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The Influence of a Thin Weak Clay Layer on the Close-Ended Pile Behaviors in Sand

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Abstract: This work studies the uncertainties in the bearing capacity of axially loaded close-ended piles. The focus is on the impact of the location of a thin weak clay on the behaviours of the piles in sand. Simulations have been conducted in Plaxis 3D by varying the position of the weak layer relative to the pile tips. The thickness of the weak layer equals one diameter of the pile (1D). It is found that the effect of the thin weak layer on the pile behaviour varies with its location. The influence zone of the weak layer is found to be 1D above and 4D below the pile tip under the 0.1D settlement criteria. The relative distance between the weak layer and pile tip is one of the critical factors that affect the failure mechanism of the piles. The weak clay layer may increase, decrease or has no impact on the bearing capacity of the piles depending on the location of the weak layer. A probabilistic analysis is performed to study the variation of the pile bearing capacity with the location of the weak layer.

Keywords: Thin weak clay layer; pile capacity; FEM simulation; influence zone.

1 Introduction

Cone penetration test (CPT) is one of the most extensively used in-situ methods that have been used for estimating pile bearing capacity. In CPT based design methods, the cone tip resistance q_c within the influence zone around the pile tip is used to predict pile base resistance using different averaging methods. However, the uncertain range of influence zone and disputable averaging methods for interpreting variable q_c measurements introduces bias into the pile base capacity estimation (White & Bolton, 2005), especially when there are laminated weak layers near the pile bottom (Khosravi et al., 2022).

In engineering practice, the Dutch (Van Mierloo & Koppejan, 1952) and French methods (Bustamante & Gianeselli, 1982) are widely adopted for the prediction of pile base capacity. The influence range in the Dutch approach is 0.7D to 4D below and 8D above the pile tip, whereas the French method uses 1.5D above and below the pile tip. These numbers are also different from many observed values. For example, Arshad et al. (2014) performed a series of CPTs on sand samples in a half-circular chamber, demonstrating that the influence zone extends to 3D below the cone tip; Tehrani (2018) conducted physical penetration tests on layered sand and concluded that the sensing and development distances are in the range of 2.2D–5.4D; Based on the analytical analysis, Yang (2006) claimed that for piles in clean sands, the influence zone is between 1.5D and 2.5D above the pile tip and 3.5D to 5.5D below the tip.

In stratified soils, the bearing mechanisms of piles are different and have not been well studied. Most existing studies have focused on ground conditions with two or three thick layers (Xu & Lehane, 2008; Tehrani et al. 2018; Khosravi et al., 2018). Mo et al. (2015, 2017) and Khosravi et al. (2022) conducted a series of CPT tests in layered silica sand and clay configurations. The authors found that the CPT resistance and the soil deformation are dependent on the relative properties between soil layers, stress state and the probe diameter. Van der Linden (2016) conducted several CPT tests in interlayered soil, finding that the mechanism in deposits containing multiple thin layers differs from that in deposits containing multiple thicker layers. Rica and Van Baars (2018) investigated the influence of a single thin weak layer on pile behaviours using Plaxis 2D. They found that both the stiffness and strength of the thin weak layer have a considerable effect on the pile bearing capacity. Despite the above studies, further effort is required to study the bearing mechanisms of piles in interlayered soil.

This study presents the results of three-dimensional FEM simulations of axial pile loading tests using Plaxis 3D to study the effects of a thin weak layer on the behaviours of close-ended piles in sand. The focus is on determining the influence zone under 0.1D settlement criteria and discovering the role of the weak layer on the pile behaviours.

2 Numerical model and simulation scheme

2.1 Numerical model and material parameters

The computations are conducted in Plaxis 3D using a symmetrical model. The computational domain is 12m x 6m x 30m as shown in Figure 1. The stratigraphy of the model includes a 1m thick sand fill at the surface, underlain by a sand layer with one laminated clay layer. The thickness (T) of the weak clay layer is 1m. The soils are modelled with the Hardening Soil model. The soils' parameters are shown in Table 1. The close-ended concrete pile is 20m long with a diameter of 1 m (L/D = 20). The concrete is modelled as a linear elastic material with the unit weight of 24kN/m^3, Poisson's ratio of 0.15 and Young's modulus of 30GPa. The water table is set at the ground surface. In the simulations, forces were applied at the pile head to reach the prescribed displacement. The pile bearing capacity in this study is determined by the threshold displacement value of 0.1D of the pile head.

