International Journal of GEOMATE, June 2019, Vol.16, Issue 58, pp.90 - 96
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2019.58.8164
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

EVALUATION OF FILLER MATERIAL BEHAVIOR IN PRE-BORED PILE FOUNDATION SYSTEM DUE TO SLOW CYCLIC LATERAL LOADING IN SANDY SOIL

*Adhitya Yoga Purnama[1], Noriyuki Yasufuku[2] and Ahmad Rifa'i[3]

[1,2]Faculty of Engineering, Kyushu University, Japan; [3] Faculty of Engineering, Universitas Gadjah Mada, Indonesia

*Corresponding Author, Received: 21 Oct. 2018, Revised: 29 Dec. 2018, Accepted: 14 Jan. 2019

ABSTRACT: Maintenance of a bridge structure is still the main issue in Indonesia due to the high cost of maintaining the elastomeric bearing especially in the remote area. Integral abutment bridges are becoming popular because the elastomeric bearings are eliminated, which can reduce the maintenance costs. Pre-bored pile foundation system is a typical foundation for integral bridge abutment to supports lateral displacement due to thermal expansion of the girder bridge. Pre-bored pile foundation system can be used to increase the pile flexibility using a pre-bored hole that filled with elastic materials such as bentonite slurry, loose sand or gravel. Some of the integral abutment bridges foundation design has proposed, but the previous studies only focus on the structural system, the soil characteristic behavior and soil response due to this system are still rarely explained. Therefore, it is necessary to examine the effects of cyclic loads on the filler material inside the pre-bored ring. The soil behavior for ground soil and filler material due to cyclic lateral loading were performed using macro-scale testing. In this paper, a series of two-way lateral cyclic loading tests were performed to evaluate the effect of slow cyclic lateral loading on the filler material behavior of the pre-bored pile foundation system. The experimental setup is explained in details, and the results are presented in the form of normalized bending moment and maximum lateral capacity charts against the number of cycles. Moreover, the densification effect of the filler material inside the pre-bored system due to the cyclic loading was evaluated.

Keywords: Pre-bored pile foundation, Filler material, Cyclic lateral loading, Experimental test

1. INTRODUCTION

Maintenance of a building in Indonesia is still the main issue. So many infrastructures are built, but long-term consideration about the maintenance of a building is still neglected. The bridge structure is a building that needs to be maintained, especially for the elastomeric bearing. The elastomeric bearing of a bridge was made from rubber combined with steel plate. In order to maintain this elastomeric bearing, the girder of the bridge needs to be lifted upward using heavy equipment that needs a high cost. Integral abutment bridges are becoming popular around the world, but the standard design is different from one country to another. This causes the different technical approach design to solve the same problem in every country. Conventional bridges are designed with elastomeric bearing and other structural releases that allow the girder to expand or shrink freely due to environmental thermal force.

The integral-abutment bridge is less expensive because elastomeric bearings are eliminated in the bridge deck which reduces the initial construction and maintenance costs [1]. However, when the elastomeric bearing and other structural releases are eliminated, thermal forces are followed into the bridge and it needs to be considered in the design approach. More than half of the state highway agencies in the United States of America have accepted the design of integral abutment bridges, but all have limitations on a safe length for such bridges [2]. Based on [3], the integral abutment bridge was not mentioned clearly, but it mentioned that all bridge design should be considered for the thermal movements of the girder. The foundation system of the integral bridge needs to consider on the girder displacement due to thermal expansion that allowed in this system. Pile foundation needs to be more flexible because there is no elastomeric bearing which is provided in a conventional bridge. There is no general standard design to analyze the foundation system of the integral bridge and it is still developed by researchers.

