INVESTIGATION OF FAILURE PATTERNS IN SAND DUE TO Laterally LOADED PILE USING X-RAY CT

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ABSTRACT

The objective of this paper is to investigate three dimensional (3-D) failure patterns in sand due to a laterally loaded pile using X-ray CT. Here, a new apparatus of model loading test in which X-ray CT is employed for monitoring failure pattern of the ground around a pile was developed and a series of model loading tests were conducted using this apparatus. CT scanning was done for the model ground at several levels of loadings which were applied at the pile head. Not only cross sectional images for the ground but also those in 3-D were reconstructed. A proper image processing analysis was conducted in order to obtain effective CT images. And, the failure patterns of the ground under laterally loaded piles were visualized. It is emphasized that three dimensional failure patterns of the ground due to laterally loaded pile were visualized for the first time using X-ray CT.

Key words: failure, lateral loading, lateral resistance, model test, pile, three dimension, visualization, X-ray CT (IGC: E4)

INTRODUCTION

Lateral bearing capacity of a pile foundation is one of the most important issues in foundation engineering practice. In general, ground failure due to a laterally loaded pile is complicated because the behavior of compression and that of stress relaxation take place at the same time in the ground around a pile shaft. As far as design calculation of a laterally loaded pile is concerned, there is a pioneer work done by Broms (Broms, 1964; Broms, 1972). This is a method to obtain the ultimate lateral resistance of a pile and the failure patterns of pile-soil interaction with the parameters of its bending stiffness, length of pile and ground stiffness was proposed. Mayerhof and Ranjan (1972); Reddy and Ramasamy (1973); Reese et al. (1974), and Kishida and Nakai (1979) have also discussed on the failure patterns on both experimental and theoretical aspects, respectively. However, it is considered that these failure patterns were developed under the purpose of conventional design calculation and besides, those have never been proposed based on the real and precise failure patterns in the ground. As far as the future prospect of pile foundation design is concerned, it is worthwhile to investigate more precise behavior of failure patterns in the ground due to a laterally loaded pile, especially its behavior in three dimensions without any destruction.

An X-ray CT scanner has become a useful tool even in geotechnical engineering as a nondestructive testing method. And the authors have done a series of studies on the application of X-ray CT in geotechnical engineering (Otani et al., 2000; Otani et al., 2002; Otani and Obara, 2003; Otani et al., 2005). Normally, the results from CT scanning can be realized as the change of material density and this apparatus produces visual images for not only in cross section but also the images in three dimensions.

The purpose of this paper is to investigate three dimensional (3-D) failure patterns in sand due to a laterally loaded pile using an industrial X-ray CT scanner. Lateral bearing capacity mechanism of a pile foundation is discussed based on the results of CT scanning. First of all, a new model test apparatus of laterally loaded pile, especially for X-ray CT is introduced, in which X-ray CT scanning can be conducted during the process of pile loading. A series of pile loading test are conducted with increasing applied load. CT scanning of the model ground is conducted at several loading steps and a number of cross sectional images of the failure patterns in each loading level are produced. From those cross sectional images, 3-D images are reconstructed using a proper image processing analysis. Based on all the results, 3-D lateral bearing capacity mechanism of pile foundation is discussed. Besides, its quantitative discussion is made on the ultimate bearing capacity of

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Photo 1. New test apparatus

Fig. 1. Details of model test apparatus

laterally loaded pile. Finally, it should be noted that three dimensional failure patterns of the ground due to laterally loaded pile are visualized using X-ray CT for the first time.

