Investigation of mechanism of ground sinking through 3-D GPR surveys and laboratory model tests

Investigation du mécanisme de l'enfondrement de terrain par le biais d'enquêtes 3-D GPR et de tests en laboratoire

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ABSTRACT: In aging urban environments such as Seoul (South Korea), the ground cavities formed under roads are continuously increasing. 3-D GPR surveys using the Stream EM device equipped with a 38 channel multi-antenna were performed to detect such cavities. Dozens of such cavities were found in Seoul, and excavations were performed to investigate their cause. It was demonstrated that the main cause of cavity formation is the damage and the detachment of the aging sewage pipelines. During a heavy rainfall, the water table quickly rises above the pipeline. When the water table drops, fine-grained soil particles are flushed into the sewage pipeline, causing a cavity to develop around the sewage pipeline. To investigate the mechanism of the cavity formation around sewage pipelines in detail, and assess the effects of soil type and other field conditions, a series of model tests was performed. Cyclic tests, in which the soil tank is saturated and then drained in multiple sequences, were performed, and the volume of the discharged soil was measured. It was shown that a number of properties including the density and the water content influence the discharge rate of soil, the rate of cavity size expansion, and the characteristics of the relaxed area around the cavity.

RÉSUMÉ: Dans les environnements urbains vieillissants tels que Séoul (Corée du Sud), les cavités de sol formées sous les routes augmentent en permanence. Des enquêtes GPR 3-D utilisant le dispositif Stream EM équipé des multi-antennes de 38 chaines ont été effectués pour détecter ces cavités. Des dizaines de ces cavités ont été trouvées à Séoul, et des fouilles ont été effectuées pour enquêter sur leur cause. Il a été démontré que la cause principale de la formation de la cavité est le dommage et le détachement des conduites vieillissantes des eaux usées. Pendant les fortes précipitations, la nappe phréatique s'élève rapidement au-dessus des conduites. Lorsque la nappe phréatique tombe, des particules de sol à grain fin sont rejetées dans les conduites, ce qui provoque la formation d'une cavité. Afin d'étudier en détail le mécanisme de la formation de la cavité autour des conduites d'eaux usées et d'évaluer les effets du type de sol et d'autres conditions sur le terrain, une série de tests de modèle a été réalisée. Les tests cycliques, dans lesquels le réservoir de terre est saturé puis drainés en plusieurs séquences, ont été effectués et le volume du sol déchargé a été mesuré. Il a été démontré qu'un certain nombre de propriétés, y compris la densité et la teneur en eau, influencent la vitesse de décharge du sol, la vitesse d'expansion de la taille de la cavité et les caractéristiques de la zone détendue autour de la cavité.

KEYWORDS: mechanism of ground sinking, 3-D GPR surveys, cavity, model tests, relaxed area, discharge rate of soil.

1 INTRODUCTION

Recently, road cave-ins, also referred to as ground sinking, have become a problem in urban environments. Public utility facilities such as sewage pipelines, communications pipes, gas pipes, power cables, and other types of underground structures are installed below the roads. It was reported that cave-ins are caused by the aging and lack of proper maintenance of underground facilities, as well as by construction problems (Korea Institute of Environmental Policy Evaluation, 2014).

A road cave-in is first initiated by the formation of cavities typically induced by the breakage of underground pipelines. The cavities then grow and reach the base of the pavement. The traffic load applied at the surface of the roads causes an abrupt plastic deformation. This type of accident can be considered as a type of disaster. A road cave-in can threaten both human safety and the economy. It may even result in the loss of human life. However, its causes and mechanisms have not yet been clearly identified. In the city of Seoul, efforts to prevent damage before cave-ins occur have been prioritized, through a method of discovering and repairing joints through the 3D GPR survey.

Effective exploration of cavities in the lower part of the road can reduce the damage to roads, but is not a fundamental countermeasure to prevent a road cave-in. It is important to understand the causes and mechanisms of roadside cavities in order to avoid them. However, it is difficult to identify the main mechanism of road cave-ins through on-site surveys, because when a road cave-in occurs, the immediate priority is recovery.

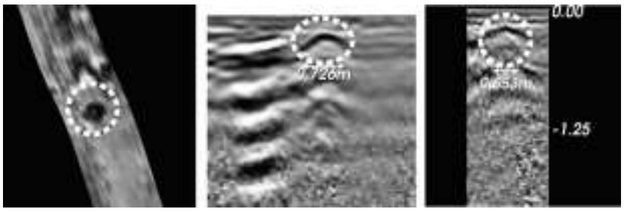
Only preliminary studies on the expansion mechanism after the development of a cavity, which is a direct cause of a road cave-in, have been performed. In Japan, a small soil tank was used to perform medium-sized model tests (Kuwano, 2012; Hewage, 2012; Sato, 2013). In this research, in order to determine the mechanism of the road cave-in, we conducted extensive 3-D GPR surveys on the roads of Seoul and model tests using small and medium sized soil tanks.