The integral abutment bridge causes the pile foundation connection to become fixed. However, it will cause relatively high pile stresses and bending moment due to lateral displacement of the bridge. In order to reduce the stresses, the connection between abutment and girder can be design as a pinned-head or create a hinge connection. The other method is attaching the piles in pre-bored holes (also called predrilled or pre-excavated) as shown in Fig. 1. Based on [4], it shows that the Iowa Department of Transportation in 2006 proposed the pre-bored hole diameter is twice of the pile diameter with 3.05 m of depth. The depth of the holes can be changed for the special condition. The pile was installed on the pre-drilled hole followed by inserting the ring in the hole. The area between pile and ring was filled with the elastic filler material to maintain the displacement of the pile due to lateral loads. A steel or concrete ring should be placed in the hole to separate the filler material and ground soil. This ring is expected to maintain the filler material properties inside the hole in long-term conditions due to cyclic loading.

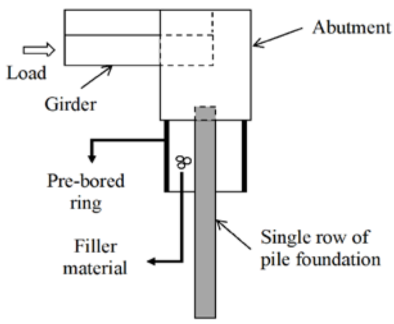

Fig. 1 Typical design of integral abutment bridge with a pre-bored hole system.

The thermal loading, equivalent to a change in temperature up to 42 °C, is corresponded to a change in displacement up to 0.023 m (about 6-7% of pile dimension) with pile dimension design of 0.376 m x 0.356 m as shown in [5]. They suggested a galvanized steel sleeve of 0.6 m in diameter filled with sand is sufficient for accommodating the lateral pressure from the girder bridge due to thermal loading. The holes in empty condition may cause long-term maintenance problems, so the holes should be filled with an elastic material, such as bentonite, loose sand, or pea gravel. The previous researchers only focus on the structural system, but the behavior of soil and soil response due to the flexible piling design is still rarely explained. The characteristic of filler material and standard design of this foundation system is still in development.

In this study, the effectiveness of filler material properties such as soil uniformity and density are evaluated to reduce the pile bending moment. The effective dimension of the pre-bored hole that can maintain the bending moment along the pile also evaluated in this research. The appropriate filler properties and dimension of this system are expected to reduce the bending moment along the pile due to lateral displacement loading which can solve the problem on the integral abutment bridge foundation. The effective system will be evaluated by considering the soil behavior due to cyclic lateral loading on the pile foundation.

2. METHODOLOGY

Macro-scale testing of single pile model was performed to determine soil behavior due to cyclic lateral loading and to evaluate the effectiveness of this system.

2.1 Properties of Soil and Pile Model

The soil, used in this experimental study, is Toyoura sand, Kumamoto sand of K7 (fine sand) and Mixed soil (K4 and K7 soil) as a filler material which has uniformity coefficient range from 1.24 to 4.67. The index properties of each soil are given in Table 1. Fig. 2 shows the grain size distribution of the soil sample used in this study.

Table 1 Index properties of soil

Soil properties	Toyoura	K-7	Mix Soil
D_{50} (mm)	0.18	0.17	0.29
Uniformity, U_c	1.40	2.96	4.67
ρ_{max} (gr/cm^3)	1.60	1.51	1.63
ρ_{min} (gr/cm^3)	1.31	1.18	1.30