The pile axial capacity consists of the base resistance (q_b) and the shaft resistance(q_s), as illustrated in Figure 1. The location of the weak layer is defined as the distance (H) between the top of the weak layer and the pile tip. All models use a medium size mesh, with a refined ratio of 0.2 for the zone between 2m above and 4m below the pile tip (see Figure 1). Comparison tests have been conducted by halving the mesh size to make sure that the mesh is fine enough.

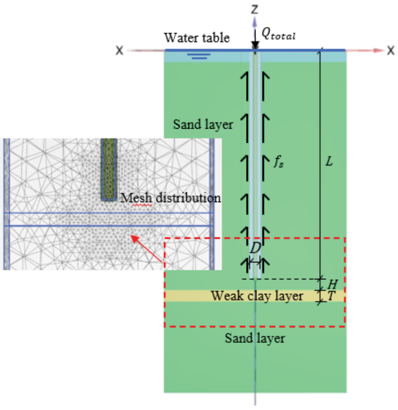


Figure 1. Diagram of the model in Plaxis 3D

Table 1. Soil parameters for the FEM modelling (from Plaxis 3D, 2022)

Soil Parameter	Fill	Sand	Soft clay
Material model	HS	HS	HS
Drainage type	Drained	Drained	Undrained
Unit weight above phreatic level (γ_{unsat}) (kN/m^3)	16	17	16
Unit weight below phreatic level (γ_{sat}) (kN/m^3)	20	20	17
Secant stiffness for CD triaxial test (E_{50ref}) (kN/m^2)	22000	43000	2000
Tangent oedometer stiffness (E_{oed}) (kN/m^2)	22000	22000	2000
Unloading/reloading stiffness (E_{ur}) (kN/m^2)	66000	129000	10000
Power for stress level (m)	0.5	0.5	1
Cohesion (c) (kPa)	1	1	5
Friction angle (ϕ') (°)	30	34	25
Dilatancy angle (ψ) (°)	0	4	0
Poisson's ratio (ν_{ur})	0.2	0.2	0.2
Interface reduction factor (R_{inter})	0.65	0.7	0.5
Over consolidation ratio (OCR)	1	1	1.5

2.2 Test series

Table 2 summarizes the 14 cases simulated in this study. The simulations include a baseline case with no weak layer (Test No. 1) and 13 cases (Tests No. 2-14) with the weak layer at different depths. The locations of the weak layer in Tests 2-14 are at -3.0, -2.0, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 4.0 m below the pile tip. A negative value of H indicates that the weak layer is above the pile tip, and a positive one means below. The basic nomination rule of legend used in the following figures is "Number of weak layers_H". For instance, when the weak layer is located at 1.0 below the pile tip, it will be denoted as "1 weak layer_1m".

Table 2. Summary of the simulation tests

Test No.	Number of the weak layer	Thickness of the weak layer (m)	Position of the weak layer (m)
1	No weak layer	-	-
2-14	Single weak layer	1.0	-3.0, -2.0, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0

3 Results

The load-settlement behaviour and the displacement fields of the soils around the pile tips are detailed in this section. In the analysis, the pile bearing capacity is defined as the load at the pile head settlement of 0.1D as recommended by White & Bolton (2005). But the settlements at the pile tips may be different to those at the pile head due to the deformation of the piles. Figure 2 shows the variation of axial pile deformation with pile head settlement. The maximum pile deformation is observed in the case when the weak layer is just above the pile tip. The value is 0.0033 m and about 3.3% of the pile head settlement. Therefore, the pile axial compressive deformation is not considered in analyzing the behaviour of the piles in the results.

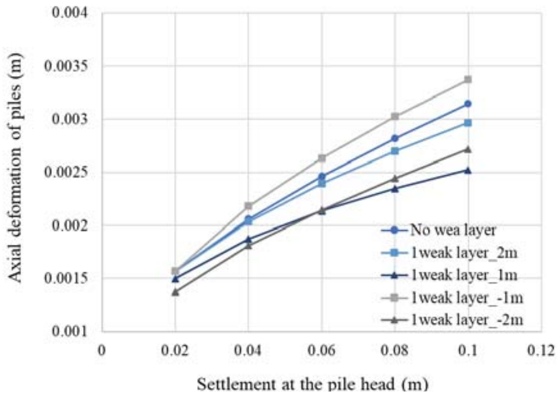


Figure 2. The variation of pile shaft deformation with pile head settlement

3.1 Load-settlement behaviour of the piles

Figure 3 compares the load–settlement (P-s) curves of the pile. The comparison shows that the location of the weak layer could greatly affect the behaviours of the piles. Based on the P-s cures, the impact of the weak layer on the bearing capacity of the piles can be divided into three categories.

