Effects of Grain Size and Density as Pre Bored Pile Filler Material on Bending Moment Due to Lateral Loading

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ABSTRACT

Integral abutment bridges are becoming popular because the elastomeric bearings are eliminated, which can reduce the construction and maintenance costs. However, the girder displacement due to environmental thermal forces is directly cope by the pile foundation which can increase the pile stresses and bending moment significantly. Pre-bored pile foundation system can be used to improve the pile flexibility using a pre-bored hole that is filled with elastic materials, but the behaviour of soil-pile interaction on this system is still rarely explained. In this study, the effectiveness of filler material properties such as soil grain size and density were examined to reduce the pile cracking possibility effectively. An experimental study will be performed using single pile model test. The behaviour of ground soil and filler material due to cyclic lateral loading was performed using macro-scale testing to evaluate the effectiveness of this system. Results were presented in the form of cyclic load-displacement curves and normalized bending moment charts against pile depth and cycle time for each soil properties. 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.

Keywords: *Pile foundation, Elastic-plastic behavior, Cyclic lateral loading, Pre-bored hole, Bending moment*

1. Introduction

Conventional bridges are usually designed with the elastomeric bearing to allow the superstructure displacement due to environmental conditions. This elastomeric bearing needs to be maintained periodically. Nowadays, integral abutment bridges are becoming popular because the elastomeric bearings are eliminated, which reduce the construction cost and maintenance costs. However, the girder displacement due to environmental thermal forces was directly cope by the substructure. In the case of pile foundation in a stiff soil, the top area of the pile cannot move freely due to the fixed condition by soil stiffness. Pile stresses and moment will increase significantly. Previous researchers have proposed a system to increase the flexibility of pile foundation using a pre-bored hole that is filled with elastic materials as shown in **Fig. 1**.

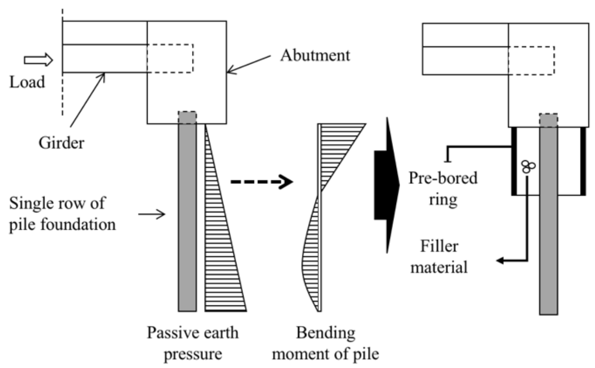

Fig. 1 Integral abutment bridge with the pre-bored hole

Fig. 1 show the configuration of the pre-bored pile foundation system. The pile is installed on the pre-augured hole followed by inserted the ring in the hole. The area between pile and ring was filled with 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.

Dunker and Liu (2007) shows the Iowa Department of Transportation in 2006 proposed the pre-bored hole diameter is twice the diameter of the pile with 3.05 m of depth. Deeper holes may be used for special conditions. Khodair and Hassiotis (2005) suggested that 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 empty holes cause long-term maintenance problems, so the holes should be filled with an elastic material, such as bentonite, loose sand, or pea gravel. In addition, to increase the pile flexibility, pre-bored holes have the advantage of eliminating down drag from compressible fills (Dunker and Liu, 2007). However, the soil characteristic and soil response due to this system are still rarely explained.

In this study, the effectiveness of filler material properties such as soil grain size and density are evaluated to reduce the cracking possibility effectively. The effective dimension of the pre-bored hole also conducted to determine the effective depth of the system that can reduce the bending moment along the pile. The appropriate filler properties and dimension of this system are expected to reduce the bending moment along the pile due to lateral displacement loading that 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

2.1. Experimental test apparatus

Macro-scale testing was performed to determine soil behavior due to cyclic lateral loading and to evaluate the effectiveness of this system. **Fig. 2** shows the experimental test setup which is used in this study. An experimental study was performed using a pile model test in sandy soil that has different soil grain size and uniformity coefficient. Lateral cyclic displacement was applied to the pile head. **Fig. 3** illustrates the cyclic loading pattern of lateral load applied on the pile head model during experimental testing.

