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PIV analysis of ground during horizontal pile loading by centrifuge tests

Analyse par PIV du sol pendant le chargement horizontal de pieux par essais en centrifugeuse

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ABSTRACT: Examining the ground's deformation characteristics is valuable in assessing the impact of ground behavior around piles on horizontal resistance. In this study, horizontal pile loading experiments in a centrifugal 50G field and PIV image analysis were conducted. The ground deformed three-dimensionally when the pile was loaded horizontally. Therefore, two experiments were conducted: one to observe the ground surface and another to observe the ground section. The displacement distribution of the ground surface was nearly circular, while that of the ground section was triangular in the initial stage of loading and became quadrangular as the pile head displacement increased. The size of the three-dimensional deformation area of ground in front of a pile at each loading stage was analyzed, and the results indicated that the horizontal resistance of a pile is related to the size of the deformation area of the ground.

RÉSUMÉ: Examiner les caractéristiques de déformation du sol est important afin d'évaluer l'impact du comportement du sol autour de pieux à résistance horizontale. Dans cette étude, des expériences de chargement horizontal de pieux dans un champ centrifuge de 50G et une analyse d'images par PIV (vélocimétrie par image de particules) ont été réalisées. Le sol se déformait tridimensionnellement lorsque le pieu était chargé horizontalement. Par conséquent, deux expériences ont été menées : une première afin d'observer la surface du sol et une seconde afin d'observer la section du sol. La distribution du déplacement de la surface du sol était quasiment circulaire, tandis que celle de la section du sol était triangulaire lors de la phase initiale de chargement, puis devenait quadrangulaire au fur et à mesure que le déplacement au point d'application augmentait. La taille de la zone de déformation tridimensionnelle du sol devant un pieu à chaque phase du chargement a été analysée, et les résultats indiquent que la résistance horizontale d'un pieu est liée à la taille de la zone de déformation du sol.

Keywords: Particle image velocimetry; pile; lateral loading; lateral resistance; centrifugal test.

1 INTRODUCTION

The pile foundations of buildings are subjected to horizontal loads due to earthquakes and winds. The evaluation of the horizontal resistance of piles is one of the most important issues in the design of pile foundations. Although many studies have focused on pile stress, it is essential to understand the deformation characteristics of the ground during pile loading. The ground resistance area and the resistance mode affect the horizontal resistance of the pile and the pile group effect.

Reese et al. (1974) performed horizontal loading tests on a full-size pile on site and determined the ultimate resistance of a laterally loaded pile, assuming a three-dimensional (3D) wedge-shaped failure pattern on sand. In recent years, laboratory tests have been conducted in addition to field tests. Various techniques, including X-ray computed tomography (CT) and particle image velocimetry (PIV), have been used to visualize ground behavior. Using X-ray CT to observe the ground during horizontal pile loading, Otani et al. (2006) proposed a cone shaped 3D failure pattern for sand. Hajialilue-Bonab et al. (2011) and Yuan et al. (2017) studied the ground deformation patterns under the horizontal loading of piles based on small-scale models in the laboratory and PIV. The authors also conducted ground surface observation experiments during horizontal pile loading in a 1G field and reported the displacement distributions on the ground surface (Odagiri et al. (2023)).

Although some studies have focused on soil deformation characteristics, as shown above, most experiments used small-scale models in a laboratory, making it difficult to quantitatively evaluate ground behavior. Since the strength of friction material is dependent on the confining pressure, it is difficult to quantitatively evaluate the behavior of the ground in a 1G field. Therefore, experiments in a centrifugal field are essential. In this study, horizontal pile loading tests in a centrifugal field and PIV image analysis were conducted. Soil deforms three- dimensionally when a pile is loaded horizontally. Therefore, two experiments were conducted under similar conditions: one to observe the ground surface and another to observe the ground section.