(A) The pile capacity decreases when the top surface of the soft layer is within 1m (1D) above or 4m (4D) below the pile tip, shown as curves in Figure 3 (a). The lowest bearing capacity is when the clay layer is just below the pile tip (or in the case of "1 weak layer_0m"). As the weak layer gets deeper, the bearing capacity of the pile improves gradually.

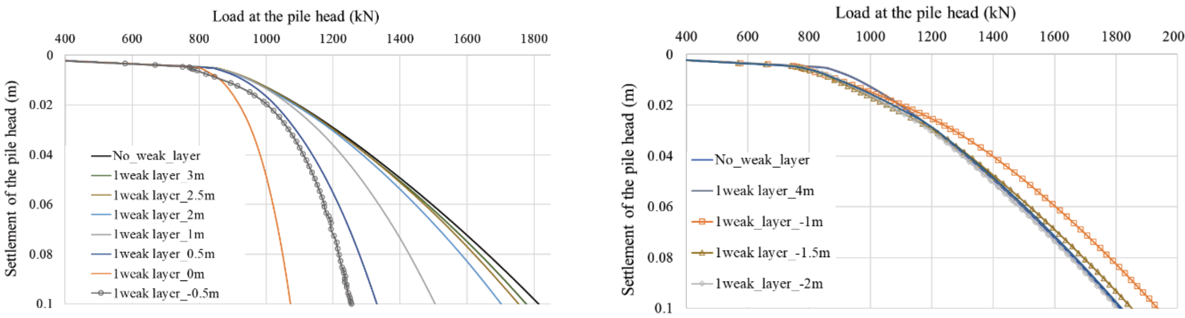
(B) The capacity increases when the bottom surface of the soft layer is located within 0 to 1D above the pile tip in Figure 3 (b). The P-s curves of these piles are smoother and have no obvious turning points compared to that of the piles in Group A. The axial capacity of the piles in group A at the turning points is around 800-1000 kN as shown in Figure 3 (a).

(C) The weak layer will have no impact on the behaviour of the pile when the pile tip is 1D below the bottom surface of the weak layer or 4D above the top surface of the weak layer, like the curves shown in Figure 3 (b) which overlap the baseline curve.

3.2 Load transfer mechanisms

3.2.1 Displacement fields around pile tips

The influence of the weak layer on the pile base resistance can be better observed through the displacement and stress fields of soils around the pile tip. The variation of the stress and displacement fields of three kinds of pile behaviour are discussed below. The three piles are in the soils with: no weak layer, a 1m thick weak layer with the top surface at 1m below, and a 1m thick weak layer with the top surface at 1m above the pile tip.



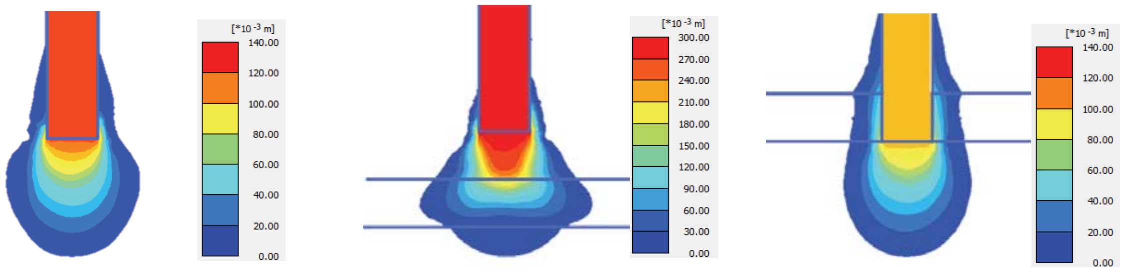
(a) Group A (b) Group B and C

Figure 3. Load-settlement curves of pile head (P-s curves) under different conditions

Figure 4 demonstrates the displacement fields in the soil around the tips of the piles under the loading of 2000kN rather than the displacement at 100 mm to study the variation of the displacement field in soils under the same loading level. The settlements at the tips of the three piles are 0.127m, 0.302m, and 0.109m respectively. The largest settlement is observed in the pile with the soft layer at 1m below the pile tip (Figure 4 (b), and the lowest settlement is in the pile with the weak layer just above the pile tip (Figure 4 (c)). In the figure, the top and the bottom surfaces of the weak layer are marked with two solid lines.