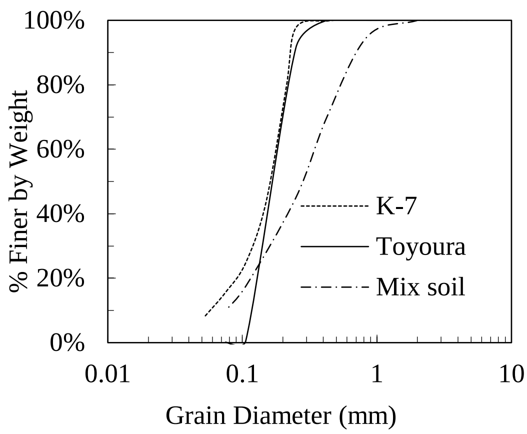

Fig. 2 Grain size distribution of soil

The pile and ring models are manufactured from a closed-end aluminum alloy pipe. The outer diameter (D) of the pile model is 15 mm with a thickness of 1.2 mm and 450 mm of pile length. Three different ring diameters (d) of 45 mm (3D), 60 mm (4D), and 75 mm (5D) with a thickness of 2 mm. Based on [6] the lateral performance of a pile was highly affected by the stiffness of the surface with the layer depth ratio (x/D) of 2. However, the plastic deformation still occurred in this area that inflicts the changing of soil properties due to cyclic loading [7]. So, in this experiment, 150 mm (10D) of ring length is used.

Young's Modulus of the used aluminum alloy pile model is 7x10^{10} kN/m^2. Equivalence law is used for designing pile material, dimensions, loading speed and displacement. The scaling formula as shown in Eq. (1), proposed by [8] is used in this research.

$$\frac{E_m I_m}{E_p I_p} = \frac{1}{n^5} \quad (1)$$

Where: E_m is the modulus of elasticity of pile model, E_p is the modulus of elasticity of prototype pile, I_m is the moment of inertia of model pile, I_p is the moment of inertia of prototype pile, and n is the scale factor for length.

2.2 Experimental Test Setup

Laboratory test setup which is used for testing during the experimental course in this study is shown in Fig. 3. The testing equipment consists of a testing tank that is made from an acrylic plate, and it is supported by a steel frame. The cyclic loading device and measuring device are used to record data and control the number of lateral displacement load applied on the pile head. The laboratory test was performed using a pile model test inserted in sandy soil. On the top area of the pile, a ring was placed and filled with filler material that has different soil grain size and uniformity coefficient. Lateral cyclic displacement was applied to the pile head.

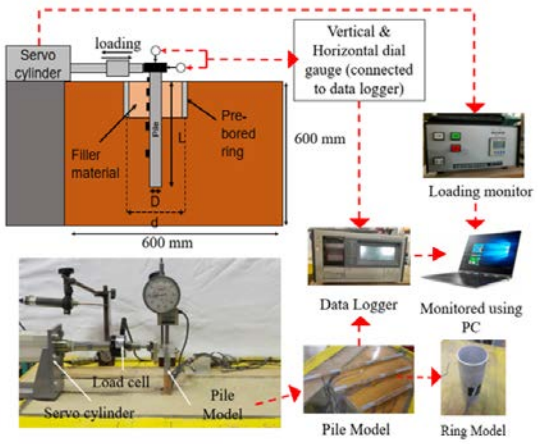

Fig.3 Experimental test setup.

2.3 Testing Procedure

The sinusoidal harmonic lateral displacement applied to the pile head model during experimental testing as shown in Fig. 4. Two-way symmetric cyclic lateral loading is applied on two opposite sides of a pile head model to provide horizontal deflection on the pile head. In case of pre-bored pile foundation model test, pile head displacement of 1 mm (about 6% of pile diameter) was applied to evaluate the behavior of soil and pre-bored pile structure impacted by girder displacement due to thermal force. The cyclic lateral load is applied by frequencies of 0.025 Hz. It is applied until 50 times of cycles (N=50) in all experiments, so it can illustrate the impact of the slow cyclic lateral displacement loading of a girder bridge. The bending moment, lateral load capacity, and horizontal displacement were measured and monitored during the test.

Three experimental characteristics were conducted in this experimental study, pre-bored ring filled with different soil density, pre-bored pile filled with different soil type, pre-bored pile with different ring diameter ratio (d/D). All of the cases were tested with two-way symmetric cyclic lateral loading of 1 mm on the pile head until reach 50 times of cyclic loading. The detailed test cases (10 tests) and the associated test conditions are represented in Table 2.