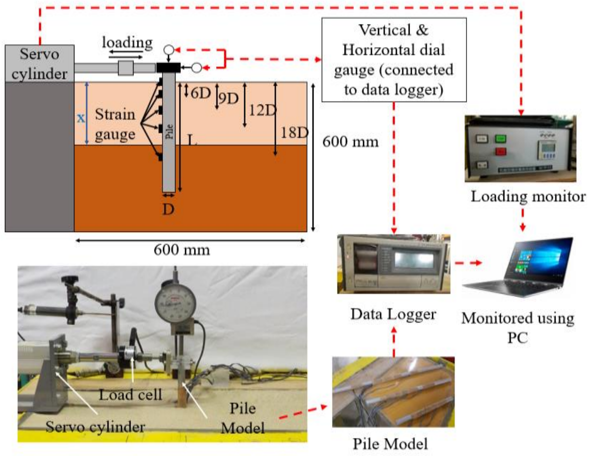

Fig. 2 Experimental testing scheme

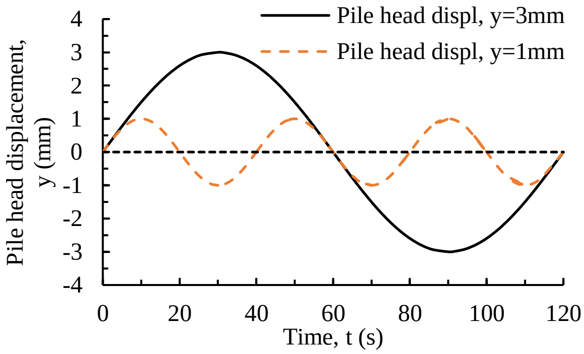

Fig. 3 Loading frequency

Two-way symmetric cyclic lateral loading is horizontally imposed on two opposite sides of a pile head model to provide horizontal deflection on the pile head. Pile head displacement of 3 mm (20% of pile diameter) was applied for each side to evaluate the soil-pile behavior in one-layered soil and two layered soil cases. 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. Khodair and Hassiotis (2005) shows 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. The cyclic lateral load is applied to 0.0083 Hz (y=3mm) and 0.025 Hz (y=1mm) and it is applied to 50 cycles in all experiments, so it generally can simulate the impact of the slow cyclic lateral displacement loading of a girder bridge. The bending moment, lateral load capacity, horizontal displacement, and vertical settlement were measured and monitored during the experimental tests.

2.2. Pile foundation model

The pile models are manufactured from a closed-end aluminum alloy pipe with the outer diameter of 15mm and wall thickness of 1.2mm. The Young's Modulus of the used aluminum alloy pile model is 7x10^{10} KN/m^2. Equivalence law is used for designing the model pile material, dimensions, the applied speed and displacement. The scaling formula as shown in **Eq. 1**, proposed by Wood *et al.* (2002) is used in this research.

$$\frac{E_m I_m}{E_p I_p} = \frac{1}{n^5} \tag{1}$$

Where: E_m is modulus of elasticity of pile model, E_p is modulus of elasticity of prototype pile, I_m is moment of inertia of model pile, I_p is moment of inertia of prototype pile; and n is scale factor for length. In the experimental work, the scaling factor for length is adopted as n=15. Hence, if an aluminum tube pile model of outer diameter 15 mm and wall thickness 1.2 mm is used, it will be equivalent to a prototype of steel hollow pile of outer diameter 0.5 m with a wall thickness of 6 mm in terms of the bending stiffness.

2.3. Soil setup

The soil, used in this experimental study, is sub-angular, Kumamoto sand type of K4 (medium sand) and K7 (fine sand) which has uniformity coefficient range from 1.24 to 2.96 and it commonly used in Japan. The index properties of each soil are given in **Table 1**. The results were compared with the experimental test conducted by Awad-Allah and Yasufuku (2013) which used Toyoura sand type as a ground soil. **Fig. 4** shows the grain size distribution of soil sample used in this study. In this study, two different states of relative densities (D_r) are considered, including medium density and dense sand of 50% and 80%. The relative density of soil was achieved using Multiple Sieving Pluviation (MSP) method (Miura and Toki, 1982). They introduced a method for preparation of sand samples using MSP apparatus by controlling the rate of sand discharge. The medium density and dense sand of relative densities of 50% and 80% have been achieved by using this method. The height of falling and nozzle diameter can control the rate of sand discharge. The calibration of the height and nozzle diameter was conducted to obtain the targeted density.