NEW MODEL TEST APPARATUS FOR X-RAY CT

General picture of a new test apparatus is shown in Photo 1. Details of this apparatus are shown in Fig. 1 and its specification is listed in Table 1. This apparatus is composed of a soil box, a loading machine, a force transmission system, and a control equipment. Confining pressure can be also applied at the top of the soil box by air. Photo 2 shows the setup of this apparatus on the specimen table of X-ray CT system. It is noted that

Photo 2. Setup of test apparatus in the CT room

Table 1. Specification of new test apparatus

Maximum capacity of loading (N)	1000
Maximum loading speed (mm/s)	100
Minimum loading speed (mm/s)	0.05
Maximum capacity of confining air pressure (MPa)	0.2
Size of soil specimen	Diameter: 120 mm × Height: 330 mm

during process of CT scanning, there should be no obstacles around the soil box that interfere with X-ray CT imaging. The soil box was made of acrylic material. Upper and lower bases of the box were made of aluminum with 35 mm and 45 mm in thickness in order to be highly stable and lightweight enough when this box is set on the specimen table. It also includes an axle for force transmission, which is connected to the loading machine by a vertical beam, as shown in Photo 1. The force is applied at the pile head under displacement control.

PILE LOADING TEST

Soil used in this test was Toyoura sand. Its properties are shown in Table 2. Figure 2 shows model pile with strain gauges. A rectangular cross sectional shape of the pile whose size was 20 mm in width and 5.0 mm in thickness made of aluminum was used in this test in order to obtain a clear failure pattern in the ground although most of the piles are circular in shape. As shown in Fig. 2, material properties of model pile were Young's modulus, E of 7.03×10^4 MPa, Poisson's ratio, ν of 0.345, and bending stiffness, EI of 9.37×10^5 Nmm². The scale of the pile and its loading levels were determined by considering in-situ displacement distribution of the pile foundation and the size of the soil box. In order to obtain the distribution of lateral displacements along the pile shaft, 20 strain gauges were installed on the model pile as shown in Fig. 2. All the measurements were operated using a personal computer. Pile loading test and CT scanning

were conducted as a consecutive test. Following is a summary of the test procedure:

- (1) As shown in Fig. 1, firstly, the model pile was fixed to the bottom of the soil box and then, sand was

Table 2. Property of Toyoura sand

Maximum dry density (t/m^3)	1.66
Minimum dry density (t/m^3)	1.34
Specific gravity	2.65
Relative density (%)	87.0–91.0

- (2) Step-by-step loading was applied under displacement control and the CT scanning was conducted at several loading steps. The displacement at the pile head was automatically measured due to the movement of axle shown in Photo 1 and CT scanning was conducted at the displacement levels of 5 mm, 7 mm, 9 mm, 11 mm, 13 mm, and 15 mm, respectively. It is noted that the loading had to be

Fig. 2. Model pile with strain gauges

Fig. 3. Distributions of strains, bending moments, and displacements on the pile

stopped during CT scanning and normally it took about 5 minutes in order to obtain single cross sectional CT image.

- (3) In each of the four displacement cases (5 mm, 7 mm, 9 mm, and 11 mm), only 4 slices with every 20 mm thickness were scanned. For the case of 13 mm displacement, 46 slices were scanned while 61 slices for the case of 15 mm displacement were scanned, respectively, with every 1 mm thickness of slice including initial condition in order to reconstruct a highly accurate 3-D images. The scanning started at the depth of 13 mm under the ground surface until the maximum depth of 73 mm.

TEST RESULTS AND DISCUSSION

Load-Displacement Relationship

Figure 3 shows the results of the measurements from strain gauges. Those are the distributions of strain along the pile shaft, and those of moment and lateral displacement-

ment distributions. After obtaining the distributions of the strain on the pile shaft, the moment can be calculated. Here, seventh-order equation for the distribution of the moments was used. Finally, displacement distribution can be obtained by integrating twice of the moment equation. Figure 4 shows the relationship between load and displacement at the pile head. It is easily realized that the load increases as the displacement increases with nonlinear characteristics.

