%, and the ground covering the sewer pipes to be compacted by more than 90% of the maximum dry unit weight based on the standard compaction test result. Gwanak soil was controlled to have 7.5% and 15.0% fine contents to satisfy the criteria for burying sewer pipes and to examine the effect of the fine contents on the deformation behavior during the experiments. This study also examined the effect of the degree of compaction on ground cave-in occurrence by compacting the model ground of Gwanak soil by 92% and 84% of the maximum dry unit weight, which satisfies and violates the criteria, respectively.

Table 2. Experiment conditions

Test No.	Soil	Fine content	Degree of compaction	Slit size	Burial depth
1	Jumunjin sand	0.0 %	92 %	2cm	90cm
2	Gwanak soil	7.5 %			
3		15 %			
4		7.5 %	84 %		

Table 3. Criteria of backfill material for burying sewer pipe

Description	Ministry of Environment, Korea (2010)	Road Association, Japan (1990)
Maximum particle size	100mm	100mm
#4 sieve passing	25 – 100 %	25 – 100 %
#200 sieve passing	≤15 %	≤25 %
Degree of compaction	≥ 90 % of $(\gamma_d)_{max}$	≥ 90 % of $(\gamma_d)_{max}$

2.4 *Digital image analysis*

The PIV (Particle Image Velocimetry) technique, one of the digital image analysis techniques, was developed and has been widely adopted in geo-mechanics for measuring the displacement and deformation of the soil specimen. The relative displacement of each pixel subset is investigated by calculating the correlations of the pixel subsets from the digital images taken at different times. In this study, GeoPIV (White et al., 2003), the most widely used software for the PIV technique, was employed. For the optimal PIV analysis conditions for the investigation of the soil behaviors, the optimal pixel subset size should be determined. The accuracy and precision of GeoPIV with various-sized pixel subsets were verified by comparing two digital images: the original image of the soil specimen and the image artificially shifted by one pixel. Based on the results of the verification tests, 100 x 100 pixels was adopted for the pixel subset size, with a 0.004 mm error in accuracy and a 0.007 mm error in precision. Figure 3 shows the 2,496 (64 x 39) center points in the first of the consecutive images.

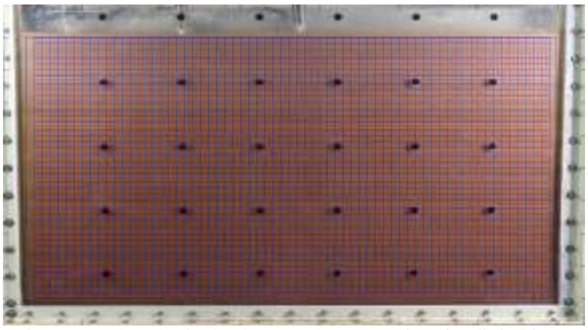

Figure 3. Selected pixel subsets and center points for digital image analysis

3 RESULTS AND DISCUSSION

3.1 *The effect of soil type and fine content*

Figure 4 shows the model ground of Jumunjin sand collapsed after one experiment cycle: the water supply and drainage stage. In the case of Jumunjin sand, it was observed that the soil adjacent to the opening was scoured by the applied hydraulic pressure during the water supply stage. As the drainage stage began after the groundwater level was stabilized by the given hydraulic head, the groundwater was drained through the slit, accompanied by the erosion of 30.0% of the total soil mass (44,945 g). Then the upper ground over the cavity collapsed, as shown in Figure 4. Poorly graded sand with few fine particles generally has a low maximum dry unit weight and low soil strength, which are considered the main reasons for its vulnerability to soil erosion and ground cave-in.

On the other hand, scouring was not observed in the model ground of Gwanak soil during the water supply stage. When the model ground of Gwanak soil satisfied the compaction criteria, the LVDT and image analysis did not detect any movement of the ground surface during the water supply stage.

