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Influence of pile arrangement and bearing stratum thickness on vertical performance of steel pipe sheet pile foundations

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ABSTRACT: Steel pipe sheet pile (SPSP) foundations are composite structural systems commonly used in port and river structures in Japan, consisting of closely spaced steel pipe piles connected by mechanical joints. While their lateral resistance mechanisms have been extensively studied, the vertical bearing behavior—particularly under group pile effects—remains insufficiently understood. This study investigates the vertical bearing capacity of SPSP foundations through a series of centrifuge model tests conducted under a 50g field at the Disaster Prevention Research Institute (DPRI), Kyoto University. The piles were modeled as non-displacement piles, and installation-induced stress changes were not considered. The experiments focused on the influence of pile configuration (single, three- and five-pile series, and five-pile cross groups) and bearing layer thickness below the pile base (10*D*, 3*D*, and 1*D*, where *D* is the pile diameter). The dense bearing layers and overlying soft strata were prepared using silica sand with controlled relative densities. The results showed a distinct group pile effect: as the number of piles increased, the unit bearing capacity per pile decreased. In particular, the five-pile cross group exhibited the most significant reduction, attributed to restricted settlement and reduced mobilization of tip resistance in the confined layout. Moreover, thinner bearing layers led to a pronounced decrease in capacity for group pile foundations, with shaft friction becoming the dominant resistance mechanism. These findings suggest that particular attention should be paid to the selection and evaluation of the bearing layer in SPSP foundation design, especially under dense pile group configurations.

1 INTRODUCTION

Steel pipe sheet pile (SPSP) foundations (Figure 1 (JASPP)) are a foundation system uniquely developed in Japan. The system consists of steel pipe piles with mechanical joints, which are installed in a closed configuration and unified by filling the joint pipes with mortar. This structure combines both load-bearing and seepage control functions, and has been widely adopted in port and bridge foundation applications.

Due to the three-dimensional behavior of the joints—such as shear deformation—SPSP foundations exhibit complex structural responses, especially under lateral loading. Accordingly, previous studies have primarily focused on joint performance evaluation (Inazumi et al., 2009; Kimura et al., 2007; Miyazaki et al., 2021) and resistance mechanisms under lateral forces (Peng and Miyazaki, 2024; 2025).

In contrast, the vertical bearing mechanism of SPSP foundations has received limited attention, despite the fact that this system consists of closely spaced pipe piles, which suggests a potentially significant group pile effect. In practice, however, empirical design formulas are still commonly applied without sufficient experimental validation.

This study aims to investigate the group pile effects

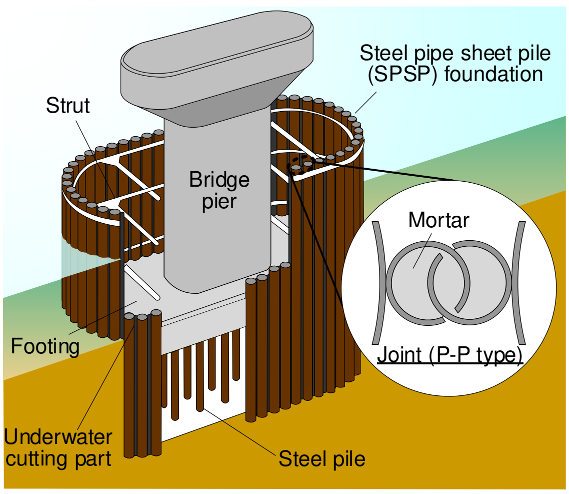

Figure 1. Steel pipe sheet pile (SPSP) foundation (modified after JASPP).

in SPSP foundations by conducting a series of centrifuge model tests using partial SPSP segments composed of interconnected pipe piles with joints. The experiments were performed under a 50g field at the Disaster Prevention Research Institute (DPRI), Kyoto University, considering both thick bearing layers and thin bearing layers underlain by soft deposits.