Cross Sectional CT Images

Figure 5 shows cross sectional images for six displacement levels (5 mm, 7 mm, 9 mm, 11 mm, 13 mm, and 15 mm) including initial condition at four different depths of the ground from its surface. In general, so called "CT-value" is the only output for X-ray CT and CT image is constructed by 256 levels of black and white colors based on the spatial distribution of CT-value in the material. Figure 6 shows the relationship between the CT-value and relative density for Toyoura sand. These results show a

Fig. 4. Load-displacement relationship

Fig. 6. Relationship between CT-value and dry density for Toyoura sand

Fig. 5. Cross sectional images

Fig. 7. 3-D reconstruction images

linear relation between CT-value and relative density, so that the CT-value can be a parameter for evaluating the change of the density. White or bright colors show the area of high density while black or dark colors show that of low density in the CT image. It is noted that for more precise information on understanding CT image, the papers by Otani et al. (2000) and Otani et al. (2002) may be referred. It can be realized from Fig. 5 that the area of strain localization, which shows the banded area of black color in the image, appears in the ground towards the direction of applied load and these are extended as loading level increases. It is also observed that the size of this localization becomes smaller as the depth of the ground increases. It is noted that there is a low density area around the pile shaft at the opposite side of the loading direction behind the pile shaft. It is considered that this behavior is caused by stress relaxation, as if the active earth pressure state was generated along the pile shaft. According to the references by Reese et al. (1974) or Kishida and Nakai (1979), this active earth pressure was included in the force equilibrium equation for the design calculation. However, the purpose of this paper is basically on the soil resistance due to laterally loaded pile. Therefore, only the failure zone at the direction of pile loading is discussed.

Visualization of Failure Patterns

Figure 7 shows 3-D reconstruction images through soil box including pile at the area from the ground surface to the depths of 53 mm and 73 mm at displacement levels of 13 mm and 15 mm, respectively. Each of these cases includes two color images depicted in two different directions. In general, some noises are included on the resulted CT-values and here, these noises were eliminated by using smoothing technique which is a common technique in the image analysis. As realized easily, a large number of low density or strain localization zones

appear. It is considered that this strain localization seem to be failure surface due to laterally loaded pile in three dimensions. As seen in those images, there is a large number of this area. The size of this area tends to decrease along the pile depth. Therefore, it can be said that the area within this localization is the area of soil resistance due to passive earth pressure against lateral pile loading and can be realized as a failure zone for the calculation of lateral bearing capacity which could be used in limit equilibrium method or upper bound analysis in the limit analysis.

Quantitative Discussion

Although the failure patterns of the ground was visualized based on CT images in both 2-D and 3-D, more quantitative discussion is indispensable. Figure 8 shows the results of image processing analysis, which are total failure surfaces at six different displacement levels (5 mm, 7 mm, 9 mm, 11 mm, 13 mm, and 15 mm). The pile shaft after displacement in each loading step is also added in these figures. The area of strain localization has always certain width in the CT image. There is a common technique in the image processing analysis called thinning technique which is a method to make a thin trace from the area of strain localization. Here, this technique was used in order to obtain the failure surface under the assumption of ellipse shape in each horizontal cross section. It is realized that when the lateral load is increased, this failure zone is enlarged. It is interesting to note that the angle of this failure zone at the bottom of conical shape against pile becomes larger with the increase in pile loading level. Figure 9 shows the failure pattern proposed by Reese et al. (1974). Mayerhof and Ranjan (1972), Reddy and Ramasamy (1973) and Kishida and Nakai (1979) have proposed the same type of failure pattern. The failure patterns obtained in this study is somewhat different from the failure patterns suggested,

Fig. 8. Failure patterns due to a laterally loaded pile

Fig. 9. Failure pattern suggested by Reese et al. (Reese et al., 1974)

Fig. 10. Definition of failure zone

so far. This paper may be the first time to investigate the progressive failure patterns during loading process in three dimensions. In order to discuss more details of this progressive failure, the changes of volume and angle of failure zone defined in Fig. 10 were calculated from the 3-D reconstruction images. Figure 11 shows the change of

Fig. 11. Relationship between failure angle and pile displacement

Fig. 12. Relationship between failure volume and pile displacement

the failure angle against the increase of pile loading while Fig. 12 shows the same change for the volume of failure zone. It is easy to realize from these results that both values increase with the increase in pile loading level but the increments of these changes become smaller at certain loading steps. This means that there are some ultimate values for this angle and the volume of failure zone.