2 METHODOLOGY OF HORIZONTAL LOADING TEST AND PIV

2.1 Experimental model

The experiments were conducted using a beam-type centrifuge at a centrifugal acceleration of 50 G at the ground surface, and the experimental models are shown in Figure 1. The experiment conducted to observe the ground surface is called the "full-section experiment," and the experiment conducted to observe the ground section is called the "half-section experiment." In the half-section experiment, the pile and ground models were half of those in the full-section experiment. The rigid soil container was 690 mm long, 510 mm wide, and 450 mm high. The soil container was identical in both experiments. In the half-section experiment, one side of the wall was removed, and a glass window was installed at the center of the container.

The piles were designed assuming cast-in-place concrete piles. The specifications of the piles are listed in Table 1. The pile for the full-section experiment (full-section pile) was an aluminum pipe with a diameter (*D*) of 20 mm (prototype scale: 1m), a thickness of 1 mm, and a length of 350 mm. The plate thickness was set such that the flexural rigidity of the pile was equivalent to that of a cast-in-place concrete pile of the same pile diameter. The strain gauges were affixed to eight levels inside the pile. The pile used for the half-section experiment (half-section pile) was a half-section aluminum pipe of equal size to the full-section pile. The inside of the half-section pile was filled with a silicone sealant, and a Teflon sheet was

Table 1. Specifications of the pile.

	prototype pile	model pile
Diameter (*D*)	1m	20mm
Thickness	-	1mm
Length	17.5m	350mm
Embedded length	15m	300mm
Flexural rigidity	1.14GN･m^2	183N･m^2

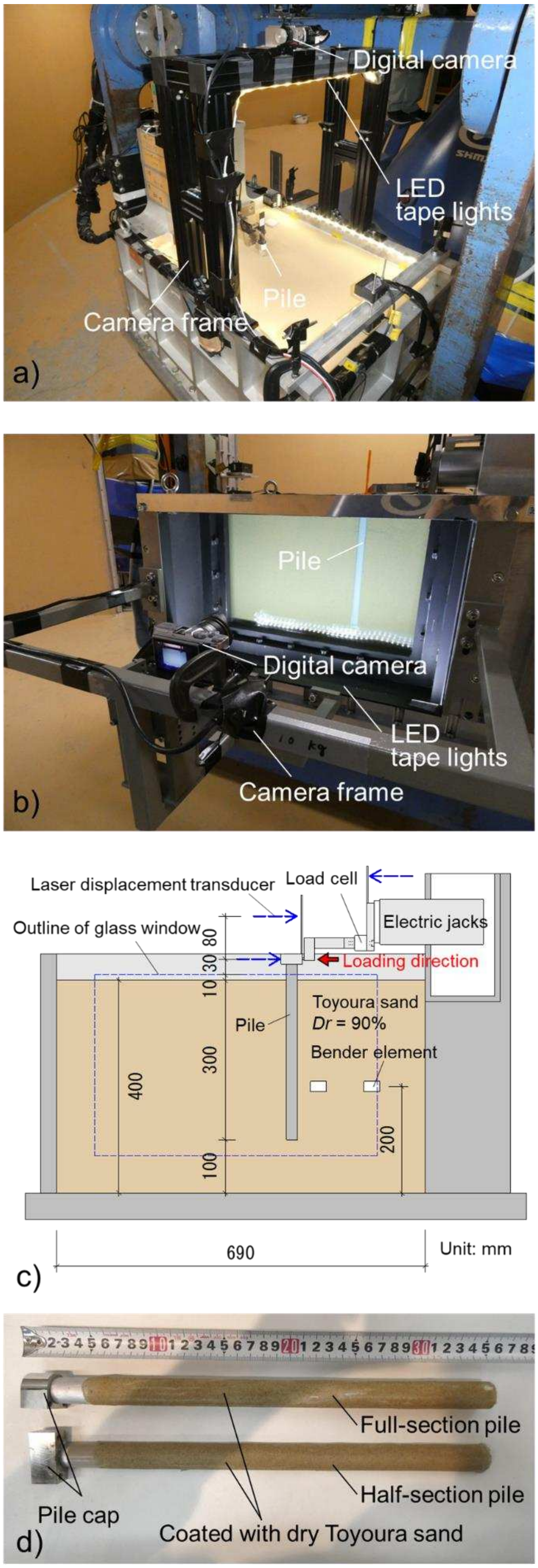

Figure 1. Experimental model: a) Full-section experiment, b) Half-section experiment, c) Detail plan, d) model piles.