2 3-D GPR SURVEY AND ANALYSIS

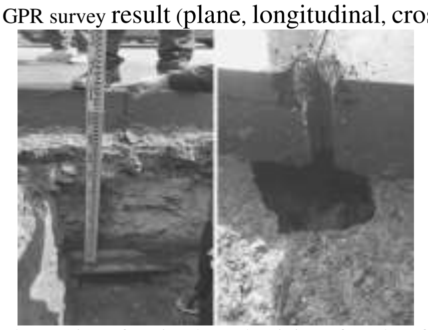
3-D GPR probe built by IDS, was connected to a vehicle and used to search for cavities. It is composed of 38 channels of multi antennas. The measurement width is 1.84m, and the optimum search speed is 15 km/hr.

Figure 1. 3-D GPR survey (Stream EM)

The results of a 3-D GPR survey are shown in Figure 2. A cavity is found at a depth of 21cm from the bottom of the pavement. The cavity is approximately 72cm in length and about 55cm in width (Figure 2a). From in-situ excavation, it was found that the cavity has already expanded up to the base of the pavement. The cause of the formation of the cavity was found to be the breakage of the sewage pipeline (Figure 2b).



a. 3-D GPR survey result (plane, longitudinal, crossing)



b. Observation of cavity through mining of road surface

Figure 2. Road cave-in survey

2.1 ANALYSIS

An average of 677 road cave-ins occurred annually in the city of Seoul between 2010 and 2016, which is an averag e of 1.8 cases per day. More than 70% of the road collap se accidents occurred in the rainy season (May to Septemb er), with 78% of those caused by sewer pipe damage, 2 0% by insufficient drilling restoration work, and 2% by a ruptured constant pipe. This indicates that a road collapse is closely related to the water flow in the lower part of th e road. In sewage pipelines, water repeatedly flows into th e gap formed in the pipe connection, and sediment flows i nto the pipe with the ground water. Gaps are formed not only because of structural damage to the sewage pipe, but also by damage to the manhole, and incomplete connection (City of Seoul, 2015).

The conditions that allow the cavity to form and eventu ally cause a road cave-in are as follows. 1) There must be a transport route through which the sediment is drained i nto the pipeline. 2) Soil with high water permeability must satisfy the fragile soil conditions, in which fine particles can flow out due to the saturation of the ground due to t he penetration of water. 3) In addition to the involvement of water penetration by sediment outflow of the perimeter of the cavity, there are areas in which the groundwater flu ctuates extensively.

It was understood that the rainfall flows into the ground through the damaged part of the sewer pipe and increases the groundwater level, and the fine granular earth and sand flows together and a cavity is generated when the groundwater level drops. A model soil testing system to confirm this road cave-in mechanism was fabricated, and an indoor test performed.

3 MODEL TESTS

A small model soil tank and a medium sized model soil tank experiment for road cave-in characterization evaluation were conducted. In the small model soil tank, the types of ground materials are different and the influence of particle size distribution and fine particle content is analyzed in order to investigate sediment discharge characteristics.

In the medium sized model soil tank, longitudinal crack and crossing crack were made in a sewer pipe with a diameter of 200mm. We assumed a situation in which the groundwater level at the cracked part during rain rises and flows in. The cavity generation and growth process was confirmed through a manual GPR survey and penetration strength test.

3.1 SMALL MODEL SOIL TANK TEST

Figure 3. shows a small model soil experiment. Each ground material was tightened to create a model ground of 30x10x20 cm. We set a soil weight of about 60cm on the ground's surface. Colored sand layers were established at 2.5cm in thickness, and the deformation of the ground was observed. A 0.5cm wide drainage was made in the center of the soil tank floor, and after a certain period of time, the process of discharging water and earth and sand was repeated.

Approximately 300ml of water was added to both tanks. When the water level after the supply of water stabilized, the drain was opened and drainage was performed. This is one cycle. Closing the drainage temporarily blocks the sewer pipe from the incoming earth and sand and suppresses sediment discharge. The small model soil tank was experimented with until it collapsed. Dry weight, particle size analysis and ground change of earth and sand flowing out in each cycle were recorded.

