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The influence of fine content on ultimate lateral pile capacity

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ABSTRACT: This study investigates the influence of fine content on the ultimate lateral pile capacity of clayey-sand (c–φ) mixtures, a common yet complex natural soil type. While most existing models focus on purely cohesive or frictional soils, this work addresses the transitional behavior observed in mixed soils as fine content varies. A limit equilibrium (LE) framework is developed and implemented to capture the non-linear interaction between cohesive and frictional components, accounting for failure geometry, load distribution, and confining stress. Using direct shear test results of mixed soils with 2–98% fines, the model shows that as fine content increases, the soil lateral resistance transitions from frictional to cohesive dominant. For intermediate fine contents (20–40%), both mechanisms are partially mobilized, resulting in lower resistance than the sum of pure soil cases. This reduction is quantified through a fine (%) and depth dependent factor. The findings highlight that simplified superposition approaches may overestimate lateral pile capacity in $c-\phi$ soils, while the proposed method offers a more realistic evaluation for natural mixed soils, which accounts for the interplay between both strength components.

KEYWORDS: Lateral pile capacity, clay-sand soil, fine content, limit equilibrium.

1 INTRODUCTION

Estimating the maximum force that soil around a laterally loaded pile can sustain is critical for the structural safety and economic efficiency of pile foundations. Piles under lateral loading typically exhibit two primary soil failure modes: a wedge-shaped failure near the ground surface, and deeper horizontal soil flow around the pile, commonly analyzed as a plane-strain problem (Barton, 1982; Fleming et al., 2008). For the latter, the ultimate lateral pile capacity per unit length, P_{ult}, is an essential parameter, representing the maximum resistance that the soil can mobilize.

Existing theoretical and experimental studies have predominantly focused on idealized soils, such as pure clays or sands (Hansen, 1961; Broms, 1964; Petrasovits and Awad, 1972; Reese et al., 1974; Stevens and Audibert, 1979; Randolph and Houlsby, 1984; Prasad and Chari, 1999; Zhang et al., 2005; Fleming et al., 2008; Awad-Allah, 2011; Zhang and Ahmari, 2013; Georgiadis et al., 2013; Burd et al., 2020; Bouzid, 2021; Gans-Or and Pinkert, 2023 & 2024 & 2025a). In cohesive soils (clays), the lateral capacity, P_{ult}^{c}, primarily depends on cohesion and typically expressed by:

$$P_{ult}^{c} = N_c S_u D \tag{1}$$

where N_c is the lateral bearing coefficient, S_u is the undrained shear strength, and D is the pile diameter. For frictional soils (sands), the capacity P_{ult}^{ϕ} is typically simplified as:

$$P_{ult}^{\phi} = K_{ult}(\phi)\gamma z D \tag{2}$$

where $K_{ult}(\phi)$ is the lateral bearing coefficient which depends on the friction angle ϕ, γ is the soil unit weight, and z is depth.

However, natural soils often consist of clay-sand mixtures ($c-\phi$ soils), and their mechanical behavior significantly depends on the amount of fine content. This study investigates how fine content influences the ultimate lateral pile capacity of such granular mixtures.

2 THE INFLUENCE ON FINES CONTENT

Clay-sand mixtures contain larger particles like sand and gravel combined with finer particles such as silts and clays. According to the Unified Soil Classification System (USCS, ASTM D2487-17, 2017), fine particles are defined as soil grains smaller than 0.0075 mm. In this study, the fine content percentage relates to the weight fraction of fine grains relative to the total mixture weight.

As fine content increases, these mixtures transition from friction-dominated behavior at low fine contents to cohesion-dominated behavior at higher fine contents. This transition arises from changes in particle packing: initially, fine particles fill the sand voids without significantly affecting sand grain contact; beyond a critical fine content corresponding to minimal porosity, sand grains become isolated within a clay matrix, enhancing cohesive behavior (Yin et al., 2021). Based on 13 studies, Yin et al. (2021) identified the transitional fine content range as 24.6% to 40.9%, where soil behavior includes substantial combination of both frictional and cohesive contributions.

