VISUALIZATION OF THREE DIMENSIONAL FAILURE IN SAND DUE TO WATER INFLOW AND SOIL DRAINAGE FROM DEFECTIVE UNDERGROUND PIPE USING X-RAY CT

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ABSTRACT

The roadway surface locally subsides due to material aging or settlement of a base course in particular, resulting in failure of the ground with a plenty of water inflow. In most cases of roadway subsidence, underground pipes exist underneath the subsidence. In order to understand significant factors leading to local subsidence at a ground surface, a series of model tests using sandy soil were performed with the concerned defect configuration of the underground pipe and hydraulic condition. An industrial X-ray computed tomography (CT) scanner was used to investigate the behaviour of the model ground at each step of monotonic water inflow, monotonic soil drainage and the cyclic water inflow—soil drainage. Then, the behaviour density change of the model ground was visualized as a density change in two-dimensions and three-dimension. This paper concludes that the cyclic condition of water inflow—soil drainage caused fatal ground failure as the water inflow process created a water path disturbing the soil. Subsequently, the soil drained and the soil particles were interlocked due to the drainage. The movement of soil particles were restricted with the arching effect; and, the factors causing the cavity in the ground were not only the existing defect in the underground pipe but also the water flow towards the defective part after the loss of capillary force.

Key words: density, image processing, model test, nondestructive test (IGC: E14)

INTRODUCTION

An underground pipe is one of the important lifelines and its construction statistics in advanced countries is greater than in developing countries. In Japan, the construction of underground pipes, such as a sewerage pipe, is diffused mostly in urban areas. Meanwhile, the number of road subsidence has increased in the last two decades (Wang and Hiesh, 1987; NILIM, 2006). It can be assumed that the underground pipes get damaged because of 1) material aging including oxidation, 2) cyclic loads such as traffic load, and 3) poor execution during the construction process. In particular, the aging effect of the underground pipe is a serious problem because almost 50 to 60 years have passed since the current underground pipes were constructed. So the serviceability of the underground pipes have expired (Tohda and Yoshimura, 2004; Tohda and Hachiya, 2005; NILIM, 2006).

Holes and cracks in the underground pipes could cause three potential issues which are 1) water leakage into the ground from the underground pipe, 2) water with soil draining into the underground pipe through the defects and 3) cavity generation in the ground above of underground pipes (Skempton and Brogan, 1994; Sekiguchi et al., 2003). As for soil drainage into an underground pipe,

the ratio of pipe diameter to the depth from the road surface is usually 2 to 6 and hence the overburden pressure should not be significantly large. Hence, the authors have focused on the water inflow into the ground through defects in the underground pipe.

Public Works Research Institute (PWRI), Japan has performed a series of model tests under plain strain condition to observe the seepage behaviour (Kuwano et al., 2006; PWRI, 2006). PWRI concluded that the seepage flow disturbed the rearrangement of the soil particles and water with soil drained into the underground pipe. The process of water inflow and soil drainage cycle would remove the contact between soil particles above of the underground pipe and eventually resulting in road subsidence due to the draining water with soil into the holes and cracks.

The key issues in this topic are 1) to find the defective part of the underground pipe and the ground cavity under the traffic road, 2) to avoid fatal road subsidence, and 3) to propose countermeasures to prevent generation of ground cavity under the traffic road. Accomplishing the first objective is the first step in solving these issues. In order to do so, it is important to understand the failure mechanism of soils due to water inflow with soil drainage using the technique of non-destructive test.

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An X-ray Computed Tomography (CT) scanner is a powerful tool to visualize the behaviour of geomaterial such as rock and soil. Desrues et al. (1996) conducted the triaxial compression test with medical CT scanner to observe the strain localization of sandy soil. Otani et al. (2000) performed the unconfined compression test on the undisturbed over consolidated clay and visualized the slip surface in the clay specimen in three-dimensions using an industrial X-ray CT scanner which was installed at Kumamoto University, Japan. In fact, the energies such as an electric voltage and current required to generate an X-ray beam in the industrial X-ray CT scanner are greater than those required for the medical CT scanner. The development of the industrial X-ray CT scanner was available to scan not only geomaterials for the triaxial compression test but also the model ground (Mukunoki, 2001; Otani and Obara, 2004; Takano, 2008).