2 EXPERIMENTAL SETUP

2.1 Centrifuge facility and soil container

Figure 2(a) shows an overview of the experimental apparatus. The setup consists of a rigid aluminum soil container and a vertical loading device. The container has inner dimensions of 400 mm × 400 mm × 500 mm and is equipped with a reinforced glass front for observation. The model foundation was placed at the center of the container.

The loading system includes a load cell (Tokyo Measuring Instruments Laboratory Co., Ltd., TCLK-50KNA) capable of measuring up to 50 kN, and a displacement-controlled screw jack (Nippon Gear Co., J2GLIK0100NSN), which allows remote control and adjustment of loading/unloading speed. The loading rate was set to 1 mm/min in model scale.

2.2 Model pile and footing

As shown in Figure 2(b), the pile model was made of aluminum alloy pipe (pile diameter $D = \phi = 25$ mm, thickness = 1 mm, length = 167 mm, Young's modulus E = 55.8 GPa, ρ = 2.7 g/cm^3). Although actual steel pipe piles are typically open-ended, the pile tip is often plugged by soil during installation, resulting in a nearly closed condition (Kido et al., 2022). In this study, since no installation process was simulated, a 3 mm thick aluminum cap was attached to the pile tip to replicate a closed-end condition. Therefore, the model represents non-displacement pile conditions without installation-induced stress changes in the surrounding soil.

The footing was made of stainless steel (E = 193 GPa, ρ = 7.9 g/cm^3) with a two-layer structure, each 10 mm thick, fastened with bolts. The pile was embedded 10 mm into the footing, leaving L = 160 mm exposed. The pile and the footing were placed in direct contact without any gap. A thin layer of epoxy adhesive (Konishi Co.,Ltd, E205) was applied solely to ensure rigid fixation and prevent slippage at the interface. Strain gauges (Tokyo Measuring Instruments Laboratory Co., Ltd., FLAB-03-23-2LHT-F) were attached inside the pile to measure axial forces.

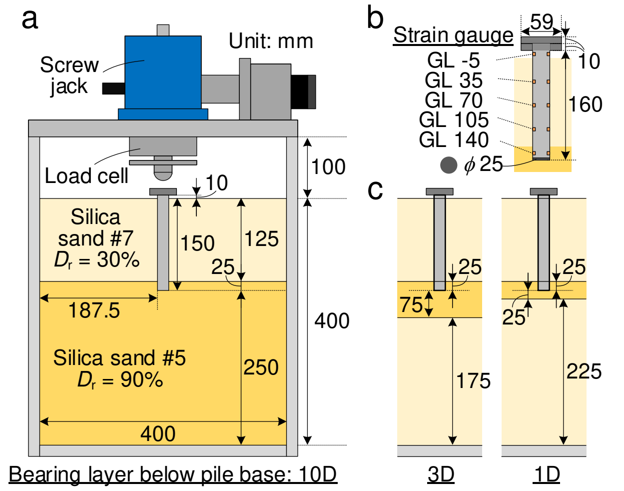

Figure 2. Experimental setup: (a) Overview of the experimental apparatus, (b) Pile model and strain gauge distribution and (c) Bearing stratum conditions.

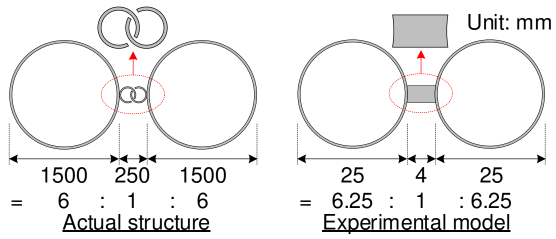

Figure 3. Modeling of the SPSP joints.