As an example to the mechanical influence of fine content, Sukmak et al. (2015) conducted direct shear tests on clay-sand mixtures with fine contents of 2%, 20%, 40%, 80%, and 98%, compacted at their optimal water content (OWC) to maximize strength properties. Table 1 shows engineering properties of these mixtures, highlighting that increasing fine content leads to higher cohesion and lower friction angles, aligning with the expected mechanical transitions.

Table 1. Engineering properties of tested soils (Sukmak et al., 2015).

Fines [%]	2	20	40	80	98
$\gamma_{dry}[kN/m^3]$	23	20.1	18.9	16.1	14.7
OWC [%]	6.5	12.2	14.8	20.2	23
$\gamma[kN/m^3]$	24.5	22.5	21.7	19.3	18
C $[kPa]$	0	20	25	38	43
ϕ [°]	40	35	32	14	5.5
USCS classification	SP	SC	SC	CH	CH

Figure 1 illustrates the relationship between fine content and shear strength parameters, depicted in Table 1. As fine content increases, cohesion rises while the internal friction angle decreases. The figure also highlights the transitional zone where both mechanisms contribute significantly to shear resistance (Yin et al., 2021).

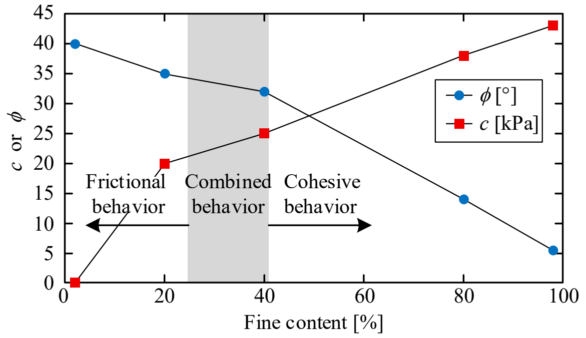

Figure 1. Relationship between strength properties, c and ϕ, and fine content for all tested soils (Sukmak et al., 2015).

3 ULTIMATE LATERAL PILE CAPACITY

Fine content notably influences ultimate lateral pile capacity through several mechanisms:

- Alteration of Failure Geometry:

Pure cohesive and frictional soils each have fundamentally different failure geometries (Gans-Or and Pinkert, 2024 & 2025a). Mixtures of these soils result in non-optimal failure geometries, reducing the mobilization of each strength properties.

- Modified Load Distribution:

Similarly, the load distribution pattern around the pile circumference is fundamentally different in cohesive and frictional soils (Gans-Or and Pinkert, 2024 & 2025a). In mixed soils, however, the optimal load distribution deviates from these idealized patterns, resulting in suboptimal mobilization of both strength components and, consequently, a reduction in the overall lateral resistance.

- Reduced Lateral Confining Pressure:

Increasing cohesion due to higher fine content reduces the initial confining stress around the pile ($K_0\gamma z$), resulting in lower frictional resistance. Pantelidis (2019) proposed the following expression for the at-rest lateral earth pressure coefficient (K_0) in $c - \phi$ soils:

$$K_0 = (1 - \sin\phi) - \frac{2c}{\gamma z}\tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \tag{3}$$

In addition, the influence of fine content is depth-dependent due to the differing stress dependency of each strength component.

4 LE SOLUTION FOR MIXED SOILS

Gans-Or and Pinkert (2025b) proposed an LE solution that incorporates the interplay of cohesion and friction properties in the lateral pile capacity problem. In this framework, the soil around the pile is discretized into horizontal rigid slices, and the mobilized shear resistance at each slice boundary is calculated, without pre-assuming the failure geometry of the soil. The shear stress upon a failure plane is calculated as:

$$\tau_{mobilized} = \tau_c + \tau_\phi = c + (K_0\gamma z + \sigma_{ext})\tan\phi \tag{4}$$

where σ_{ext} is the lateral stress normal to each slice which develops due to the pile load.

The critical failure geometry and its associated ultimate lateral resistance is obtained through optimization process, identifying the geometry that minimizes the external force which fulfills full equilibrium at limit state conditions. The solution introduces a reduction factor, R_d, which quantifies the difference between the combined cohesive-frictional resistance, $P_{ult}^{c-\phi}$, and the sum of each individual ideal soil resistance:

$$P_{ult}^{c-\phi} = R_d\left(P_{ult}^{c} + P_{ult}^{\phi}\right) \tag{5}$$

This factor accounts for the interplay of cohesion and friction, highlighting the non-linear interaction between these mechanisms, as reflected by $R_d \leq 1$ across all cases.