The objective of this study is to clarify the failure mechanism of soils due to water inflow and soil drainage from defective underground pipe using the X-ray CT scanner (as referred X-ray CT scanner, herein). In this study, the model tests were conducted using three different approaches, which are 1) water was supplied into each model ground from the defect model using the same hydraulic head in the monotonic inflow test, 2) water with soil were drained from the same defect model as in the monotonic drainage test, and 3) the first and second approaches were repeated as in the cyclic test. X-ray CT images give the density distribution of model ground due to water inflow—soil drainage through the defects in the underground pipe in two and three dimensions (as referred 2-D and 3-D, herein).

TEST METHODS

X-ray CT Method

X-ray CT Scanner

The X-ray CT scanner used was the industrial type and this equipment was installed at Kumamoto University in 1996. Table 1 shows the specification of the X-ray CT scanner. In this study, the voltage to generate the X-ray beam was 300 kV, and the electric current was 2 mA. The thickness of the X-ray beam was collimated to 1 mm. The voltage, electric current and thickness of the X-ray beam should be calibrated before starting the test to obtain a high enough accurate CT image. The diameter of the scan area was chosen as $\phi = 150$ mm and the number of voxel in the image was 512×512 ; hence, the dimension of one voxel was $0.293 \times 0.293 \times 1$ mm³. Mukunoki (2001) describes the specification of the X-ray CT scanner used in detail.

X-ray CT Image

An X-ray CT image is composed of a CT-value proportional to the material density. It is a digital grey scale image with 256 levels between black and white colors. Black in the two-dimensional (2-D) image indicates the lowest density area while white color indicates the greatest density in the CT image. 3-D CT image can be reconstructed

Table 1. Specification of X-ray CT scanner installed in Kumamoto University

Specification	Configuration
Scanning configuration	translate/rotate with a fan beam (30° aperture angle)
X-ray tube voltage and current	150 kV (4 mA), 200 kV (3 mA) and 300 kV (2 mA)
Number of detectors	176
Scanning conditions	half (180°), full (360°) and double full (720°)
Time resolution	2.5 min (half), 5 min (full) and 10 min (double full)
Spatial resolution	74, 147 and 293 μ m
Beam thickness	0.3, 0.5, 1, 2, 3 and 4 mm
Maximum sample size	150 or 400 mm in diameter
Maximum sample weight	981 N

Fig. 1. Liner relationship between CT-value and density

convoluting 2-D images. Figure 1 presents the relationship of CT-value with the wet density of the soil used as a model ground. As shown in Fig. 1, the CT-value is linear with the material density and represents the density status in the voxel with the above mentioned dimension. This indicates that the CT-value can evaluate the bulk density of the model ground and the particle density of a grain whose size is greater than the dimension of voxel defined. This issue is called “Partial Volume Effect” (Ketchum and Carlson, 2001). In order to evaluate the change of the bulk density in the model ground, the maximum grain size was limited to less than 850 μ m. Therefore partial volume effect was negligible. All details of the CT image analysis can be referred to in Otani et al. (2000) and Mukunoki (2001).

Fig. 2. (a) Illustration of the test apparatus and (b) Photograph of the test apparatus

Test Apparatus

The photos in Fig. 2 illustrate the schematics of the test apparatus and the defect model, respectively (Mukunoki et al., 2006; Mukunoki et al., 2007). The entire shape of the soil box was cylindrical with an inner diameter of 130 mm and was made of acrylic material. The dimensions of the model ground are shown in Fig. 2. Defect configuration as shown in Table 2 (i.e., a square defect, a rectangular defect, a straight slot along the length underground in a half pipe model and a radiation slot along the diameter of a half pipe model) were set at the bottom of the soil box. As for the last two defect cases in Table 2, a space was established in a half pipe model. During the process of soil preparation in the soil box, there was concern about the loss of soil particles through the defective part in the underground pipe. In order to avoid the extra loss

Table 2. Configuration of defects tested

Hydraulic applications	Defect configurations	
Monotonic water inflow test
	Case 1 (Square shape)	Case 2 (Rectangular shape)
Monotonic soil drainage test
	Case 3 (Square shape)	Case 4 (Rectangular shape)
Cyclic test of water inflow-soil drainage
	Case 5 (Square shape)	Case 6 (Rectangular shape)
	B5mm × L50mm D: 50mm Case 7 A straight slit along the length of underground
	B5mm × L78.5mm D: 50mm Case 8 A radiation slit along the direction of diameter	

of soil, sugar was well placed in the underground pipe model at first followed by the soil which was compacted from the top surface of the pipe model. Once water poured through the underground pipe from the bottom of the soil box in step one, the sugar gradually melted and the water poured to the ground without any loss of soil particle in the initial condition. An overburden pressure of 10 kPa was applied through the plate placed on the ground surface by air pressure in order to account for the confining pressure in the soil. Also, holes were present in the plate to drain water from the ground surface.