bonded to the glass contact surface to reduce friction between the glass and pile. The pile surfaces were adhered to Toyoura sand to account for the friction between the pile and ground. The ground conditions, loading conditions and sensor arrangement were the same for both experiments.The ground models were 400 mm high (20 m). The embedment length of the piles in the ground was 300 mm (15 m). Dry Toyoura sand was used as ground material. Figure 2 shows the grain size distribution curve. The average grain size (D_{50}) of the Toyoura sand was 0.196 mm and the relative density (D_r) of the ground was set to 90% using the air pluviation method. A model pile was set up when the ground was piled up to 100 mm from the bottom of the soil container, and a surface layer was then formed. Bender elements were used to measure the shear wave velocity at the center depth of the ground. Horizontal loading was applied to the pile cap (40 mm above the ground surface) using an electric jack at a loading rate of 0.5 mm/min. The pile head was free. Load cells were used to measure the load on the pile head, and laser displacement transducers were used to measure the horizontal displacement of the jack, pile head at the loading level, and upper part of the pile 80mm above the loading point (Figure 1 (c)) .

2.2 Photographic method and post processing

A digital camera with a resolution of more than 20 million pixels (Fujifilm X-A5) was used. A single-focus lens was used in this study. A digital camera was placed on a frame fixed to the soil container. Photographs for image analysis were captured from the top of the soil container in the full-section experiment and from the side of the container in the half-section experiment. During the experiment, the room lights were turned off, and the ground surface was lit using LED tape lights placed in the soil container and camera frame. Instead of lighting from a single spot, lights were placed around the pile to prevent shadows from forming in the analysis area. The ground was captured every 5 s during the holizontal pile loading.

PIV is used for obtaining displacement by calculating the cross-correlation coefficient of the luminance distribution of two images. PIV is commonly used for the visualization of ground behavior (e.g., White et al. (2003)).The image analysis steps were as follows. 1) Photographs were selected for every 1 mm of pile head displacement. 2) The positions in the photographs were corrected. 3) The photographs were trimmed around the piles. 4) The relative displacements were obtained using PIV between the image at a 0-mm pile head displacement (initial pile head displacement) and each photo at every 1-mm pile head displacement. In this study, the open-source platform JPIV was used for PIV analysis. The size of one pixel in the ground plane was 0.15 mm square in the full-section experiment, and 0.14mm square in the half-section experiment, which are approximately equal in size. Therefore, the variance in the image analysis results owing to differences in the conditions of the two experiments is expected to be negligible.

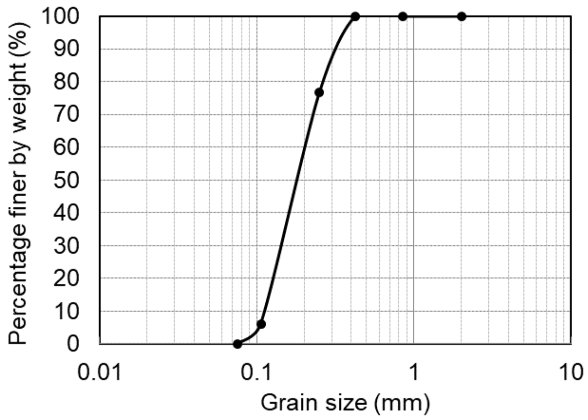

Figure 2. Grain size distribution curve of Toyoura sand.