The influence depths of the piles are similar (about 2.2D) in the soil with no weak layer (Figure 4 (a)) and the soil with the weak layer above the pile tip (Figure 4 (c)). However, the influence zone is slightly wider at the interface of the clay layer and the underneath sand layer in Figure 4 (c). This could be one of the reasons why the pile with the weak layer above the pile tip has greater bearing capacity.

The location of the weak zone affects the displacement fields of soils around the pile tips. Though the influence zone of the pile tip with the weak layer below the pile is the largest among the three piles, its bearing capacity at 0.1D settlement is the lowest. The difference in the bearing capacities can also be explained with the sizes of the influence zones along the end sections of the pile shafts as shown in Figure 5. The respective height and the width of the influence zones above the tips of the three piles are: 2D, 0.5D; 1D, 0.3D; and 3D, 0.7D. The largest values are in the pile with the weak layer above the pile tip, and the lowest values are in the pile with the weak layer below the pile tip.



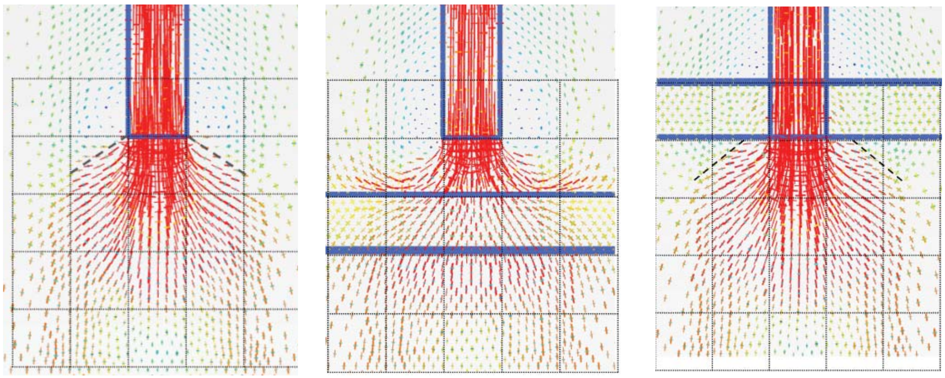
(a) No weak layer (shading) (b) Weak layer_1m (shading) (c) Weak layer_-1m (shading)

Figure 4. Displacement fields at the axial load of 2000 kN

3.2.2 *Stress fields around pile tips*

The stress fields in the soils around the tips of the three piles are revealed in Figure 5 to further reveal the impact of the weak layers on the pile behaviours. The state of the stress fields is captured at the pile head settlement of 0.1m (0.1D). The effective stress state of a soil element is demonstrated as a cross. The longer and shorter arms of the cross indicate the maximum and minimum principal stresses respectively. The longer the arms, the greater the principal stresses are. The directions of the principal stresses are reflected by the directions of the arms. The soil's principal stresses at rest are vertically and horizontally distributed throughout the area. Therefore, the rotation of the crosses indicates the deviation of the stresses to their initial states.

The figures show that there is a distinct difference between the stress fields in the soils around the pile tips. When there is no weak layer or the weak layer is below the pile tip, Figure 5 (a, b), the stress distribution angles meet the edge of the pile. However, when the weak clay layer is above the pile tip, the stress distribution angles start at about 0.5D away from the pile edges as shown in Figure 5 (c). When there is no weak layer below the pile tips (Figure 5 (a, c)), the soils in the zone directly below the pile tips are nearly under one-dimensional compression. But in Figure 5 (b), when there is a weak layer at 1D below the pile tip, the principal stresses in the soil above the weak zone rotate greatly and a passive resistance zone has been formed.



(a) No weak layer (b) Weak layer at 1.0m below (c) Weak layer at -1m above

Figure 5. Stress fields at the top head settlement of 0.1m

4 Reliability analysis

In engineering practice, the relative distance between the pile base and the thin weak layer is hard to determine. The main reason is the unpredictable depth of the thin layer and the spatial variability of the thin weak layer. This results in the uncertainty in pile capacity prediction. The location of the thin weak layer on the reliability of pile bearing capacity is discussed using the cases analyzed in Table 1.