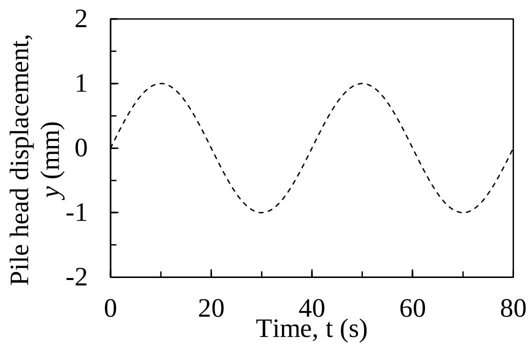

Fig. 4 Typical sinusoidal loading pattern.

Table 2 Number of experimental tests conditions.

Pre-bored system (Ground soil: K7 sand, Dr=80%)				
Test ID	Filler type	Dr (%)	d/D	Load freq. (Hz)
OL01	1-Layered	80	-	0.025
PB01	Toyoura	40	4	0.025
PB02	Toyoura	70	4	0.025
PB03	Toyoura	90	4	0.025
PB04	Toyoura	70	3	0.025
PB05	Toyoura	70	5	0.025
PB06	Toyoura	70	4	0.0125
PB07	Toyoura	70	4	0.05
PB08	K7	70	4	0.025
PB09	Mix soil	70	4	0.025

3. RESULTS AND DISCUSSIONS

The main focus of this experiment is the measurement of the pile bending moment and lateral load capacity which is periodically monitored by using attached strain gauges along the pile. To investigate the effect of filler material to the lateral capacity of the pile, the initial modulus of soil subgrade reaction $(K_h)_i$ was generally calculated by using the Eq. (2).

$$(K_h)_i = \frac{\Delta H}{\Delta y.D} \tag{2}$$

Where ΔH is lateral load, Δy is lateral displacement and D is the diameter of the pile. Initial modulus of soil subgrade reaction $(K_h)_i$ has an essential role in calculating lateral pile capacity [9]. The normalized bending moment, which is the ratio of the measured bending moment to the yielding moment of pile material (M_m/M_y), were estimated. The bending moment is calculated from the bending strain measured at various points along the length of the instrumented model piles using the Eq. (3).

$$M_m = \frac{EI\varepsilon}{r} \tag{3}$$

Where E is Young's modulus of the model pile material, I is a moment of inertia of the model pile, ε is measured bending strain and r is horizontal distance between strain gauge position (outer surface of the pile) and neutral axis. Yielding moment (M_y) of the pile model is calculated by using Eq. (4), with σ_y is yield stress of model pile material.

$$M_y = \frac{\sigma_y I}{r} \tag{4}$$

3.1 Lateral Capacity of Pile

Results of cyclic lateral load-displacement tests for the pre-bored system with different filler material density of 40%, 70%, and 90% are shown in Fig. 5. The change of maximum lateral pile capacity during the cyclic loading is shown in Fig. 5. It was observed that the maximum lateral pile capacity at the first time of cyclic loading reached to 19.68 N, 21.63 N, and 24.79 N for each density of 40%, 70%, and 90%. Based on Fig. 5, it can be noticed that the filler material with 40% of density generates a lowest lateral capacity and also the lowest value of $(K_h)_i$. However, these values significantly increase with increasing of loading cycles number (N) as shown in Fig. 6. For another density, the lateral capacity and $(K_h)_i$ were increased, but it is not in a significant different from the first cycle until 50 times of the cycle. It indicates that the cyclic loading leads to improve the properties and reduction of the void ratio of filler material inside the ring. The soil particle was moving and causing the hardening of soil. Consequently, enhancement of soil properties occurs for loose sand and confining pressure increases during cyclic loading. On the other hand, the 70% and 90% of density provide a stable lateral capacity and $(K_h)_i$ until 50 times of cyclic loading.