Table 1. Index properties of ground soil

Soil properties	K-7	K-4	Toyoura (Awad-Allah and Yasufuku, 2013)
D_{50} (mm)	0.17	0.75	0.18
U_c	2.96	1.24	1.4
Max. dry density	1.51	1.48	1.6
Min. dry density	1.18	1.24	1.31
Ground density	1.44 (Dr=80%) 1.34 (Dr=50%)	1.43 (Dr=80%) 1.36 (Dr=50%)	1.53 (Dr=75%) 1.44 (Dr=45%)

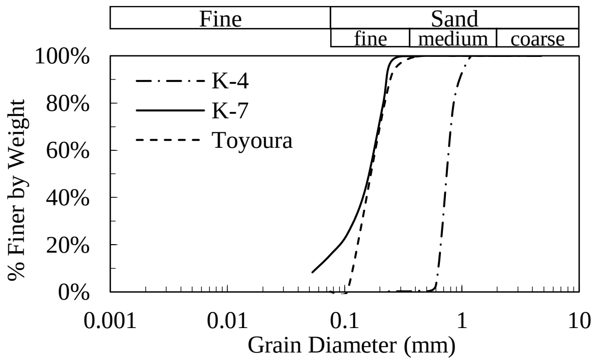

Fig. 4 Grain size distribution of soil

2.4. Testing procedure

The pile model is placed at the center of the testing tank by clamping it into the guide bar to maintain the center position of the pile, while the measurement of its vertical alignment was done. Then, sand is poured evenly by the layer thickness of 10 cm using the MSP method. After reaching to the uppermost layer of sand, the guide beam is removed, and the top surface is flattened. Three pile experimental characteristics were conducted in this experimental study, single pile in the one-layered soil, single pile in the two-layered soil, single pile with the pre-bored ring system. Three different pile slenderness ratios of 10, 20 and 30 were used in one-layered soil test. On the two-layered soil and pre-bored ring system test, pile slenderness ratio of 30 was used. The detailed test cases (20 tests) and the associated test conditions are represented in **Table 2**.

Table 2. Total number of experimental tests conditions

One-Layered Soil					
Test ID	Dr (%)	Soil type	*L/D*	Cycle time (N)	Pile head displc. (mm)
OL01	80	K7	10	50	3
OL02	80	K7	20	50	3
OL03	80	K7	30	50	3
OL04	80	K4	10	50	3
OL05	80	K4	20	50	3
OL06	80	K4	30	50	3
OL07	50	K7	10	50	3
OL08	50	K7	20	50	3
OL09	50	K7	30	50	3
OL10	50	K4	10	50	3
OL11	50	K4	20	50	3
OL12	50	K4	30	50	3
OL13	80	K7	30	50	1

Two-Layered Soil					
Test ID	Dr (%)	Soil type	*x/D*	Cycle time (N)	Pile head displc. (mm)
TL01	80	K7 (bottom) K4 (upper)	3	50	3
TL02	80	K7 (bottom) K4 (upper)	10	50	3
TL03	80	K7 (bottom) K4 (upper)	15	50	3

Pre-bored system (Ground Soil: K7 sand, Dr=80%)				
Test ID	Dr (%)	Filler type	Cycle time (N)	Pile head displc. (mm)
PB01	-	Empty	50	1
PB02	40%	Toyoura	50	1
PB03	70%	Toyoura	50	1
PB04	90%	Toyoura	50	1

3. Results and Discussions

3.1. Bending moment of the model pile

In most cases, the maximum bending moment of the pile is considered as the key parameter in laterally loaded piles design. The main focus of this experiment is measurement of the pile bending moment which is periodically monitored by using attached strain gauges along the pile. Then, those measured values were analyzed and the maximum measured value (M_m) was normalized against the yielding moment (M_y). 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 following equation.

$$M_m = \frac{EI\varepsilon}{r} \tag{2}$$

Where, E is Young's modulus of the model pile material, I is 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. 3**, with σ_y is yield stress of model pile material.