The bearing capacities of the piles in cases 1-14 are summarized in Figure 6. It should be noted that the horizontal axis is the distance from the pile tip to the weak layer's top surface. When the weak layer's top is at -1m, it means the 1m thick weak layer is fully above the pile tip. As such, when the top of the weak layer is at -2m, the shortest distance between the weak layer and the pile tip is -1m, as 1D above the pile tip. The figure clearly shows that once the 1m thick weak layer is 1D above or 4D below the pile tip, the weak layer will have no impact on the pile bearing capacity when 0.1D settlement is used as the bearing capacity criterion. When the weak layer is just below the pile tip, the bearing capacity of the pile could reduce by 40%. If the soft layer is just above the pile tip, the bearing capacity of the pile would increase slightly by about 10%.

If we know that a 1m thick weak clay exists in the influence zone of the pile tip as shown in Figure 6, but do not know its exact location, we can estimate the probability of the pile capacity being less than a given value. The probability can be anticipated by calculating using the bearing capacity curve shown in the figure. For instance, there is a 47% of possibility that the pile capacity is less than 1625 kN (10% drop in the capacity of the pile in sand). The value is obtained by comparing the length of the curve under the 10% dashed line and the whole curve length in the -2D to the 4D range shown in Figure 6. Table 2 summarizes some of the typical values.

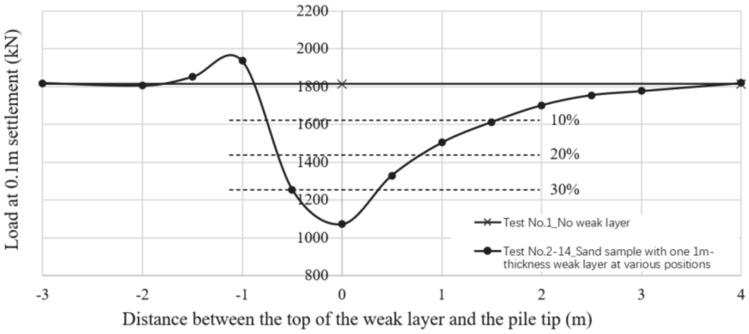


Figure 6. The bearing capacity of the piles in the sand with one layer of 1 m thick weak layer at different locations

The above conclusion is based on the assumption that the possibility of the thin weak layer's location is uniformly distributed within the range of 2D above to 4D below the pile tip. The curve in Figure 6 is drawn from an Excel scatter plot with smooth lines using Bézier interpolation method. Different interpolation methods may also have an impact on the prediction. In addition, this case only considers the variation of the vertical position of a 1m thick soft soil layer, but does not consider the variation of other properties of the weak layer, such as the thickness, and the strength and stiffness of the soil. Further research has been performed to analyze the reliability of more complex geological situations and the coupling of multiple variables.

Table 2. Probability of the weakening effect on pile capacity due to the 1m thick weak layer in the range of 2D above and 4D below the pile tip

Pile capacity	Probability
Lower than 1625 kN (10% reduction)	47%
Lower than 1445 kN (20% reduction)	30%
Lower than 1264 kN (30% reduction)	16.6%
Greater than 1806 kN	17.7%

* The pile capacity is 1806 kN with no weak layer.

5 Conclusions

A number of three-dimensional finite element analyses were conducted in Plaxis 3D to study the impact of a weak layer on the bearing capacity of close-ended piles in a sand ground. The weak clay layer is located near the pile tip. The thickness of the weak layer is assumed to be the same as the diameter (D) of the pile. The location of the weak layer varies near the pile tip. The pile bearing capacity is determined at the settlement of 0.1D. As such, the pile capacity obtained here may be different from the studies using other criteria. The applicability of the results to other cases needs to be further investigated.

Based on the limited number of simulations with the assumptions used, it was found that the influence zone for the piles is 1D above to 4D below the pile tip. The values are obtained using the displacement and stress fields of soils around the pile tips. Three kinds of pile behaviours have been observed depending on the positions of the weak layer. When the weak layer locates under or around the pile tip within the influence zone, the weak layer weakens the pile bearing capacity by up to 40% and leads to punching failure. When the weak layer is located above the pile tip, it would increase the pile capacity by 10%. When the clay layer is out of the influence zone, it has no impact on the pile bearing capacity.

A probabilistic analysis was performed to study the impact of the weak layer on the bearing capacity of the piles considering the uncertain location of the weak layer. The analysis shows that, if there is a weak layer within the vicinity of the pile influence zone, there is nearly 50% of probability the the pile bearing capacity would drop by 10%.

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