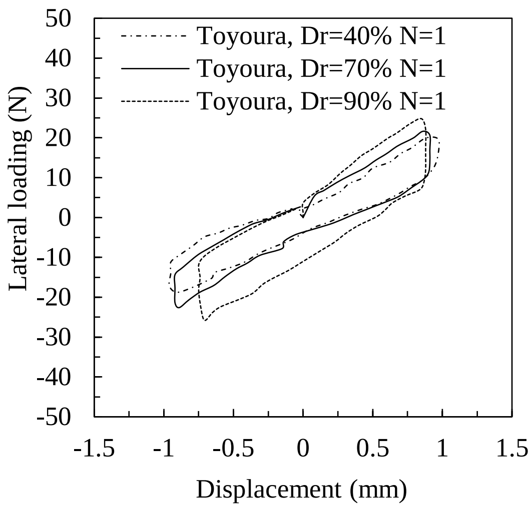

Fig. 5 Hysteretic lateral displacement curve for the pre-bored system filled with different soil density

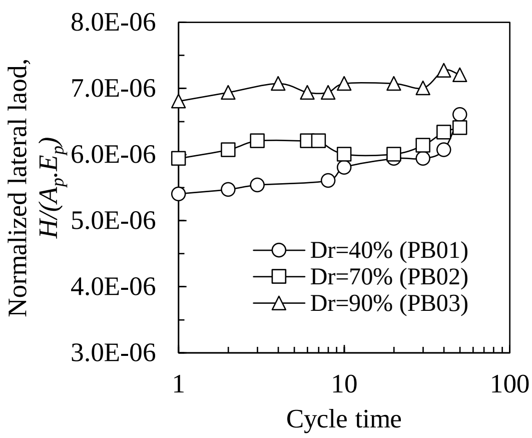

Fig. 6 Effect of soil density on the lateral capacity of pre-bored pile system

3.2 Effect of Soil Type

The effect of soil type also evaluated to determine the effect of filler material properties that can maintain the pile bending moment during the lateral cyclic loading. Three types of soil with uniformity coefficient in a range of 1.40 to 4.67 were used as filler material. Toyoura sand with the lowest and Mix soil with the highest uniformity coefficient. The result was shown in Fig. 7. Based on Fig. 7, the K7 soil provides the lowest and Toyoura sand provide the highest bending moment at the first time of loading (static load).

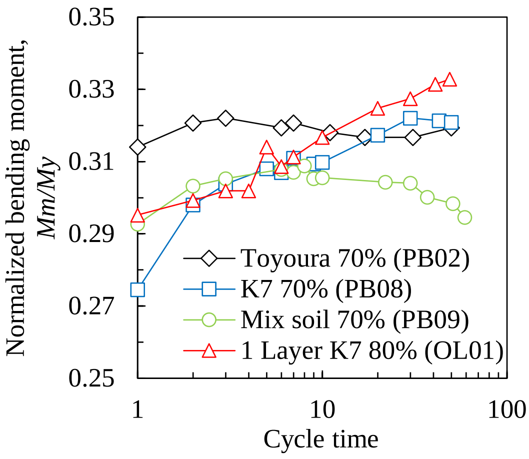

Fig. 7 Effect of soil uniformity on bending moment of pre-bored pile system

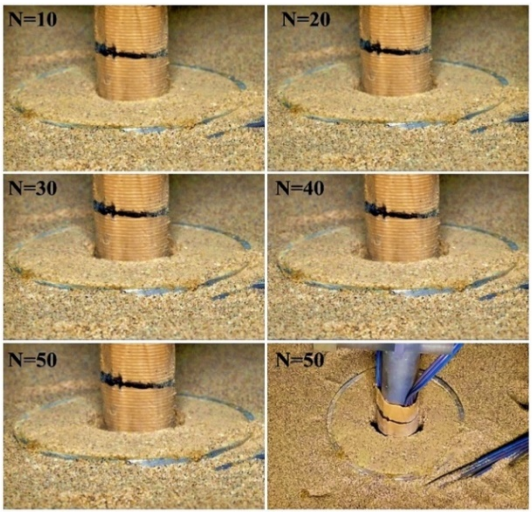

Fig. 8 Plastic deformation after cyclic loading applied.