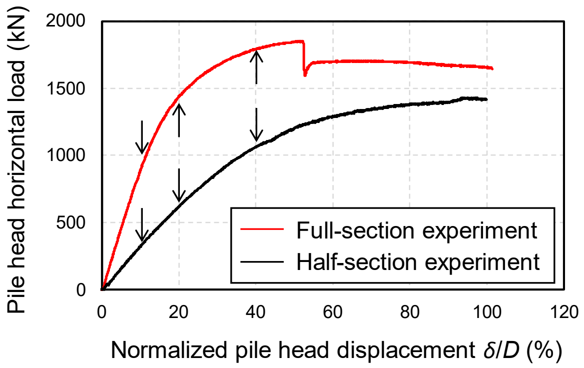

Figure 3. Relationships between horizontal load and displacement at the pile head.

3 EXPERIMENTAL AND IMAGE ANALYSIS RESULTS

3.1 Pile head load and displacement relationship

The experimental results are presented on a prototype scale. The shear velocity at the center depth of the ground was 247 m/s in the full-section experiment and 244 m/s in the half-section experiment at a centrifugal acceleration of 50G. The ground conditions for both experiments were approximately the same. Figure 3 shows the relationship between the horizontal load of the pile head and pile head displacement (loading point height). The pile head displacement δ was normalized by the pile diameter D. In the full-section experiment, the pile-head load decreased rapidly when the pile-head displacement was 52% of the pile diameter. After the test, the pile exhibited significant residual deformation, and buckling was considered to have occurred when the pile head displacement was 52% of the pile diameter. Therefore, the image analysis results showed pile head displacement of up to 50% of the of the pile diameter.

In the full-section experiments, the pile head load increased almost linearly until the pile head displacement was about 15% of the pile diameter, and the increase in pile head load became smaller when the pile head displacement exceeded 20% of the pile diameter. In the half-section experiments, the pile head load increased almost linearly until the pile head displacement is about 30% of the pile diameter, and the increase in pile head load became smaller when the pile head displacement exceeded 40% of the pile diameter. The initial slope of the pile head load in the half-section experiment was approximately 40% of that in the full-section experiment.

3.2 Deformation of ground surface during horizontal pile loading

Figure 4 shows contour charts of the ground surface displacement. Ground surface displacement occurred during the loading stages of 10, 20, and 40% of the pile diameter, as indicated by the arrows in Figure 2. The black circles in Figure 4 represent the projections of the pile at the loading point height on the ground surface, and the loading equipment is indicated in gray. The contour lines of the displacement are shown every 10 mm (0.01D). As the pile head displacement increased, the deformed area of the ground widened almost circularly. When the pile head displacement was 40% of the pile diameter, the area of displacement beyond 10 mm expanded 5.7 m in the loading direction and 7.5 m orthogonal to the loading direction.

Figure 5 shows the displacement in the loading direction, the displacement in direction orthogonal to the loading and the displacement vector of the ground surface. The ground in the area close to the axis of the loading direction was displaced primarily in the