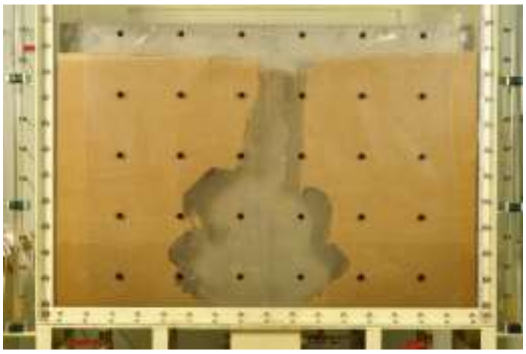

Figure 4. Ground collapse after first cycle of Test 1

Figure 5 shows the displacement arrows obtained from the image analysis during the drainage stage at the first cycle in the case where the model ground had 7.5% fine contents and satisfied the compaction criterion (Test 2). The divergent displacement vectors, which showed excessively large displacement for estimation with the image analysis condition used in this study, were removed. As shown in Figure 5, the model ground below the groundwater level (70 cm from the bottom of the chamber) was displaced towards the slit in the mid-bottom part of the chamber, experiencing larger displacements as it approached the slit. The decrease of the soil strength due to saturation during the water supply stage, and the seepage pressure, caused the downward movement of the soil particles during the drainage stage (Fredlund, 2012).

As the soils were discharged through the slit, the cavity gradually expanded. Although the cavity developed up to 1,580 cm^2 in an elliptic shape at the end of the drainage stage, it sustained the weight of the upper ground through the arching of the soil particles. The quantity of the eroded soil (dry mass) after the first cycle was measured as 28,182 g, which was about 64% of the result of the Jumunjin sand.

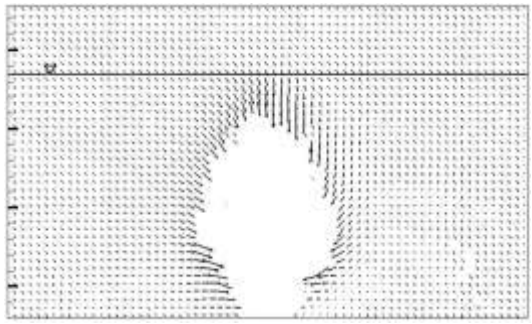

Figure 5. Displacements during the drainage stage of the first cycle of Test 2 (10 times exaggerated)

During the second cycle of Test 2, the soil adjacent to the boundary of the cavity was eroded as water was supplied, then the cavity came to have an inverted triangle shape. In the drainage stage, the soils that were disturbed during the water supply stage were discharged together with the water. After the end of the second cycle, the quantity of discharged soil (dry mass) was 1.5 times larger than that in the first cycle, which is shown in Table 4. Neither the settlement at the ground surface nor ground cave-in was observed during the experiment, however, due to the relatively high unsaturated soil strength of the upper ground.

To investigate the effect of the amount of fine particles, a model experiment with Gwanak soil controlled to have 15% fine content was additionally performed (Test 3). Test 3 showed similar internal behaviors as those in Test 2 during the two cycles of water supply and drainage stages. The elliptical-shaped cavity that was developed at the first cycle was extended in an inverted triangle shape at the second cycle, but it was much smaller than that in Test 2. The total quantity of discharged soil (dry mass) during the two cycles decreased to 40,030 g, which was almost 50% of that in Test 2. It can be expected that the higher amount of fine content in soil decrease void ratio and increase soil strength (cohesion) preventing soil erosion (Lade, 1998; Al-Shayea, 2001).