However, the value of bending moment on K7 soil is increased significantly during the cyclic loading. This occurred due to the K7 sand consists of some fine particles that are filled the particle void during the cyclic loading and increase the stiffness of soil. The Mix soil which has a well-graded particle distribution provide the small bending moment and increases with the increasing of cycle number. However, after 20 times of cyclic loading, the values of bending moment are reduced until the end of loading. This happened due to the plastic deformation occurred on the soil, as shown in Fig. 8, that reduced the soil-pile interaction.

Based on Fig. 8, it shows that the plastic deformation occurred after cyclic loading number (N) of 20 and it increases until 50 times of cyclic loading. This plastic deformation effect on the soil-pile interaction that reduces the soil resistance on pile during the lateral cyclic loading.

3.3 Effect of Ring Diameter

The plastic deformation of soil was created on the soil surface due to cyclic lateral loading. It was extended laterally as a shape of an ellipse with major and minor axes of 6*D* and 4*D* after applying 50 two-way lateral cyclic loading with 3 mm of pile head displacement [10]. Based on the test results of the one-layered test with 1 mm pile head displacement (OL01), the plastic deformation width of soil is about 30-40 mm, or 2 to 3 times of pile diameter as shown in Fig. 9. Three types of ring diameter were used in this experimental study. The ring diameter ratio, the ratio between ring diameter (*d*) and pile diameter (*D*), of 3*D*, 4*D*, and 5*D* were used to determine the effect of ring diameter on filler material behavior due to cyclic lateral loading.

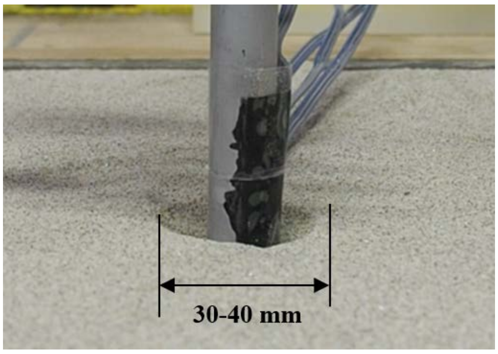

Fig. 9 Conditions after 50 times of loading with pile head displacement of 1 mm.

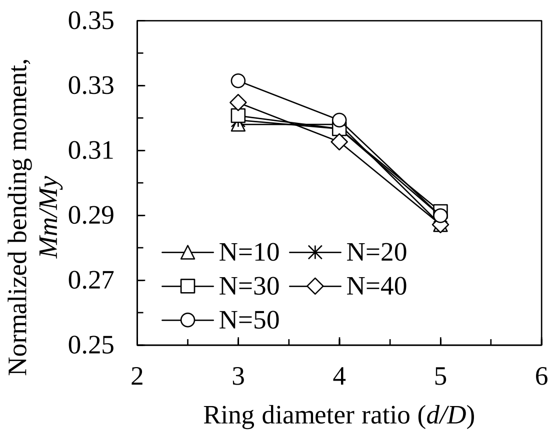

Fig. 10 Effect of ring diameter due to cyclic loading.

The effect of ring diameter on the bending moment of the pile during the cyclic loading is shown in Fig. 10. Based on Fig. 10, the bigger diameter of the ring provides a smaller bending moment of the pile during the cyclic loading. The ring diameter ratio lower than 4 provides a similar result of bending moment during the cyclic loading. It indicates that the bending moment of the pile can be affected by attachment of pre-bored ring. However, the ring diameter inside the plastic deformation area of soil is not recommended because it can inflict the movement of the pre-bored ring.

3.4 Comparison of Experiment and Numerical Analysis

Numerical analysis using 2D Finite Element Analysis (FEM) was performed to evaluate the effect of pre-bored ring diameter when monotonic lateral loading applied on the pile head. In this numerical analysis, the pile assumes as a continuous wall in plain strain conditions. Geometrical idealization used for soil analysis according to equivalent pile stiffness method and soil conditions idealized by the hardening soil model. In this analysis, the wall thickness is same with the pile model width, and the equivalent stiffness of the wall (E_{eq}) is the average of pile and soil stiffness [11] as shown in the Eq. (5).

$$E_{eq} = \frac{E_p A_p + E_s A_s}{A_t} \tag{5}$$

Where, E_p, A_p, E_s, A_s, A_t are pile stiffness, pile area, soil stiffness, soil area and the total area of pile and soil. The initial condition of the numerical model is shown in Fig. 11. The parameter input is conducted based on the Triaxial consolidated drained (CD) laboratory test. The input parameters used in the modeling are shown in Table 3.