5 APPLICATION AND RESULTS

To demonstrate the effect of increasing fine content on the ultimate lateral pile capacity, Figure 2 shows the calculated R_d vs. fine content, for the soil mixtures in Table 1 and a 1 m diameter pile, based on Gans-Or and Pinkert (2025b). The figure plots the reduction factor R_d for each mixture across different depths, with linear trendlines connecting points for each fine content.

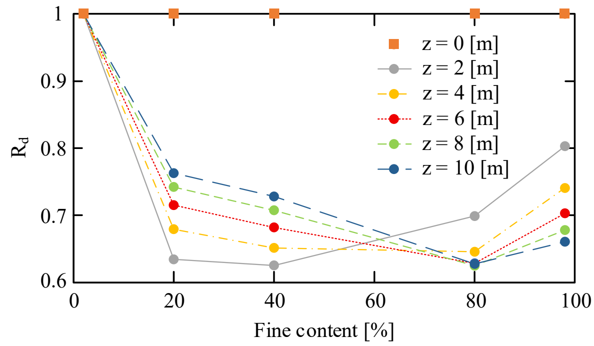

Figure 2. Calculated reduction factor, R_d, versus fine content at different depths for all clayey-sand mixtures listed in Table 1.

As illustrated in the figure, at the ground surface ($z = 0$), R_d equals 1 for all soil mixtures. This is due to the absence of confining pressure, resulting in a fully cohesive-dominated resistance equal to P_{ult}^{c}, independent of fine content (i.e., $P_{ult}^{\phi}(z = 0) = 0$). With increasing depth, the 20% and 40% fine content mixtures exhibit increasing values of R_d, indicating a reduced capacity loss and an enhanced mobilization of the frictional component. In contrast, mixtures with higher fine content, such as 80% and 98%, show a decreasing trend in R_d with depth, reflecting greater capacity reduction. This behavior signifies a transition from cohesion-dominated resistance near the surface to a mixed cohesive–frictional response at depth, as the friction becomes more pronounced due to the increasing confining pressure.

Figure 3 illustrates the depth-dependent variation of the ultimate lateral capacity, $P_{ult}^{c-\phi}(z)$, for a pile with a 1 m diameter and a smooth soil–pile interface, embedded in various soil mixtures as detailed in Table 1. The total capacity is computed using R_d (Equation 5), with the implementation of P_{ult}^{c} and P_{ult}^{ϕ} is according to:

$$P_{ult}^{c} = 9.14c_uD \tag{6}$$

for pure clays (Gans-Or and Pinkert, 2023 & 2024), and:

$$P_{ult}^{\phi} = 0.21\phi^{\circ}\gamma zD \tag{7}$$

for pure sands (Gans-Or and Pinkert, 2025a).

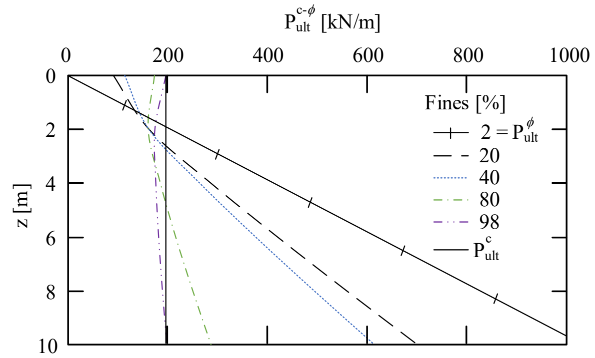

Figure 3. Distribution of ultimate lateral pile capacity, $P_{ult}^{c-\phi}$, with depth for a 1 m diameter pile with a smooth soil–pile interface, in all clayey-sand mixtures listed in Table 1.

The figure shows that the variation of $P_{ult}^{c-\phi}$ with depth is strongly influenced by the fine content, confining pressure, and the interaction between cohesive and frictional resistance components. At the ground surface, the soil resistance behaves as purely cohesive for all mixtures, as the absence of confining pressure results in zero frictional resistance. For the 2% fines case which associated with $c = 0$ (Table 1), the response is purely frictional ($P_{ult}^{c-\phi} = P_{ult}^{\phi}$) and increasing linearly with depth as dictated by Equation 7. A solid reference line representing the purely cohesive response (for $c = 43\ [kPa]$) is also shown in the figure, remaining constant with depth since cohesive resistance, which is given in Equation 6 is unaffected by confining pressure.