Soil Materials and Properties

Toyoura sand was used in each model test case. The uniformity coefficient and the coefficient of curvature for Toyoura sand was 5.7 and 1.2 respectively. The model ground was prepared using the static compaction method and the relative density of 80% was controlled for each test. The initial moisture content was regulated to 10–11%; and the initial saturation degree of model ground was 39%.

Test Procedure and Test Cases

The basic concept of the model test conducted in this study is to pour water into the model ground through the defect and to drain water with soil from the defective part. In order to understand the soil behavior due to the condition of water inflow and model ground, several test cases were prepared as shown in Table 2. The parameters to compare the test results are defined as follows:

- 1) Hydraulic application; and,
- 2) Defect configuration.

In this study, the model test apparatus was newly developed to conduct CT scanning.

Monotonic Water Inflow Test

The model ground was scanned to confirm the initial conditions following which 80 cc of water was supplied into the model ground by applying a hydraulic pressure of 10 kPa with a constant hydraulic head of 1 m. In this test, water was supplied through the defective part at the bottom of the soil box and water was drained from the top of the ground surface. The model ground was scanned again. This process was defined as one cycle and this was repeated three times.

Monotonic Soil Drainage Test

The model ground was scanned to confirm initial condition as well as the case of monotonic water inflow test. The model ground had a 100% saturation degree in the initial condition. Water with soil only drains from the bottom of the soil box through the defect model monotonically. A valve at the bottom of the soil box was opened for three seconds to drain the soil. The model ground was then scanned again. This process was defined as one cycle and was repeated 3 times in this case. This test is called soil drainage test in the following section.

Water Inflow—Soil Drainage Cyclic Test

In this case, water was supplied and soil was drained repeatedly through the defect part in the underground pipe. The model ground was scanned to confirm the initial condition following which 100 cc of water was supplied by a hydraulic pressure of 10 kPa. Once 100 cc of water was supplied, the valve was closed and the model ground was scanned to investigate the behavior due to water inflow. After scanning, the valve was opened and kept open till there was no further water dripping with soil. Again, to observe the inner condition after water draining effect, the model ground was scanned. This

process was defined as one cycle, and was repeated until the surface of the model ground was submerged.

Shape of the Defect Configuration

Four different defect configurations were prepared in shapes of 1) square, 2) rectangle, 3) straight slot along the length of the ground on the pipe model, and 4) radiation slot along the direction of diameter on the pipe model. All defects were located at the bottom of the soil box. Each dimension of the defect configuration is summarized in Table 2.

RESULTS AND DISCUSSIONS

Comparison of the Defect Configuration for Water Inflow Test

Figures 3 and 4 present 2-D X-ray CT images for Case 1 (i.e., square shape) and Case 2 (i.e., rectangular shape) at height of 5 mm from the bottom of model ground at each cycle after an inflow of 80 cc water. Figures 3 and 4(a) explain each test case. As shown in both Figures, the defect model existed at the bottom and at the centre of the soil box. The CT images for both cases show low-density area being already generated in the model ground in the 1st cycle. Figure 5 presents the CT-value distribution for both cases. During the 1st cycle of water inflow in both Case 1 and Case 2, the CT-value increased by 200 due to water inflow and the increase of CT-value as shown in Fig. 5 corresponds to an increase in wet density of 0.2 t/m^3 . On the other hand, the CT-value around the centre of the model ground drops by 150 after the 1st cycle and the drop corresponds to a density decrease of 0.15 t/m^3 . Besides, the drop in CT-value developed due to increasing the number of cycles. The drop in CT-value in Figs. 5(a) and (b) corresponds to the low density area ob-

Fig. 3. 2-D X-ray CT images at the height of 5 mm from the bottom of the soil box obtained from the monotonic inflow test for Case 1

Fig. 4. 2-D X-ray CT images at the height of 5 mm from the bottom of the soil box obtained from the monotonic inflow test for Case 2

Fig. 5. CT-value distribution along the diameter of model ground for the monotonic inflow test

Fig. 6. 2-D X-ray CT images obtained from the monotonic drainage test for Case 3

served in the Figs. 3 and 4 respectively. The area where the CT-value drops, which corresponds to the low-density area, can be called “loosening area” in the model ground. However, the apparent difference in the loosening area cannot be observed for both Case 1 and Case 2 despite the area of cross section for Case 1 being the same as for Case 2 (i.e., 5.0×5.0 in Case 1 = 2.5×10.0 in Case 2 = 25 mm^2) comparing Fig. 3 with Fig. 4 or Fig. 5(a) with 5(b).

