FEM ANALYSIS ON A PILE SUPPORTED BY A THIN SAND LAYER SUBJECTED TO STATIC AND CYCLIC AXIAL LOADING

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1. INTRODUCTION

Pile foundations are often designed to support the applied load by transferring the stresses through shaft friction and to an underlying bearing layer, often made of rock or dense sand. However, in some sites, the thickness of the dense sand layers may be insufficient to meet standards set by local codes to be considered as a bearing layer for pile foundations. Thus, there may be a limitation to design the piles as friction piles, which may be more costly due to the larger required depth. Therefore, it is necessary to investigate the minimum thickness of the dense sand layer that can be considered as a bearing layer.

The objective of the current study is to conduct numerical analyses on a pile supported by a dense sand layer of various thicknesses subjected to both static and cyclic axial loading. In particular, static loading was applied to investigate the effects of the dense sand layer thickness on the bearing capacity. Additionally, cyclic load tests were performed to investigate displacement and stress levels in the soil surrounding the pile after repeated loading and unloading.

2. METHODOLOGY

Analysis using a Finite Element Method (FEM) was performed using the FEM code DBLEAVES (Ye *et al.*, 2007). Reproduction analyses of centrifuge model tests (Martinez *et al.*, 2020) were first conducted. Numerical analyses were then conducted using the same parameters considering a larger study area. Figure 1 shows the dimensions of the study area. The soil used in the analysis was Toyoura Sand, modeled using the subloading t_{ij} model. Table 1 shows the properties and parameters of the soil. The dense sand layer was set to have a relative density of D_r = 90%, while the underlying loose layer was set to D_r = 30%. The pile was modeled as a closed-ended hollow cylinder with a diameter of D = 1 m. The hybrid element method used by Danno and Kimura (2009) was adopted to maintain the rigidity of the pile under axial loading. The method uses vertical beam elements surrounded by solid elements to model the pile. The rigidity of the pile is maintained using horizontal beams with high rigidity. Table 2 shows the properties of the pile. The soil-pile interface was modeled using joint elements, with properties shown in Table 2. In the DBLEAVES code used, the shear rigidity of the joint elements decreases to 0.001 times the initial value once separated.

Seven cases were performed to investigate the effects of the dense sand layer thickness, H, on the behavior of the pile under both static and cyclic axial loading. Figure 1 shows the cases. Here, the dense sand layer thickness, H, is presented as a multiple of the pile diameter, D.

Static axial loading was first applied on the pile head to investigate the effects of the dense sand layer thickness on the bearing capacity of the pile, or the total axial resistance at a displacement of $0.1D$. A separate load-controlled cyclic load test was then performed for each case with the same initial stresses as that in the static load test. The load-controlled cyclic load tests were performed to determine the displacement after 10 cycles.

The cyclic load was defined using a mean load P_m and a cyclic load P_c, which were both taken as 0.05 times the bearing capacity of the pile. The pile is first loaded (compression) by P_m, then a cyclic load of P_c is applied initially in the compressive direction. The effects of the cyclic load on the stress in the surrounding soil layers were also investigated.

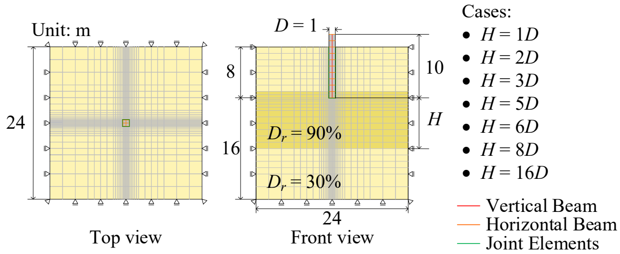

Figure 1. Experimental set-up and cases

Table 1. Toyoura sand – subloading t_{ij} parameters

Principal stress ratio at failure R_{cs}	3.2
Poisson's ratio, ν	0.310
Static earth pressure coefficient, k_0	0.45
Parameter for stress-dilatancy relation, β	2.0
Compression index, λ	0.07
Swelling index, κ	0.0045
a(ANN)	60

Table 2. Pile and joint properties

Young's modulus of vertical beam, E_v [kPa]	1.39×10^8
Young's modulus of solid elements, E_s [kPa]	2.82×10^6
Area of beam element [m^2]	0.149
Shear rigidity of joints [kPa/m]	1.55×10^5
Vertical rigidity of joints at pile tip [kPa/m]	1.55×10^9
Vertical rigidity of joints at pile shaft [kPa/m]	1.55×10^9
Cohesion [kPa]	5
Internal friction angle [deg]	28

3. RESULTS

3.1. Static load: Bearing Capacity

Figure 2 shows the relationship between the dense sand layer thickness (normalized by the pile diameter) and the total bearing capacity. It can be observed that there is a

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significant difference between Cases 1 and 2. However, once the bearing thickness exceeds 3*D* (*H* > 3*D*), there is no significant increase in the total bearing capacity. This result is consistent with the findings from the centrifuge model tests (Martinez *et al.*, 2020). This suggests that such cases may be considered to have properties similar to that a full bearing layer.