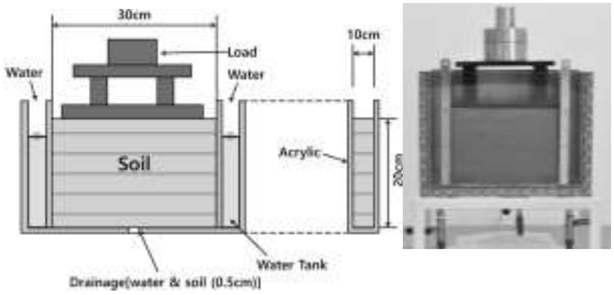


Figure 3. Small model soil tank

3.1.1 CHARACTERISTICS OF GROUND MATERIALS

Table 1. describes the basic physical properties of the ground material used for the small model soil experiment. The particle size distribution curve is as shown in Figure 4. "S1d, S1t" and "S2d, S2t" in Figure 4. are in a state in which the particle size is constant and the particle size distribution is relatively poor as compared with "S3d, S3t".

Table 1. Result of basic property test of ground material

No.	ρ_s g/cm^3	Grain Size Distribution %, Finer than, (mm)						U.S. C.S
		4.75	2.0	0.425	0.075	0.005	0.002	
S1d	2.603		100.0	5.9	0.4	-	-	SP
S1t	2.603		100.0	6.7	0.2	-	-	SP
S2d	2.604	100.0	99.8	44.7	1.3	-	-	SP
S2t	2.601	100.0	99.9	51.6	1.6	-	-	SP
S3d	2.642	98.5	89.4	45.3	27.0	12.7	9.7	SM
S3t	2.644	99.6	89.3	45.5	25.9	13.2	11.1	SM

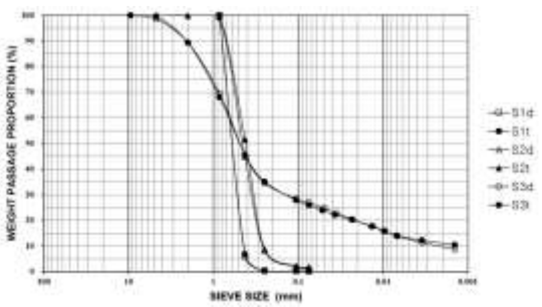


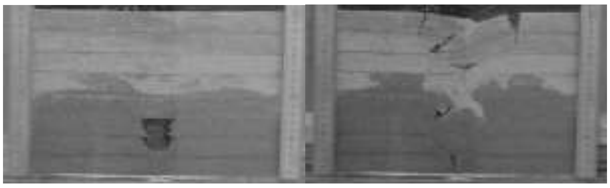
Figure 4. Particle size distribution curve of soil material

3.1.2 CHARACTERISTICS OF SEDIMENT DISCHARGE BY GROUND MATERIAL

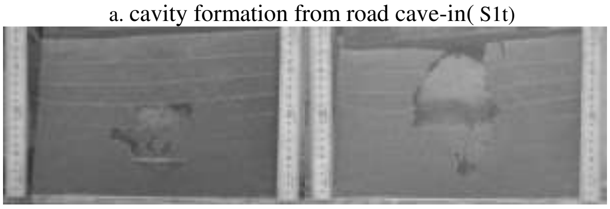
Figure 5. shows the cavity formation from and road cave-in shape for each soil material. The rate of progression from the generation of the cavity to the collapse is the fastest in the standard company Figure 5.a, which is a material with a small grain size and a uniform grain size.

The grain of the river Figure 5.b and Masan with good particle size distribution Figure 5.c.

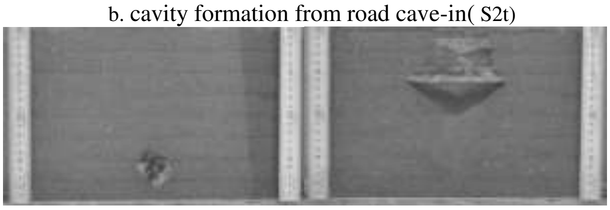
The cavities generated near the drainage in response to the cycling of the water supply and drainage cycles are continuously expanded in each cycle. After the shape of the angle of repose was observed, it was confirmed that the cavity was recessed.



a. cavity formation from road cave-in(S1t)



b. cavity formation from road cave-in(S2t)



c. cavity formation from road cave-in(S3t)

Figure 5. Cavity formation from road cave-in by ground material

The results of sediment discharge accumulated for each cycle in the sediment runoff experiment in the event of sediment runoff are shown in Figure 6. Comparing the results of sediment discharge in the standard company (S1d, S1t) and in the river sand (S2d, S2t), the sediment runoff progressed more rapidly than that of Masan (S3d, S3t), with relatively good particle size distribution.