Comparison of the Defect Configuration in the Soil Drainage Test

Figures 6 and 7 show the CT images at a height of 5 mm and 20 mm for Case 3 and Case 4 at each drainage cycle. Compared to the loosening area of Case 1 and Case

2 as shown in Figs. 3 and 4, the shape of the area for Case 3 and Case 4 is circular; however, they are not at a height of 20 mm in Case 4. The soil behaviour near the defective area due to draining was affected by the defect configuration but it was not far from the defect part.

Figures 8(a) and (b) show CT-value distribution for Case 3 and Case 4. Comparing the distribution of Case 3 and Case 4 with those of Case 1 and Case 2, the CT-value in the loosening area in each cycle in Case 3 and Case 4 change locally only above the defective part within the 3 cycles. The driving force for soil drainage would be gravity in the monotonic soil drainage test. Besides, the elevation head in the water drainage test reduced due to the draining of the soil and therefore, the loosening area did not expand. However, the loosening area obtained from

Fig. 7. 2-D X-ray CT images obtained from the monotonic drainage test for Case 4

Fig. 8. CT-value distribution along the diameter of model ground for the monotonic drainage test

Fig. 9. 2-D X-ray CT images at the height of 5 mm from the bottom of the soil box obtained from the monotonic inflow test for Case 5

the monotonic soil drainage test is apparently greater than that from the monotonic water inflow test.

Comparison of the Defect Configuration in Water Inflow—Soil Drainage Cycle Test

Figures 9 and 10 show CT images at a height of 5 mm from the bottom of the soil box for Case 5 (i.e., square

Fig. 10. 2-D X-ray CT images at the height of 5 mm from the bottom of the soil box obtained from the monotonic inflow test for Case 6

Fig. 11. 2-D X-ray CT images obtained from the monotonic drainage test for Case 7

configuration) and Case 6 (i.e., rectangular configuration) after each water inflow—soil drainage cycle. It was observed that a cavity was generated at the height of 5 mm in the soil box in the 2nd cycle. The cavity vanished in the 3rd cycle for Case 6. These results indicate the following two points: 1) soil particles were interlocked due to draining and 2) wide movement of water caused “interlocking” of soil particles. Likewise, the combined effects of water inflow—soil drainage would cause fatal road subsidence as the base of the road is composed of the sandy soil with uniformed grain size.

Comparison of the Different Defects Configuration on Underground Pipe Model in Water Inflow—Soil Drainage Cyclic Test

Figures 11 and 12 show the 2-D CT images for Cases 7 and 8 at a height of 5 and 30 mm from the bottom of model ground. The image brightness increases with water supply-drainage cycles as shown in Figs. 11(I) and (II) because the saturation degree (i.e., wet density of model ground) increased due to water inflow. As in Case 7 in

Fig. 11(II), water infiltrated through the defects at the bottom of the model ground resulting in the bright area taking a fan shape. This indicates that water radically permeates into the model ground in the 1st cycle. During the soil drainage cycle, soil drained from the defects eventually generating cavity areas as shown in Fig. 11(II).

In CT images taken at the height of 30 mm for Case 7 as shown in Fig. 11(II), cavity area (i.e., black area in images) elliptical in shape generated in Cycle 1 can be observed. Besides, the cavity area expands due to the cycle of water supply-drainage. Similarly, Fig. 12(II) shows a circular cavity generated in Case 8. The cavity in Case 8 did not generate along the curved slot (i.e., defect) but generates from both tips of the slot in the underground pipe model as shown in Fig. 12(II). Based on the results of Case 8, it can be deduced that the cavity was generated from the defective part during the 1st water-supply cycle. Namely, the process of water-supply develops a water pass in the ground which dominates the passage of water-soil drainage. The significant cavity in the soil is developed due to soil draining into the underground pipe.

Fig. 12. 2-D X-ray CT images obtained from the monotonic drainage test for Case 8

Fig. 13. CT-value contour map of model ground for the cyclic test on Case 7

Figures 13 and 14 show CT-value contour maps for Cases 7 and 8, respectively. As shown in Fig. 13, it can be seen that the loosening area grows with an elliptical cylindrical configuration in Case 7, while, two loosening areas grow with concentric circle from the defect part in Case 8. In the plain dimension of the cavity in Case 7, the larger diameter was 84% less than the length of the underground and the shorter diameter is 20% greater than the diameter of the underground model. As in Case 8, the configuration of cavity was almost spherical and the diameter is 52.5 mm.