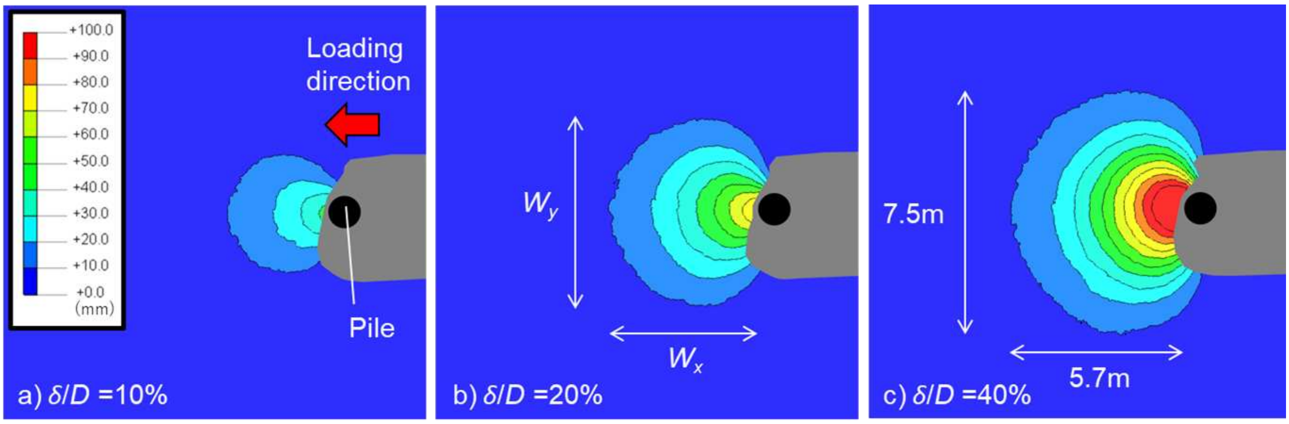

Figure 4. Displacement of the ground surface: pile head displacements of a) 100 mm (δ/D=10%), b) 200mm (δ/D=20%), and c) 400mm (δ/D=40%).

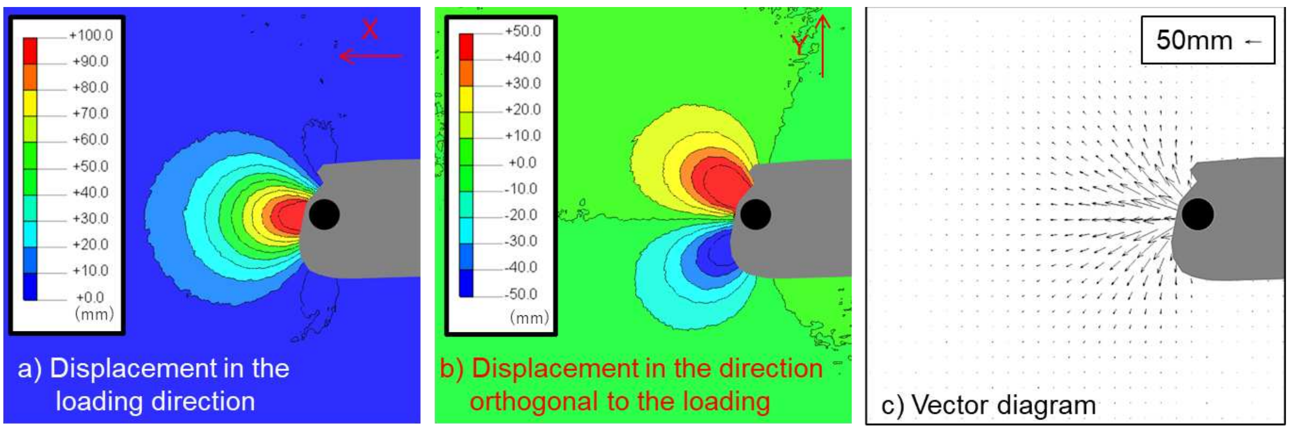

Figure 5. Displacement of the ground surface at pile head displacements of 400mm (δ/D=40%): a) loading direction, b) direction orthogonal to the loading, and c) vector diagram.

loading direction and not in the orthogonal direction of loading. As shown in Figure 5 (b), the ground in the area located at a distance from the loading axis was also displaced in a direction orthogonal to the loading.

3.3 Deformation of ground section during horizontal pile loading

Figure 6 shows the contour charts of the ground section displacement. This occurred during the loading stages at 10, 20, and 40% of the pile diameter. In the initial stage of loading, the displacement distribution in front of the pile was triangular (Figure 6 (a)), and as the pile head displacement increased, the displacement distribution became into a quadrant (Figure 6 (c)). When the pile head displacement was 40% of the pile diameter (Figure 6 (c)), the area of displacement beyond 10 mm expanded 6 m in the depth direction and 5.7 m in the loading direction, which is approximately the same as the results of the full-section experiment. On the rear side of the pile, the ground within 2.1 m of the pile was displaced.

Figure 7 shows the displacement in the loading direction, the vertical displacement, and the displacement vector of the ground section. Figure 7 (b) shows that ground shallower than 3.2 m in depth was displaced vertically upward, and Figure 7 (c) shows that the ground in that area was displaced in the surface direction. Deeper ground was displaced horizontally. The ground at the rear side of the pile settled significantly.