2.3 Ground conditions

Figure 2(c) illustrates the bearing stratum conditions, where the thick case (10D) comprises a soft surface layer and a dense sand layer beneath, while the thin cases (3D and 1D) consist of relatively shallow bearing layers directly underlain by soft ground. In the 10D case, the pile was embedded 1D into the dense bearing layer, which was 250 mm thick from the pile base. For the thin bearing cases, the dense layer was placed between soft layers, with 1D or 3D thickness beneath the pile base. The dense bearing layer was prepared using Silica sand #5 (ρ_s = 2.64 g/cm³, ρ_{dmax} = 1.58 g/cm³, ρ_{dmin} = 1.29 g/cm³) at a relative density D_r = 90%. The soft layer was prepared using Silica sand #7 (ρ_s = 2.65 g/cm³, ρ_{dmax} = 1.50 g/cm³, ρ_{dmin} = 1.16 g/cm³) at D_r = 30%. Both layers were placed by air pluviation.

2.4 Joint modeling and test configurations

Figure 3 shows the modeling of the SPSP joints. Actual SPSP structures typically use p–p type joints (Figure 1) filled with mortar. However, given the small scale of the model, it was difficult to reproduce detailed joint geometry. Therefore, aluminum alloy blocks were used to simulate the joints. Since vertical

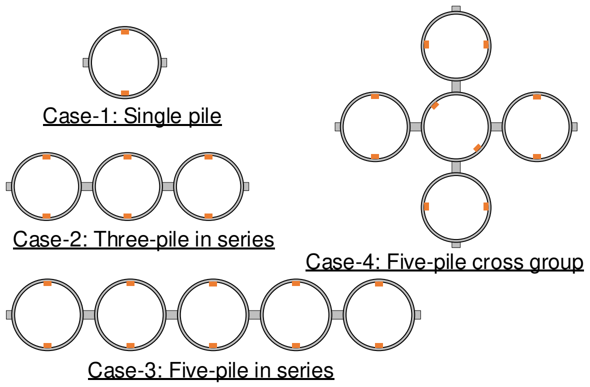

Figure 4. Layout of group piles.

slippage of the joints is unlikely under vertical loading, emphasis was placed on accurately reproducing the spacing between piles rather than the mechanical behavior of the joints. To reflect realistic pile-to-joint dimensions, standard joint blocks were 3 mm × 4 mm × 170 mm. Half-width blocks (3 mm × 2 mm × 170 mm) were used at the ends of pile rows.

Four pile configurations were tested (Figure 4): a single pile, a three-pile group in series, a five-pile group in series, and a five-pile cross group. The influence of pile number was assessed by comparing the single, 3-pile, and 5-pile series cases. The effect of pile layout was evaluated by comparing the 5-pile series and 5-pile cross configurations. All layouts were tested with a bearing layer thickness of 10*D* below the pile base, while only the single, 5-pile series, and 5-pile cross configurations were tested in the thin bearing cases (1*D* and 3*D*).

3 EXPERIMENTAL RESULTS

3.1 Sufficiently thick bearing layer (10*D* below the pile base)

Figure 5 shows the load–displacement relationships for all pile group configurations. Both load and displacement were corrected by subtracting the values just before loading, and the vertical displacement δ was normalized by the pile diameter *D*, resulting in the dimensionless parameter δ/D. From Figure 5, it is observed that the overall bearing capacity increases with the number of piles. However, even when the number of piles is the same (i.e., five piles), different behaviors were observed between the series and cross configurations. In particular, within the practical displacement range ($\delta/D \leq 10\%$), where bearing capacity is most relevant in design, the cross-shaped pile group—where piles are more densely arranged—exhibited a more pronounced reduction in capacity.

Figure 6 presents the load–displacement curves

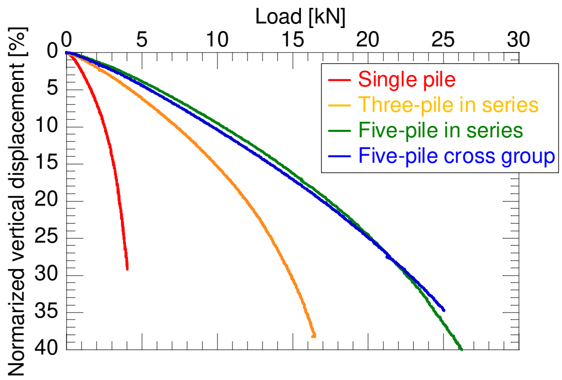

Figure 5. Load–displacement relationships for all pile group configurations.