$$M_y = \frac{\sigma_y I}{r} \tag{3}$$

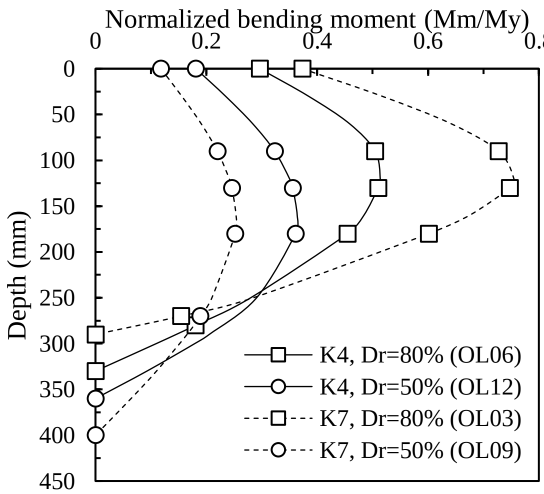

Fig. 5 Effect of soil density on bending moment

Fig. 5 illustrate the relationships between normalized bending moment and pile depth for single piles constructed into medium dense sand (*Dr*=50%) and dense sand (*Dr*=80%) on a static lateral loading. It is noticed that the higher density will provide the higher bending moment. K7 sand with high density provides 3 times higher bending moment value than the medium density. While the high density of K4 sand provides 1.5 times higher bending moment value than the medium density. It indicates the potential of increasing bending moment on the K4 sand that has lower uniformity coefficient, is smaller than the K7 sand. The maximum bending moment location and point of rotation (bending moment ≈ 0) also changed on the different soil density. This phenomenon occurred due to the different stiffness of dense and medium density of soil. Dense sand provides lower point of rotation due to the soil stiffness is higher to hold the pile movement. **Fig. 6** shows the effect of the ground soil type for each pile slenderness ratio. Pile with higher slenderness ratio provides the higher bending moment for all soil cases. It shows that soil with the higher grain size (D_{50}) and lower uniformity coefficient (U_c) such as K4 sand provides a lower bending moment with the similar soil relative density. The cyclic lateral loading effect is shown in **Fig. 7**. While the cyclic loading was conducted 50 times, there is no significant increase in the bending moment in piles in sand with lower uniformity coefficient. It indicates that small densification effect occurred due to the cyclic loading.

3.2. Lateral capacity of the model pile

Monitoring of lateral loading (*H*) and lateral displacement (y_H) were also measured by using load cell and dial gauge that was recorded using data logger and PC. The incremental ratio gives the tangent stiffness modulus of the system. Typical results of cyclic lateral loading tests are shown in **Fig. 8** for each K4 and K7 sand with high and medium density and the cyclic loading is performed to 50 two-way cycles. It can be noticed that the first loading cycle generates a lower lateral load then increase during the cyclic loading until it reaches 50 times of cyclic load. The tangent stiffens related to the first cycle is lower than those related to cyclic phase. The stiffness increases with the number of cycles, *N*, tending then towards a maximum value. This happened due to cyclic loading leads to hardening of sandy soil and reduction of void ratio. Consequently, enhancement of soil properties occurs for loose sand and confining pressure increases during cyclic loading.

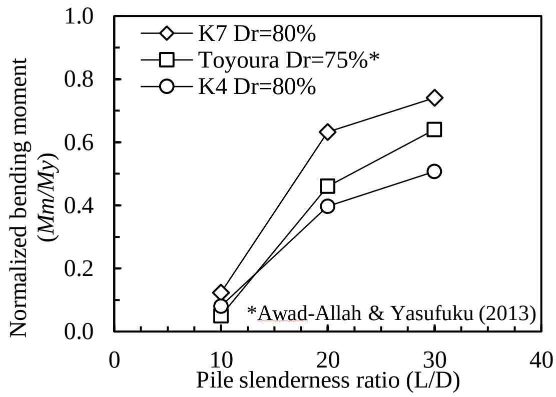

Fig. 6 Effect of pile slenderness ratio due to the static lateral loading for each soil type