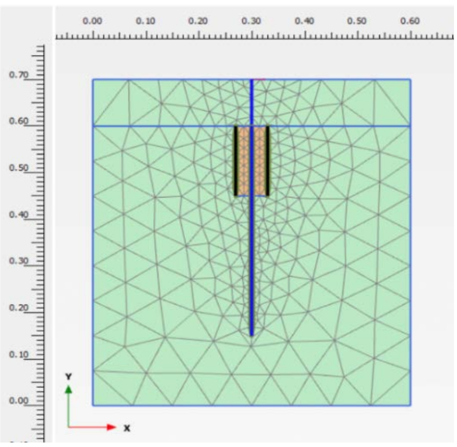

Fig. 11 Finite Element Method (2D) analysis mesh

Table 3 Input parameter for 2D FEM analysis

Soil properties	Toyoura (Filler)	K-7
Dry density (kN/m^3)	14.72	14.13
Cohesion (kN/m^2)	0.91	0.11
Friction angle, ϕ (°)	36.67	38.03
Elastic modulus (kN/m^2)	12685	7590
Poisson's ratio, ν	0.26	0.25
Dilatancy angle, ψ (°)	7.61	7.30

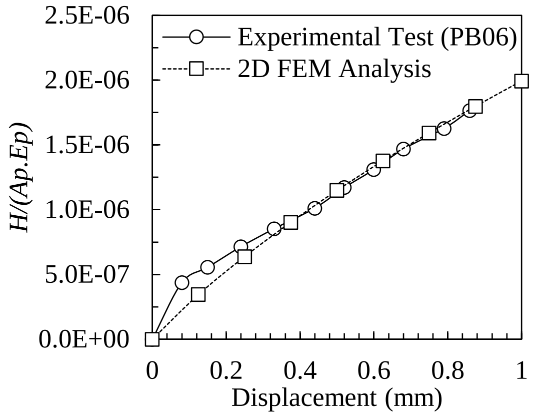

Fig. 12 Comparison between experimental and 2D numerical analysis

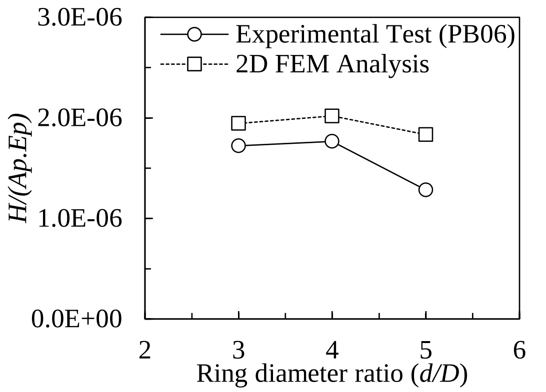

Fig. 13 Effect of ring diameter on the experimental test and 2D FEM analysis conditions

The result of 2D FEM analysis is shown in Fig. 12 compared to the experimental test for monotonic loading condition. Based on Fig. 12, the result of normalized lateral loading, $H/(A_p.E_p)$, for both numerical and experimental test provide a similar relation. The comparison of normalized lateral loading, $H/(A_p.E_p)$, between 2D FEM analysis and experimental results are shown in Fig. 13. The changing of the pre-bored ring diameter results the bigger diameter of the ring provides a smaller lateral load, *H*, for both experimental and 2D FEM analysis in monotonic loading conditions. The ring diameter ratio lower than 4 provides a similar result of lateral pile capacity. It indicates that the lateral pile capacity of pile also affected by of pre-bored ring dimension. The gap between 2D FEM analysis (plain strain) and experimental test (1g model) results occurred due to the effect of boundary conditions from each analysis.