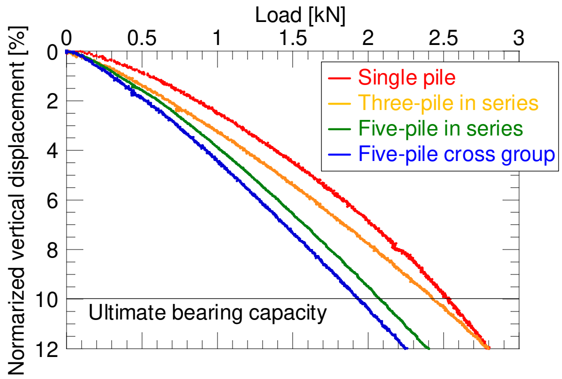

Figure 6. Load–displacement curves normalized by the number of piles.

normalized by the number of piles, showing the load per pile. In this study, the ultimate bearing capacity is defined as the load corresponding to a pile head settlement of 10% of the pile diameter. Based on this definition, the normalized comparison shows a clear group pile effect. The ultimate bearing capacities were found to be 2.55 kN for the single pile, 2.43 kN for the three-pile series group, 2.08 kN for the five-pile series group, and 1.93 kN for the five-pile cross group. These correspond to reductions to 95%, 82%, and 76% of the single pile capacity, respectively, clearly indicating a reduction in unit bearing capacity with increasing pile number.

Figure 7 shows the average axial forces acting on individual piles at different settlement levels (δ/D = 2%, 4%, 6%, 8% and 10%). In this study, short model piles with a diameter *D* of 25 mm and a length *L* of 160 mm (*L*/*D* = 6.4) were used, and sufficient bearing layer thickness was provided. Although the short embedment leads to minimal loss of axial force along depth, a decrease in axial force from the pile head to the tip was still observed, confirming the contribution of shaft friction.

Figure 8 summarizes the proportion of shaft friction and tip resistance at the settlement level of

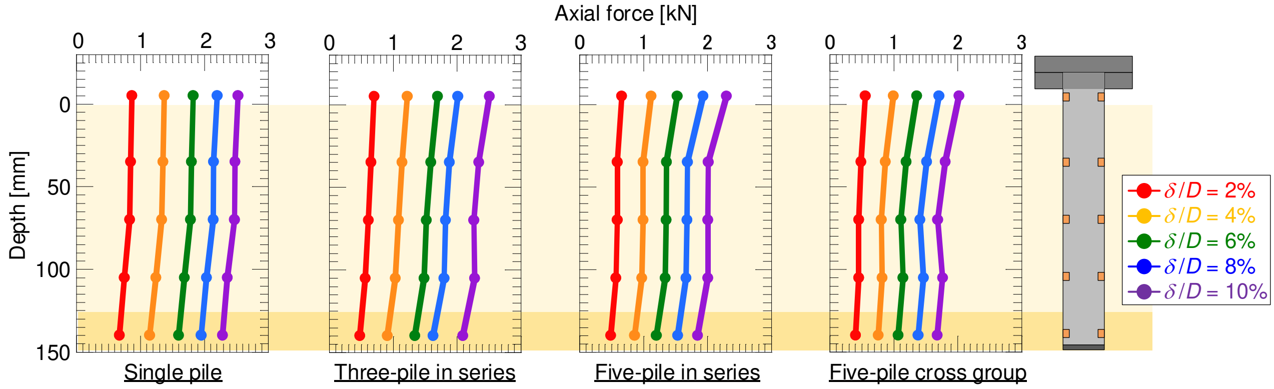

Figure 7. Average axial forces acting on individual piles at different settlement levels (δ/D=2%,4%,6%,8%,10%).