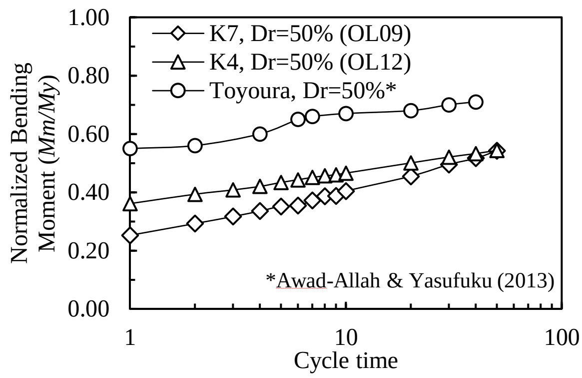

Fig. 7 Effect of cyclic lateral loading on medium soil density

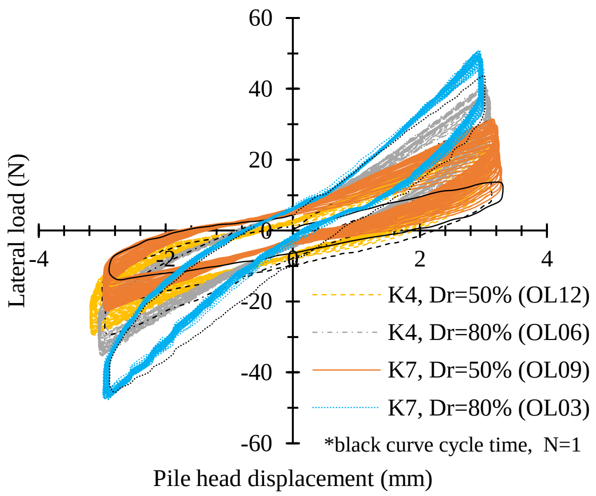

Fig. 8 Cyclic load-lateral displacement curves for single piles in dense and medium density soils

3.3. Effective properties of filler material

Fig. 9 shows the summary of bending moment due to static and cyclic loading on each soil type and density. Sand with high uniformity coefficient and high density provides stable bending moment during the cyclic loading, but the values of bending moment are so high. If the density is reduced to be medium, the bending moment will be smaller, and it will be increase significantly of 54.71% (OL12) after 50 times of cyclic loading was applied. However, the sand with lower uniformity coefficient, such as K4 sand and Toyoura sand (Awad-Allah and Yasufuku, 2013), provides a stable bending moment during the cyclic loading.

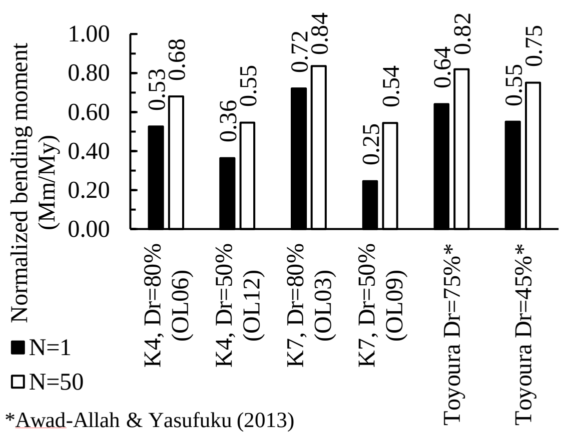

Fig. 9 Summary of bending moment on each soil type

3.4. Two-layered soil system

This section presents an experimental study on laterally loaded pile models in two-layered sandy soil with different soil properties to determine the effective depth of the system. An experimental study was performed using pile test model in two-layered sandy soil using K7 sand as the bottom layer and K4 sand as the top layer with the same relative density. Three different upper layer depth ratio (*x/D*) of 3, 10, and 15 were tested and lateral cyclic displacement was applied on the pile head. **Fig. 10** shows the results of maximum normalized bending moment with various layer depth ratio. Based on **Fig. 10**, it shows the maximum bending moment of the pile can be reduced by changing the top soil layer using sandy soil with lower uniformity coefficient. There is no significant further reduction of bending moment observed by changing the top layer depth beyond the layer depth ratio (*x/D*) of 3 for static lateral displacement loading. The result is in accordance with Yang and Robert (2006), that explained the lateral performance of a pile was highly affected by the stiffness of the surface with the layer depth ratio (*x/D*) of 2. During the cyclic loading, there is no significant increase in the bending moment on the layer depth ratio (*x/D*) of 3 as shown in **Fig. 10**. However, this condition only occurred in the layer depth ratio (*x/D*) of 3, for the other layer thickness, the bending moment increases during the cyclic displacement loading. It occurred due to the plastic deformation of the soil on surface layer during the cyclic lateral loading.