3.4 Size of the three-dimensional deformation area of ground

Since the ground deformed as the load was transmitted, and the deformation area of the ground was quantified. W_x is the extent of the ground deformation area in front of the pile in the loading direction with a displacement of 10 mm (0.01D) or more (from the results of the full-section experiment). The extent of the deformation area in the direction orthogonal to the loading is W_y, and the extent of the deformation area in the depth direction is W_z. Figure 8 shows the relationship between pile head displacement and the extent of deformation area. The pile head displacement and extent of the deformation area were normalized by pile diameter D. When the pile head displacement was 50%

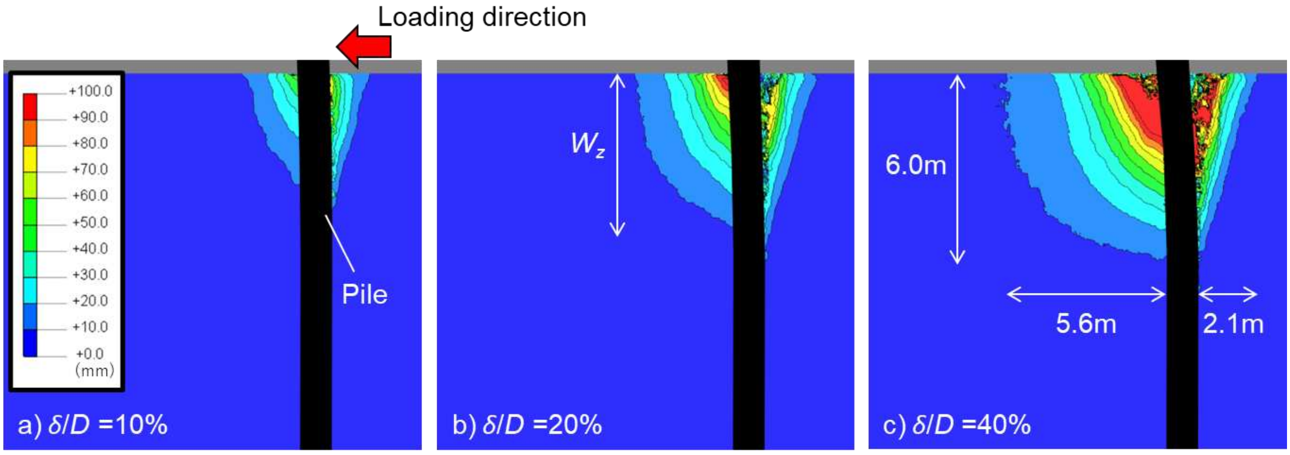

Figure 6. Displacement of the ground section: pile head displacements of a) 100 mm (δ/D=10%), b) 200mm (δ/D=20%), and c) 400mm (δ/D=40%).