In the 20% fines mixture, the capacity at the surface is entirely governed by cohesion, but the frictional component rapidly becomes significant with depth. This is evident from the increasing slope of the capacity curve up to approximately 2 meters, beyond which friction dominates and the capacity continues to increase linearly. The 40% fines mixture follows a similar pattern; however, at shallow depths ($z < 2\ m$), the higher fine content results in greater cohesion, yielding a higher capacity than the 20% case. At greater depths ($z > 2\ m$), the 40% capacity falls slightly below that of the 20% mixture and increase with a smaller slope.

For the 80% fines mixture, the response up to approximately 4 meters depth is lower than the purely cohesive capacity at the surface. This reduction is attributed to the partial loss of cohesive mobilization due to the emerging frictional component. Beyond 4 meters, friction becomes dominant, but the capacity increases at a significantly lower rate compared to mixtures with less fines. In the 98% fines case, the behavior remains strongly cohesion-dominated with depth. Similar to the 80% mixture, the presence of friction reduces the effective mobilization of cohesion, leading to an overall decrease in capacity compared to the ideal cohesive case.

These trends underscore the non-linear and non-additive nature of the interplay between cohesion and friction in $c - \phi$ soils and highlight the importance of $P_{ult}^{c-\phi}$ analysis.

6 DISCUSSION

This study highlights the significant and multifaceted impact of fine content on the ultimate lateral pile capacity of clay–sand mixtures. A limit equilibrium framework was employed to rigorously capture the interplay between cohesive and frictional resistance mechanisms. This interaction was quantified using the reduction factor R_d, defined as the ratio between the actual lateral resistance of a $c - \phi$ soil and the sum of the idealized capacities from purely cohesive and purely frictional components acting independently.

The findings indicate that the lateral capacity of mixed soils, and its variation with depth, can be categorized into three distinct behavioral regimes based on the fine content:

1. Low fine content

In mixtures with a small amount of fines, the soil exhibits a friction angle close to that of pure sand, with minimal cohesion. Near the surface (low confining pressure), the response is initially cohesion-dominated. However, as depth increases, frictional resistance rapidly becomes dominant. This transition is reflected by an increasing R_d with depth, indicating reduced interaction effects and convergence toward the idealized sand response.

2. High fine content

Soils with high fine content typically exhibit substantial cohesion and a reduced friction angle, close to the behavior of pure clays. Surprisingly, these mixtures demonstrate a non-trivial reduction in total resistance, particularly at shallow depths, where the combined resistance is not only lower than the sum of the individual cohesive and frictional capacities, but even lower than the cohesive capacity alone. This counterintuitive outcome arises from the significant suppression of cohesive mobilization when even modest frictional components are introduced.

3. Intermediate fine content

For mixtures with non-negligible cohesion and friction values, the resistance is initially governed by cohesion near the surface, with increasing frictional contribution at greater depths. Nevertheless, at nearly all depths (except under very low confining pressures), the overall resistance remains significantly below the sum of the pure clay and pure sand capacities. This reduction is attributed to the mutual inhibition of component mobilization caused by their interaction, which prevents full activation of either resistance mechanism.

7 CONCLUSIONS

The main findings of this study are summarized below:

- The combination of cohesive and frictional resistance in $c - \phi$ soils is nonlinear and non-additive; the overall response cannot be approximated by a simple superposition of the idealized pure clay and pure sand solutions.
- The presence of fine content significantly influences the lateral pile capacity of clay-sand mixtures by altering both strength parameters and failure mechanisms.
- Intermediate fine contents result in partial and inefficient mobilization of both cohesion and friction, leading to a significant reduction in overall capacity compared to the summed capacities of the individual idealized cases.
- The reduction factor R_d effectively quantifies the capacity loss due to the interaction between cohesive and frictional components, as is shows systematic behavioral trends with depth and fine content.
- In mixtures with high fine content, even a small presence of friction can suppress cohesive mobilization to such an extent that the overall resistance becomes lower than that of the purely cohesive case, contrary to intuitive expectations.

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