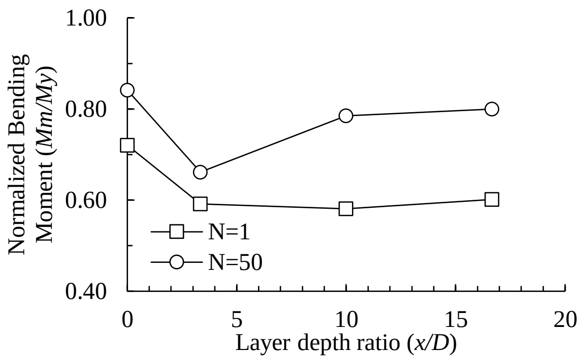

Fig. 10 Normalized bending moment with various depth ratio of upper layer

(a) (b)

Fig. 11 Conditions after 50-time of cyclic loading (TL01)
(a) condition on surface layer (b) condition on the border layer

Plastic deformation that occurred in the surface area (**Fig. 11a**) causes reduction of soil-pile interaction, and it makes the bending moment, and lateral capacity insignificantly increases during the cyclic loading. Moreover, on the layer depth ratio (*x/D*) equal to 3, the upper soil layer was moving down into the bottom layer (**Fig. 11b**) due to the high lateral deflection of the pile in this area and it can increase the plastic deformation of the upper soil layer. This condition does not occur on the layer depth ratio (*x/D*) of 10 and 15 because of the lateral pile displacement is very small on this area, so the upper soil layer cannot penetrate the bottom layer.

3.5. Effective diameter of pre-bored ring

To optimize the utilization of filler material, the effective diameter of pre-bored ring need to be determined. It is expected to maintain the bending moment with the optimum utilization of filler material. The pre-bored ring diameter is determined based on the failure zone during the cyclic lateral loading. Awad-Allah et al. (2017) illustrated the plastic deformations which was created on the top soil surface were extended laterally as a shape of ellipse with major and minor axes of 6*D* and 4*D* after applying 50 two-way lateral cyclic loading. The plastic deformation width on the surface area, in the loading direction, occurred about 5-7cm or 3 to 5 times of pile diameter and 3-4cm or 2 to 3 times of pile diameter for 3mm and 1mm pile head displacement respectively (**Fig. 13a**). Experimental tests on pile with pre-bored ring system using ring diameter of 4*D* (60mm) and ring depth of 10*D* (150mm) were conducted with pile head displacement load 3mm and 1mm. Based on the results of cyclic lateral loading in pre-bored system foundation, the ring was moved up about 10 mm after 50 times of cyclic loading due to 3mm pile head displacement (**Fig. 12**), but for 1mm pile head displacement the ring was not significantly moved as shown in **Fig. 13 (b)**, **(c)** and **(d)**. This occurred because of the ring was placed in the area of failure zone. In this area, the plastic deformation of the soil occurred during the cyclic lateral displacement, so the friction between soil and ring inflict the movement of the ring. The different properties of soil inside and outside the ring also could affected the ring movement.

Fig. 12 Conditions after 50 times of cyclic displacement with ring diameter 4*D* and 3mm pile head cyclic displacement

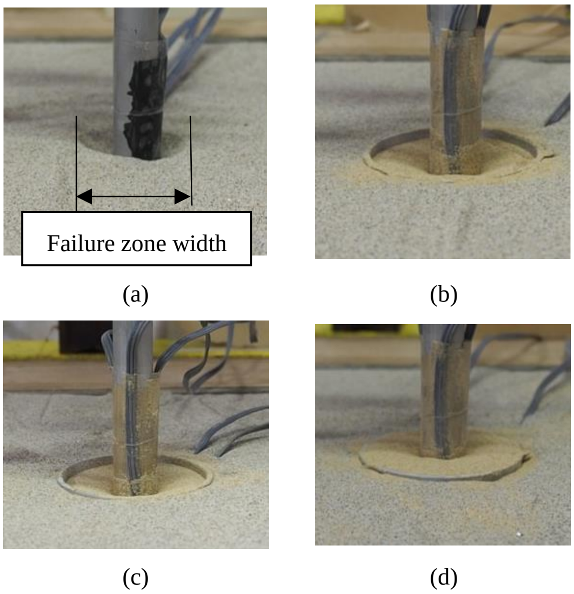

Fig. 13 Conditions after 50 times of cyclic lateral displacement with lateral displacement in pile head of 1mm (a) K7 80% without ring (b) Filler Toyoura 40% (c) Filler Toyoura 70% (d) Filler Toyoura 90%