4. CONCLUSIONS

The filler material with low uniformity (uniform soil) provides a stable bending moment value during the cyclic loading. On the other hand, the utilization of filler material using non-uniform soil is difficult to maintain the filler properties because the soil hardening has occurred during the cyclic loading. This soil hardening inflicts a plastic deformation on the top area of the pile and it is effected on the soil-pile interaction that reduces the soil resistance on pile during the lateral cyclic loading.

Filler material with low uniformity coefficient and medium or high density provide a stable pile performance during the cyclic loading. So, it can maintain the lateral displacement due to thermal expansion on the integral bridge abutment foundation system. The effective diameter of the ring is recommended more than the plastic deformation area of the soil for a shallow depth of ring to separate the filler material inside the ring and ground soil. In this research there is a limitation of data to evaluate the system, further data is required to get comprehensive results in the future.

5. ACKNOWLEDGMENT

The authors express their gratitude to Dr. Ryohei Ishikura, Associate Professor of Kyushu University, for his helpful and fruitful discussion and advice in conducting the research. Furthermore, the authors would also like to acknowledge with much appreciation the crucial role of the staff of Mr. Michio Nakashima who gave the support to prepare all the required equipment and the necessary materials to complete the research.

6. REFERENCES

[1] Girton D. D., Hawkinson T. R., and Greimann L. F., Validation of Design Recommendations for Integral-Abutment Piles. Journal of Structural Engineering, Vol 117, Issue 7, 1991, pp.2117-2134.

[2] Greimann L. F., Abendroth R. E., Jonshon D, E., and Ebner, P. B., Pile Design and Tests for Integral Abutment Bridges. Final Rep. Iowa DOT Project HR-273, Iowa State Univ., 1987, pp.3-6.

[3] The American Association of State Highway Officials, Standard Specifications of Highway and Bridges. The Association of General Offices, Ed. 11, 1973, pp.108.

[4] Dunker K. F., and Liu D., Foundations for Integral Abutments. Pract. Period. Struct. Des. Constr., Vol 12, Issue 1, 2007, pp.22-30.

[5] Khodair Y.A., and Hassiotis S., Analysis of Soil–pile Interaction in Integral Abutment. Computers and Geotechnics, Vol 32, 2005, pp.201–209.

[6] Yang K., and Liang R., Numerical Solution for Laterally Loaded Piles in Two-Layer Soil Profile. J. Geotech. And Geoenviron. Eng. Vol. 132, Issue 11, 2006, pp.1436- 1443.

[7] Purnama A. Y., Yasufuku N., and Rifa'I A., Effect of Grain Size and Density as Pre-bored Pile Filler Material on Bending Moment Due to Lateral Loading. In Proc. The 1st International Conference on Press-in Engineering, 2018, pp.109-116.

[8] Wood D., Crewe A., and Taylor C., Shaking Table Testing of Geotechnical Models. International Journal of Phys Model Geotech, Vol 1, 2002, pp.1–13.

[9] Awad-Allah M. F., Yasufuku N., and Abdel-Rahman A. H., Factors Controlling the Behavior of Piled Foundations Due to Cyclic Lateral Loading. In Proc. The 6th Japan-Taiwan Joint Workshop on Geotechnical Hazards from Large Earthquakes and Heavy Rainfalls, 2014, pp.555-568.

[10] Awad-Allah M. F., Yasufuku N., and Mandandhar S., Three-dimensional (3D) Failure Pattern of Flexible Pile Due to Lateral Cyclic Loading in Sand. Lowland Technology International, Vol 19, Issue 1, 2017, pp.1-12.

[11] Satibi S., Numerical Analysis and Design Criteria of Embankments for Floating Piles. P.A. Vermeer (ed.) Dissertation, DCC Siegmar Kastl e K., 2009, pp.22-24.