δ/D = 10%. The axial force obtained from the strain gauge at the top of the pile was considered the applied load, while the force from the bottom strain gauge was regarded as the tip resistance. The difference between these two values was taken as shaft friction. The results in Figure 8 indicate that, in the series configurations, as the number of piles increases, the contribution of tip resistance decreases, and the proportion of shaft friction increases. This suggests that the reduction in unit ultimate bearing capacity with more piles is mainly attributed to a decrease in mobilized tip resistance. Furthermore, even with the same number of piles, the five-pile cross group exhibited a smaller proportion of shaft friction compared to the five-pile series group. This is likely due to the more confined arrangement in the cross configuration, where piles are closely spaced within a limited area. In such configurations, each pile's settlement is constrained by the interaction with surrounding piles through the ground, making it more difficult to achieve the amount of settlement required to fully mobilize tip resistance. As a result, both the mobilized tip resistance and shaft friction per pile tend to decrease in the cross group.

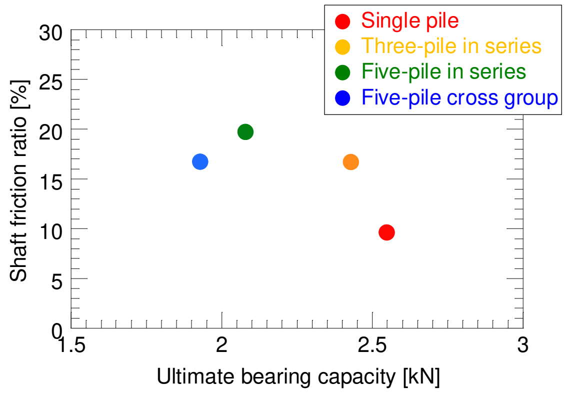

Figure 8. Proportion of shaft friction and tip resistance at the settlement level of δ/D=10%.

3.2 Thin bearing layers (3*D* and 1*D* below the pile base)

Figure 9 presents the load–displacement relationships for different bearing layer thicknesses below the pile base (10*D*, 3*D*, and 1*D*). The pile configurations include a single pile, a five-pile group in series, and a five-pile cross group. All results are compared within a displacement range up to δ/D = 40%. As shown in Figure 9, in all cases, the bearing capacity decreased as the thickness of the bearing layer was reduced. This reduction is primarily attributed to the limited mobilization of tip resistance when the dense bearing layer is shallow. According to Suezawa et al. (2020), a bearing layer thickness below the pile base of approximately three times the pile diameter is generally sufficient to limit the reduction in bearing capacity and can be considered acceptable for practical design. This trend was also observed in the present tests: for the single pile, the ultimate bearing capacity at a thickness of 3*D* was approximately 86% of that at 10*D*, indicating that the effect of a thin bearing layer was relatively limited. In contrast, for the five-pile groups (both in series and in cross configuration), the ultimate bearing capacities at a thickness of 3*D* dropped to 58% and 61% of those at 10*D*, respectively, showing a more significant impact of reduced thickness compared to the single pile. These results suggest that in closely spaced pile group foundations, such as SPSP foundations, the conventional rule of "bearing layer thickness = 3 times the pile diameter" may not be sufficiently conservative, and a more appropriate assessment based on actual soil conditions is needed.

Figure 10 illustrates the proportion of shaft friction under each bearing layer thickness condition. It was clearly observed that the contribution of shaft friction increased as the bearing layer became thinner across all pile configurations. Interestingly, while the five-pile cross group exhibited a smaller proportion of shaft friction under the condition of a thick bearing layer, it showed the largest shaft friction ratio when the bearing