Table 4. Quantity of discharged soil and size of the cavity for each model experiment

Test no.	First cycle		Second cycle	
	Quantity of discharged soil (Dry mass)	Size of cavity	Quantity of discharged soil (Dry mass)	Size of cavity
1	44,945g (27.2%*)	3,228 cm^2	-	-
2	28,182g (13.0%*)	1,570 cm^2	47,090g (21.7%*)	4,479 cm^2
3	20,051g (9.5%*)	887 cm^2	19,979g (9.4%*)	2,293 cm^2
4	30,080g (15.1%*)	1,700 cm^2	69,613g (35.1%*)	4,250 cm^2

* : Ratio of the amount of discharged soil to the total soil mass

(a) After 1st cycle (b) After 2nd cycle

Figure 6. Development of cavity during Test 2

3 .2 *The effect of the soil compaction*

A model experiment with Gwanak soil, which was compacted to 84% of the maximum unit weight based on the standard compaction test result, was performed (Test 4) to confirm the validity of the compaction criterion for burying sewer pipes. When the compaction criterion of the model ground was not satisfied, different internal behaviors were observed from the beginning of the water supply stage. Figure 7 shows the displacement arrows during the water supply stage of the first cycle. As the groundwater level rose, the model ground cracked in the mid-part, as indicated as a bold line in Figure 7. To fill the cracks, the soils above the cracks moved towards the mid-part of the model ground, inducing surface settlement.

Instead of cavity development, ground cave-in and soil subsidence occurred in the mid-part of the surface, along with the progress of soil leakage during the drainage stage. At the second cycle, the loosened soil was eroded in the shape of an inverted triangle as water was supplied, which was similar to the result of the well-compacted soil. At the water drainage stage, most of the soil particles lost their strength when the supplied water leaked through the slit. The discharged soil (dry mass) after the second cycle was 69,613 g, almost 1.5 times larger than the result of the well-compacted soil.

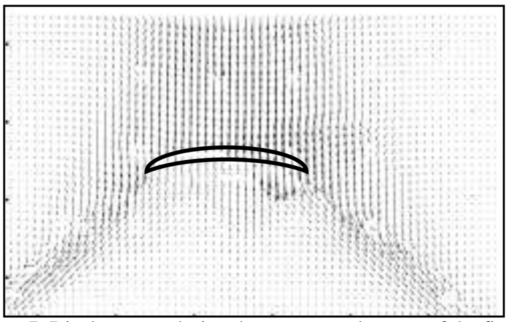

Figure 7. Displacement during the water supply stage of the first cycle of Test. 4

The results of Test 2 and 4 indicate that the degree of compaction influences the amount of discharged soil, resulting in the occurrence of ground cave-in and soil subsidence. Loose soil, which has low soil strength with a high void ratio, eroded easily and widely during the water supply compared to the well-compacted soil. The eroded soil particles cannot resist during the water drainage, and as a result, the larger quantity of discharged at loose soil causes ground cave-in.

(a) After 1st cycle (b) After 2nd cycle

Figure 8. Development of ground cave-in during Test 4

4 CONCLUSIONS

This study investigated cavity development with internal deformation behavior during the ground cave-in model experiments. The model experiments were performed with a large-scale model chamber for poorly graded soil (Joomunjin sand) and well-graded soil (Gwanak soil) for the representative conditions of the site in South Korea. The vertical displacement at the surface, the size of the cavity, and the quantity of discharged soil were measured during the test. In addition, digital images were captured in two second intervals to evaluate the internal behavior of the soil. Based on the experiment results presented in this paper, the conclusions shown below were drawn.

(1) The internal behaviors of the poorly graded sand and well-graded sand were observed to evaluate the effect of the soil type. The experiment results indicate that poorly graded sand is vulnerable to ground cave-in due to the groundwater level rise and drawdown compared to the well-graded sand.

(2) The effect of fine content was investigated for the well-graded and compacted sand with 7.5% and 15% fine contents. Both experiments showed the development of an elliptical-shaped cavity without ground cave-in and soil subsidence. When the model ground contained more fine particles, however, the quantity of discharged soil decreased, meaning the model ground had larger resistivity to ground cave-in.

(3) The well-graded sand was compacted to 92% and 84% of the maximum dry unit weight to evaluate the effect of soil compaction. The loose soil subsided during the water supply, and ground cave-in occurred during the water drainage with a larger amount of soil discharge, which showed the significance of following the compaction criteria.

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