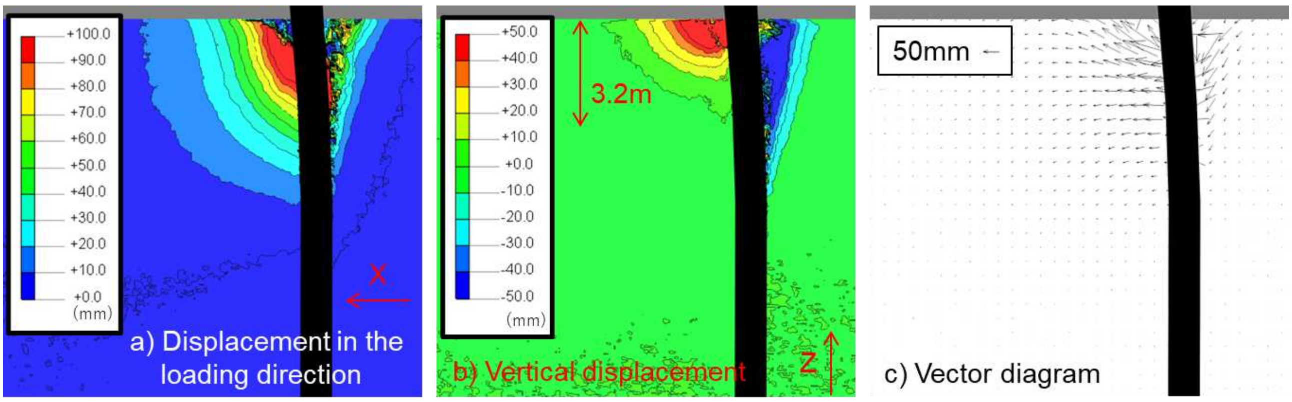

Figure 7. Displacement of the ground section at pile head displacements of 400mm (δ/D=40%): a) loading direction, b) vertical displacement, and c) vector diagram.

of the pile diameter, W_x and W_z were approximately six times the pile diameter, and W_y was approximately eight times the pile diameter. Odagiri et al. (2023) reported that a 0.01*D* displacement occurred at a distance 10 times the pile diameter (10*D*) in the loading direction from the pile when the pile head displacement was 20% of the pile diameter in a 1G field test. The results of this centrifugal field experiment demonstrated that the size of the deformed region was smaller than that in a 1G field. This is because the results of this centrifugal experiments were able to take into consideration the effect of ground confining pressure, which closely approximates actual ground conditions.

Figure 9 shows the relationship between the pile head horizontal load and the extent of the deformation area. The results are shown for pile head displacements up to 50% of the pile diameter, at which point the pile head load has almost reached its ultimate state. The pile head load on the horizontal axis was determined by the full-section experiment. As the pile head load increases, W_x, W_y, and W_z increase almost linearly. Thus, the size of the deformation area in the front of the pile is related to the resistance force of the pile.

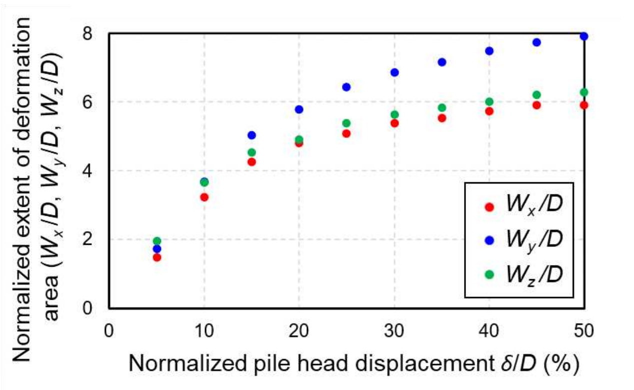

Figure 8. Relationships between the extent of deformation area and the displacement at the pile head.

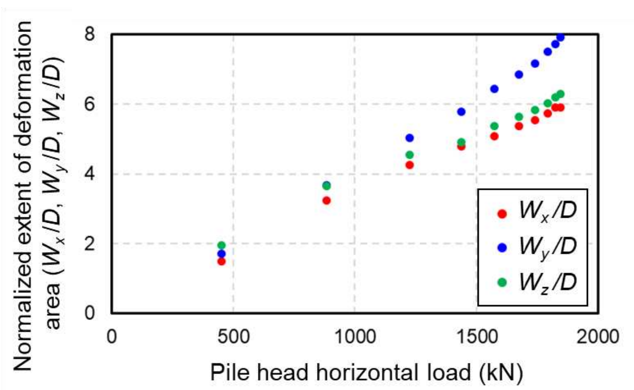

Figure 9. Relationships between the extent of deformation area and the pile head horizontal load.

4 CONCLUSIONS

The behaviors of the ground surface and section during horizontal pile loading in the centrifugal field were observed. The displacement distribution in front of the pile on the ground surface exhibited a nearly circular pattern, whereas that on the ground section exhibited a triangular pattern during the initial loading and became quadrangular as the pile head displacement increased. The shallow part of the ground in front of the pile was displaced in the direction of the ground surface owing to pile displacement. The size of the 3D deformation area of the ground in front of a pile at each loading stage was analyzed, and the results indicated that the horizontal resistance of a pile is related to the size of the deformation area of the ground.

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