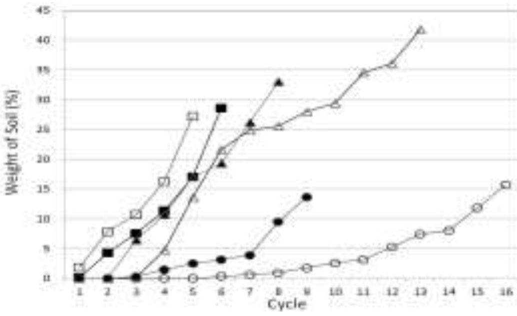


Figure 6. Sediment runoff by ground material

3.2 MEDIUM-SIZED MODEL SOIL TANK TEST

Figure 7. shows a medium-sized model soil experiment. Each ground material was tightened to create a model ground of 150x50x60cm. Color sand layers were established at 10cm in thickness, and the deformation of the ground was observed. A 0.5cm wide drainage was made in the center of the soil tank floor, and after a certain period of time, the process of discharging water and earth and sand was repeated.

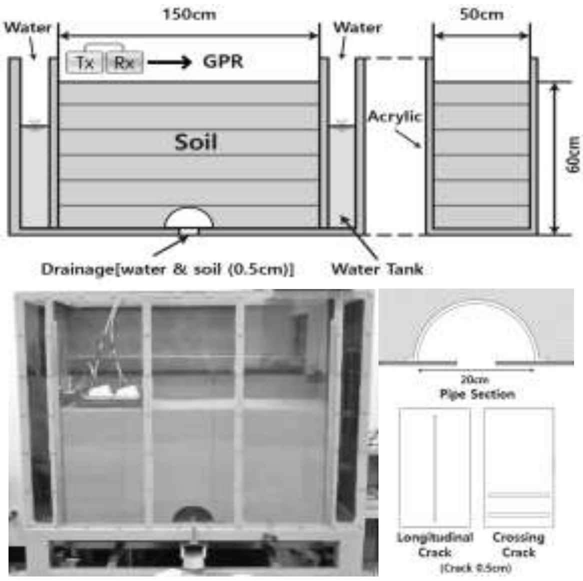


Figure 7. Medium model soil tank

3.2.2 SEDIMENT RUNOFF AND WEAKENING

After the water level was stabilized following the stabilization of the water supply to the medium model soil tank, the openings were opened and the water supply and drainage cycle tests were repeated with regard to the end breaks and transverse cracks of the underwater pipes; this cycle was repeated until drainage was complete.

The amount of sediment discharge due to longitudinal cracks and transverse cracks in the underwater pipe observed in the experiment is shown in Figure 8. The end cracks of the underwater pipes continued to decrease and then increased again at 5 cycles during the increase of sediment discharge. The sediment outflow of transverse cracks decreased at 7 cycles and then increased again.

The tendency of the end seepage and transverse cracks of the underwater pipes to increase due to the repetition of water supply and drainage cycles is similar, although the sediment outflow is more likely to be terminated due to the difference in the length of the cracks, and proceeds rapidly.

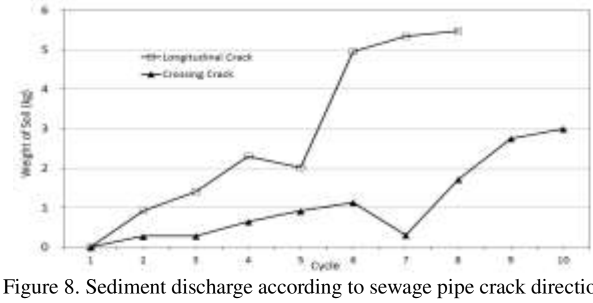


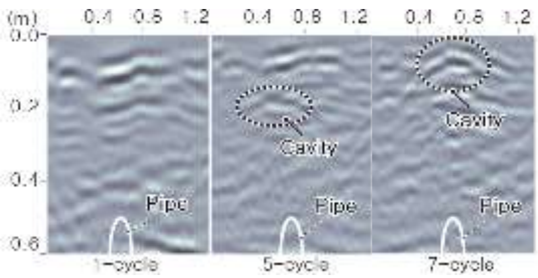
Figure 8. Sediment discharge according to sewage pipe crack direction

3.2.3 GROWTH PROCESS OF CAVITY

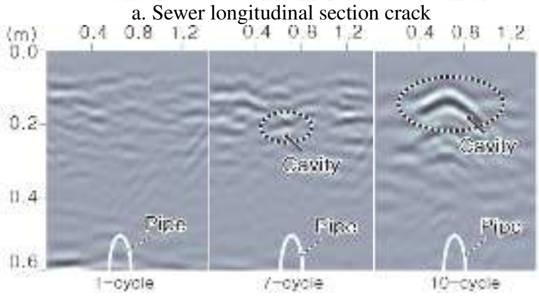
The penetration strength of the ground cavity was measured and the sign of the pre-sinking cavity was confirmed by manual GPR survey, following which the penetration strength test was carried out to measure the penetration strength q (kN/m^2) of the ground.