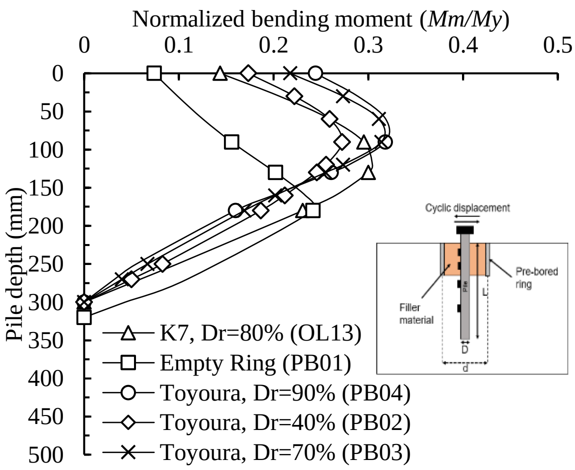

Fig. 14 Effect of filler material properties on static lateral loading with 1 mm pile head displacement

3.6. Pre-bored system using filler material

After the effective dimension of pre-bored ring was selected, an experimental test on the pre-bored ring system with trial of filler material density using Toyoura sand was carried out. Three types of soil density of 40%, 70% and 90% of Toyoura sand were used to determine the effect of soil density on filler material of pre-bored foundation system. The experimental test of the empty ring also conducted. **Fig. 14** shows the results of bending moment along the pile depth with various density of filler material on static loading condition. Based on **Fig. 14**, the smallest bending moment provided in the empty ring case. However, the concentrated moment occurred in the maximum value, so it is possibly to inflict a pile buckling. For the loose sand filler material, densification happened, so it needs to determine the optimum filler material properties (optimum density or material with similar diameter size). Toyoura sand with 40% density provide the lower bending moment than other density, but densification occurred on the surface area. The soil surface of filler material moves down for each density 40% and 70% for 0.7mm and 0.4mm and there is no densification on the 90% of filler density for pile head displacement of 1mm as shown in **Fig. 13**. The result of static loading illustrates the filler density of 70% and 90% providing a little higher bending moment, but after 50 times of cyclic loading it provide a lower bending moment as shown in **Fig. 15**. It indicates that the sand with lower uniformity coefficient provides a stable bending moment of pile during the cyclic loading as a filler material.

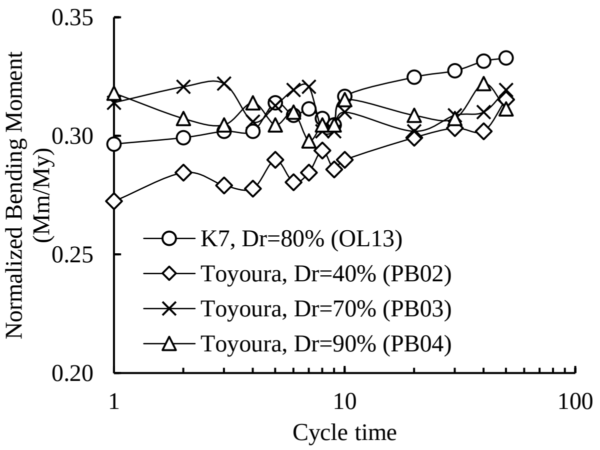

Fig. 15 Effect of filler material properties after 50 time of cyclic lateral loading with 1 mm pile head displacement

4. Conclusions

1) Pile bending moment due to lateral loading are affected by ground soil density, pile slenderness, and soil properties. Increasing the slenderness ratio of pile will provide a higher bending moment. The higher density of ground soil provides bigger bending moment due to the increasing of soil stiffness. The ground soil with lower uniformity coefficient results a smaller bending moment.
2) Substitution of the top soil layer using sandy soil with lower uniformity coefficient can reduce the bending moment of the pile. There is no significant reduction of pile bending moment observed by changing the top soil layer beyond the layer depth ratio (*x/D*) of 3 for static lateral displacement loading.
3) Bending moment of the pile on the layer depth ratio (*x/D*) of 3 during cyclic loading did not significantly increase until cycle time of 50 due to the plastic deformation occurred on the surface layer and reduced the soil-pile interaction.
4) The diameter of pre-bored ring smaller than the failure zone area can inflict the pre-bored ring movement.
5) The density of filler material effects on reducing pile bending moment. However, enhancement of soil properties occurs for loose sand during cyclic loading.

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