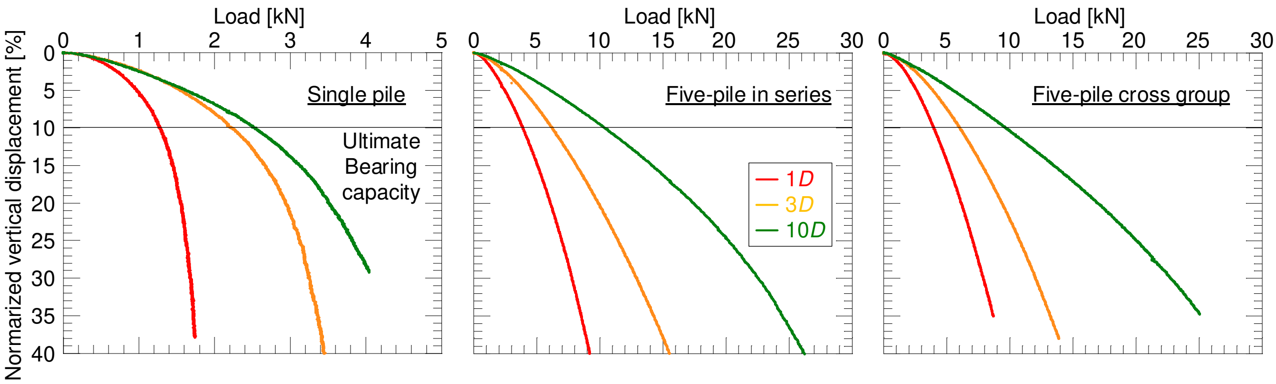

Figure 9. Load–displacement relationships for different bearing layer thicknesses below the pile base (10D, 3D, and 1D).

layer was thin. This reversal indicates that in densely arranged configurations like the cross group, the mobilization of tip resistance is more significantly hindered when the bearing layer is thin, resulting in a greater reliance on shaft friction. Furthermore, the shaft friction ratios were nearly identical between the single pile with a 1*D* bearing layer below the pile base and the five-pile cross group with a 3*D* bearing layer below the pile base. This implies that, with a 3*D* bearing layer below the pile base, the cross group behaves similarly to a single pile with an effective bearing layer thickness of 1*D*, due to the confined nature of the group and its comparable scale.

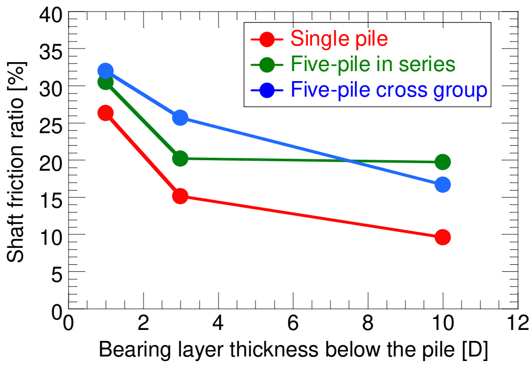

Figure 10. Proportion of shaft friction under each bearing layer thickness condition at the settlement level of δ /D=10%.

4 CONCLUSIONS

The following conclusions were drawn from centrifuge model tests investigating the vertical bearing behavior of steel pipe sheet pile (SPSP) foundations under varying pile configurations and bearing layer thicknesses, representing non-displacement pile conditions without installation-induced stress effects:

1) A significant group pile effect was observed, reducing the unit bearing capacity as the number of piles increased. In particular, the five-pile cross group exhibited the lowest capacity per pile, due to constrained settlement and limited mobilization of tip resistance in the densely arranged configuration.
2) Bearing layer thickness strongly influenced the load-bearing performance of group piles. While single piles retained over 85% of their bearing capacity with a 3*D* bearing layer below the pile base, five-pile groups showed reductions to approximately 60%, suggesting that the conventional 3*D* criterion may be insufficient for SPSP foundations.
3) As the bearing layer became thinner, shaft friction became the dominant load transfer mechanism. The five-pile cross group, which had a smaller friction ratio in thick layers, exhibited the highest friction ratio under thin-layer conditions, suggesting a shift in resistance mechanism from tip to shaft as confinement increases.

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