1) MANUAL GPR SURVEY

The results of the GPR survey are shown in Figure 9.a as a result of end-culling survey from 5 cycles, and the group after 5 cycles can be ascertained that the index will increase or decrease. As shown in Figure 9.b, the co-occurrence of cross cracks has been confirmed from the 7th cycle, and after 7 cycles, the group can be used to ascertain whether the index will increase or decrease.



a. Sewer longitudinal section crack



b. Sewer cross-section

Figure 9. Results of the GPR survey

2) RESULTS OF PENETRATION TEST

After the end of the test, the penetration test was carried out again multiple times at a distance of 15cm from the center to the right of the underwater tube, as shown in Figure 10., at a depth of 5cm to hold the positions of the five testers.

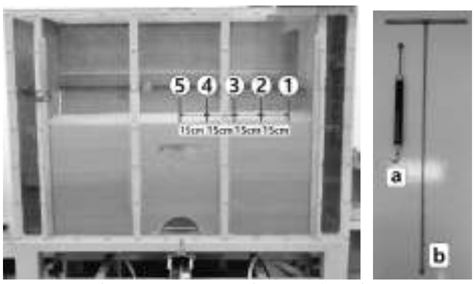
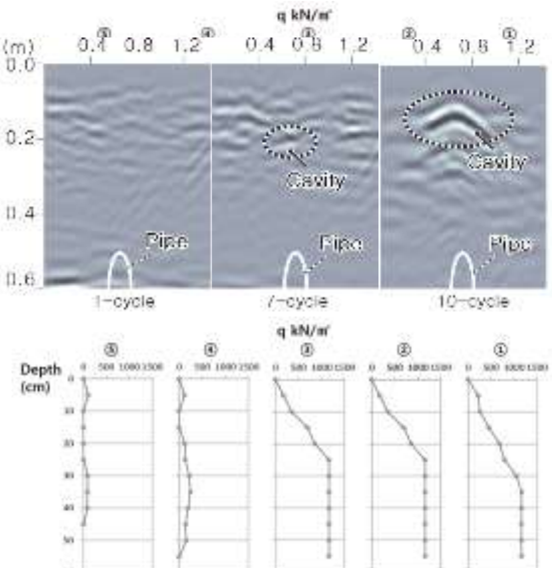


Figure 10. Penetration test location

As shown in Figure 11. the test results, the size of the flexible area and the area that can not be confirmed with the naked eye can be grasped at a maximum of 30cm or more.



b. Sewer cross-section

Figure 11. Results of the Penetration test

4 CONCLUSIONS

The findings obtained through a 3-D GPR survey and in-situ tests demonstrated that road cave-in accidents are primarily related to damage in sewer pipes. Therefore, a series of model tests were performed using small and medium sized soil tanks. The conclusions of the study are as follows.

a) According to the results of the small model test, the rate of increase of soil erosion, road cave-in, and relaxation area is higher for soils with poor grain size distribution and lower fine particles content.

b) Medium sized model tests showed that longitudinal cracks caused higher soil erosion, a higher rate of cavity formation and more frequent road cave in compared to the transverse cracks. This is because the length of transverse cracks was shorter and therefore soil discharge was smaller.

c) The cavity had a flat oval shape when the water level is constant, whereas the shape became sloped when there was a rise in the water level.

d) It was found that the decrease in the shear strength of soil dueto groundwater seepage and the sediment discharge including the fine particles cause weakening of the cavity and eventually induce a road cave-in.

E) In homogeneous soil, which was used in model test, as long as there is no groundwater flow caused by the hydraulic grad ient, cavity, relaxation area, and road cave in is formed at the upper vertical section of the source. This is consistent with the result of the GPR survey.

F) Based on the test results, the causes of the road cave-in due to the formation of the cavity generated by the damag e of the sewer pipe can be summarized as follows:

① increase in the groundwater level due to inflow of ground water into the ground,
② decrease in shear strength due to infiltration of groundwat er,
③ sediment discharge into the cracks of sewer pipeline,
④ and instability of the ground due to expansion of cavities.

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