Therefore, it may be concluded that there exists an ultimate failure stage for lateral bearing capacity of a pile and this should be considered to be a failure pattern for the calculation of ultimate bearing capacity.

CONCLUSIONS

Failure patterns in sand due to a laterally loaded pile were observed precisely by conducting model loading test with X-ray CT scanning. A new model test apparatus of laterally loaded pile especially for X-ray CT was developed in order to discuss more precise behavior. Not only visualization of the failure patterns but also its quantitative discussion were examined in three dimensions. The conclusions drawn from this study are summarized as follows:

- 1) The failure patterns in sand due to a laterally loaded pile were visualized for the first time using X-ray CT scanner.
- 2) The failure of the ground due to lateral pile loading is the type of progressive one and the failure zone is extended with the increase in pile loading level.
- 3) The size of failure zone decreases with the increase in the ground depth along the pile and the shape of this failure zone is almost conical in three dimensions.
- 4) Volume and angle of failure zone increase with the increase in pile loading level but there exists an ultimate value at some loading stages.

The density of the model ground was relatively high in this study and therefore, the discussion on the results obtained here may be limited to the condition of relatively high density of the ground. However, it is the first time that the failure patterns in sand due to laterally loaded pile were obtained in three dimensions without any destruction using industrial X-ray CT scanner. Based on the results here in this paper, quantitative bearing capacity analysis will be able to be conducted with the assumption of the failure patterns obtained in this paper

and those of progressive ones will be also calculated. The final goal of this research is to show the nonlinear characteristics of force-displacement relationship with step-by-step failure patterns and at the same time, the progressive bearing capacities are calculated using those progressive failure patterns. Therefore, although the scale effect of the model test should be verified more precisely, it is confirmed that the failure patterns obtained from this paper could be a valuable information for the progress of lateral bearing capacity of pile foundations. It is believed that the proposed model loading apparatus with CT scanning make quantitative pile foundation design possible after conducting a series of those tests with several different test conditions.

REFERENCES

- 1) Broms, B. B. (1964): Lateral resistance of piles in cohesionless soils, *Proc. ASCE* 90, **SM** (3), 27–63.
- 2) Broms, B. B. (1972): Stability of flexible structures (Pile and pile groups), *Proc. 5th Eur. Conf. SMFE*, **2**, 239–269.
- 3) Kishida, H. and Nakai, S. (1979): Analysis of a laterally loaded pipe with non-linear subgrade reaction, *Transaction of Architectural Institute of Japan*, **281**, 41–55 (in Japanese).
- 4) Mayerhof, G. G. and Ranjan, G. (1972): The bearing capacity of rigid piles under inclined loads in sand I: vertical piles, *Can. Geotech. J.*, **9**, 430–446.
- 5) Otani, J. and Obara, Y. (2003): *X-ray CT for Geomaterials*, Balkema Publishers, Netherlands.
- 6) Otani, J., Mukunoki, T. and Obara, Y. (2000): Application of X-ray CT method for characterization of failure in soils, *Soils and Foundations*, **40**(2), 111–118.
- 7) Otani, J., Mukunoki, T. and Kikuchi, Y. (2002): Visualization for engineering property of in-situ light weight soils with air foams, *Soils and Foundations*, **42**(3), 93–105.
- 8) Otani, J., Mukunoki, T. and Sugawara, K. (2005): Evaluation of particle crushing in soils using X-ray CT data, *Soils and Foundations*, **45**(1), 99–108.
- 9) Reddy, A. S. and Ramasamy, G. (1973): Analysis of an axially and laterally loaded tapered pile in sand, *Soils and Foundations*, **13**(4), 15–27.
- 10) Reese, L. C., Cox, W. R. and Koop, F. D. (1974): Analysis of laterally loaded piles in sand, *Proc. Offshore Technol. Conf.*, Houston, TX, OTC2080.