3.2. Cyclic load

Cyclic axial tests were performed to simulate the behavior of small cyclic loads, such as wind. Two sets of cyclic load test were performed. The first test, CLT1, was performed with a mean load, P_m, and a cyclic load, P_c, both equal to 0.05 of the total bearing capacity of each case. The second test, CLT2, was performed on Cases 1*D*, 2*D*, 3*D*, and 5*D* with a mean load and a cyclic load both equal to 0.05 of the total bearing capacity of Case 16*D*. Figure 3 shows the pile tip and head loads for Case 8*D* in CLT1. The pile tip load is observed to decrease, which may be due to the friction at the soil-pile interface during tensile loading. Figure 4 shows the maximum displacement and the displacement after 10 cycles. The discrepancy between the two values is attributed to the elasto-plastic behavior of the soil.

In the CLT1 tests, the max. displacement is lowest for *H*/*D* = 1 and increases until *H*/*D* = 5, which has the largest value among the cases. The max. displacement then slightly decreases as *H* is further increased. These suggest that when the load is taken in proportion to the total bearing capacity corresponding to the dense sand layer thickness, the max. displacement occurs when the thickness is between 3*D* and 5*D*. However, as pile foundations are designed to resist large loads, the CLT2 tests were performed to investigate the behavior of a pile supported by a thin layer compared to that supported by a full bearing layer. It is evident that larger displacements are obtained for a thinner dense sand layer. The displacements, however, approach nearly similar values when the thickness is at least 5*D*.

Figure 5 shows the volumetric strain in the soil after 10 cycles of CLT1. For Cases 1*D* and 2*D*, large strain is observed in the underlying loose layer. For Case 3*D*, the region with large strain reaches the bottom of the dense layer. For the other cases (thicker dense sand layer), the region with large strain is limited to the dense layer. These suggest that when the dense layer thickness is less than 3*D*, the resistance would be highly dependent on the strength of the underlying layer. For thicknesses larger than 5*D*, the load may be fully resisted by friction along the shaft and the dense sand layer.

4. CONCLUSIONS

Analysis using a finite element method was performed on a pile supported by a dense sand layer of various thicknesses. Simulations of both static and cyclic axial tests were performed. Static loading test was performed to investigate the total bearing capacity. The findings suggest that a dense sand layer thickness *H* greater than 3*D* may be considered to have a similar resistance to that of a full bearing layer. Moreover, the findings from the cyclic tests suggest that when the thickness is at least 5*D*, the displacement is similar to that for a pile supported by a full bearing layer.

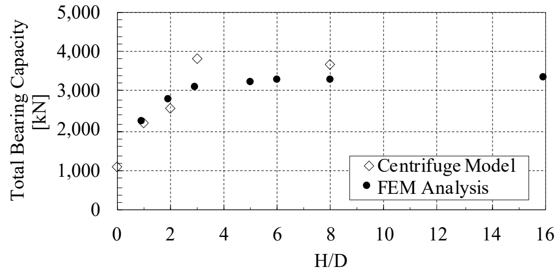

Figure 2. Dense sand layer thickness vs. bearing capacity

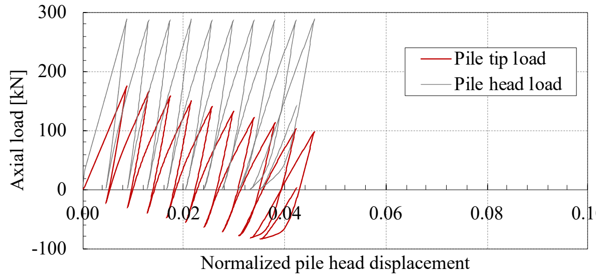

Figure 3. Pile tip load vs. pile head displacement for Case 8*D* (CLT1)

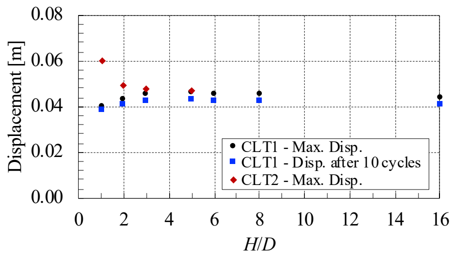

Figure 4. Pile head displacement (maximum and after 10 cycles)

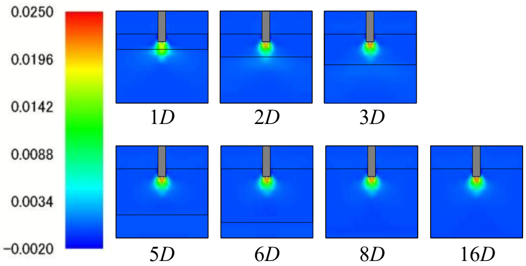

Figure 5. Volumetric strain in soil surrounding pile tip after 10 cycles (CLT1)

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