Fig. 14. CT-value contour map of model ground for the cyclic test on Case 8

Three Dimensional CT Image of Cavity in Soil

Figures 15(I) and (II) present the three-dimensional (3-D) CT images of the loosening area in the model ground reconstructed by convoluting 2-D CT images at each cycle for Case 7 and Case 8 respectively. After image convolution, the CT-values of interest are extracted and then, only loosening area is visualized as shown in Fig. 15. It is important to reasonably define the threshold CT-value to categorize the different areas and to display

Fig. 15. 3-D X-ray CT image of loosening area

them. Authors searched the best threshold value to visualize only the loosening area by repeatedly reconstructing 3-D images until they did not see noise data. In this study, the interested area (i.e., the loosening area with cavity in model ground) with CT-value between -1000 and 350 are presented in Fig. 15. Then, the dimensions of loosening area are measured and presented in each 3-D image from the top and side view in Fig. 15. The image processing program developed in this study can be used for calculating the volume of full-cavity and of loosening area, separately. The volume increment of loosening area in 3rd cycle is 5.2 and 9.0 times greater than those in 1st cycle for Case 7 and Case 8, respectively. As for the defective configuration with a straight slit in Case 7 as shown in Fig. 15(I), the shape of loosening area was affected by the configuration of defective part. The 3-D image from the top view as shown in Fig. 15(I) (a) indicates that the horizontal width of the loosening area is 10 times greater than the width of the straight slit of 2 mm. Probably the loosening area progressively developed due to the draining of water with soil just above the straight slit at first followed by spontaneous movement of soil particles towards the area above the straight slot. This behaviour continued due to the number of test cycles.

On the other hand, the defective configuration with a radiation slot in Case 8 as shown in Fig. 15(II), did not affect the shape of loosening area. Two loosening parts were horizontally grown first at the edge of the radiation slit and were then developed in a vertical direction. This behaviour should be related to the water level in the underground pipe model due to the application of water inflow. In this test, water raised up slowly so there was enough time to lose capillary force between soil particles. Therefore, the model ground around the edge of radiation slit started to create the loosening area. Due to increase in the number of test cycle, two large loosening parts were developed and they were combined in the 3rd

cycle. If water pressure was applied to the model ground along the radiation slot, the shape of loosening part would be a fan shape affected by the defect configuration.

Failure Mechanism in Sand due to Water Inflow and Soil Drainage from the Defected Underground Pipe

From the monotonic water inflow and the monotonic soil drainage tests, fatal failure of model ground could be observed in three steps. The monotonic water inflow test only took the capillary force due to saturation and this condition created the loosening area but not cavity. Then, the monotonic soil drainage test caused the water flow toward the defective part with the hydraulic head in the 100% saturated condition. Therefore, some soils near the defected part were drained at first just after opening the valve so that the cavity was created but it was not large. Spontaneously, the capillary force started to work due to decrease in saturation degree so that large cavity was not created in the sandy ground.

On the other hand, the large cavity was observed at the end of the water inflow—soil drainage cyclic test. Once, water was supplied into the sandy soil, the capillary force was lost. Moreover, soil particles flew into the pore water after water pressure exceeded the effective stress. When the water with soils was immediately drained toward the defective part after water supply, sandy soil kept developing the loosening area and finally created the cavity. Likewise, the factors causing the cavity in the ground were not only the existing defects in the underground pipe but also water flow toward the defective part after the loss of capillary force and effective stress between soil particles.

CONCLUSIONS

A series of model tests subjected to monotonic water inflow test, monotonic soil drainage test and the cyclic test of the water inflow—soil drainage were performed to visualize the ground failure due to each hydraulic appli-

cation. The density change of the inner model ground was visualized in three dimensions without any destruction using the X-ray CT scanner. The following is a summary of conclusions:

- 1) The process of monotonic water inflow developed the water path due to disturbance to the ground and did not create the cavity in the ground;
- 2) Monotonic soil drainage caused the loosening area in the ground to not create the cavity;
- 3) The cyclic condition of water inflow—soil drainage caused a fatal ground failure because the process of water inflow created the water path disturbing the soil and eventually, the soil drained just after being disturbed;
- 4) As the soil did not drain quickly, soil particles interlocked due to drainage and the movement of soil particles were restricted due to the arching effect; and,
- 5) The factors causing the cavity in the ground were not only existing defects in the underground pipe but also the water flow towards the defective part after the loss of capillary force.

For future work, the soils tested will be changed from only sandy soil to decomposed granite which is used in the actual site and the test apparatus will be enlarged to account for scale effect.

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