

Impact of Diaphragm Wall Installation on Vertical Piles Behavior in Granular Soils

Bosco Poon

GHD, Sydney, Australia, bosco.poon@ghd.com.au

Chia Weng Boon

Gamuda Laing O'Rourke Consortium, Sydney, Australia, chiaweng.boon@oxfordalumni.org

Kim Chan

Formerly GHD, Sydney, Australia, kimfchan@outlook.com

ABSTRACT: This study investigates the impact of slurry trench excavation on the axial performance of existing piles in granular soils using three-dimensional finite element analysis with the Hardening Soil model incorporating small-strain stiffness (HS Small), and systematically examines how trench width, slurry level, pile length, applied load, and soil density influence stress redistribution, ground deformation, and pile response. A three-zone conceptual framework is developed to characterize pile behavior near the trench: Zone A, characterized by soil yielding and significant settlement; Zone B, marked by down-drag and reduced shaft friction; and Zone C, where trenching effects are minimal. The results demonstrate that reducing trench width and maintaining a high slurry level are effective strategies for mitigating soil yielding, limiting settlement, and preserving the pile capacity. However, short, heavily loaded piles located close to the trench remain susceptible to plastic deformation despite these mitigation measures. These findings highlight the importance of excavation design and construction practice to consider the influence of diaphragm wall trenching to adjacent piles, the impact of which depends on the stress changes and the sand relative densities.

KEYWORDS: Slurry trench excavation, diaphragm wall trenching, axial pile performance, granular soils.

1 INTRODUCTION

Diaphragm walls are widely employed in deep excavations for their ability to provide both structural support and groundwater control. However, when constructed adjacent to existing pile foundations of neighboring buildings, the excavation process of a diaphragm wall panel with slurry support can induce significant stress changes in the surrounding soil. The reduction in horizontal effective stress due to trenching can lead to soil yielding, settlement, and a loss of shaft resistance, all of which can compromise the performance of nearby piles. These effects of trenching are more onerous for granular material, as beneficial negative excess pore water pressures are dissipated quickly.

In granular soils, where strength is derived primarily from confining stress and interparticle friction, excavation-induced unloading can trigger pronounced deformation and plastic behavior, especially in the zone closest to the trench. While the importance of soil-structure interaction during excavation is well recognized, the combined effects of trench geometry, slurry level, and pile characteristics on stress redistribution and pile behavior are not yet fully understood.

This study employs 3D finite element analysis with the Hardening Soil model incorporating small-strain stiffness (HS Small) to investigate the influence of slurry trench excavation on axial pile performance across loose to dense sand conditions. Parametric analyses were conducted to evaluate the relative impact of trench width, slurry level, pile length, and load magnitude on effective stress changes and deformation patterns. A zoning framework is introduced to interpret the pile response, distinguishing between zones of (i) significant yielding, (ii) down-drag, and (iii) negligible trenching effects. The focus is restricted to axial behavior because, in many projects, loss of axial capacity particularly for heavily loaded vertical piles near diaphragm walls represents the more immediate serviceability or ultimate limit state concern. In addition, field monitoring and load test data for settlement and load transfer are generally more available and reliable than data for bending moments or lateral deflections, making axial studies more readily verifiable.

2 PROBLEM DEFINITION

The problem investigated in this paper is shown in Figure 1, which shows an existing single pile of diameter d , subjected to sustained pile head axial load P , located at a distance x from the edge of a slurry trench during diaphragm wall panel construction. The distance x is measured along a line perpendicular to the trench through its center. The vertical response of the pile was examined by varying trench width T_w , trench depth H , slurry level S_L , offset distance x , pile length L_p , applied load to the pile, and soil properties. Other parameters including guide wall dimensions, water level W_L , slurry density, trench thickness t , pile diameter d , and pile stiffness were kept constant, with their values shown in Figure 1.

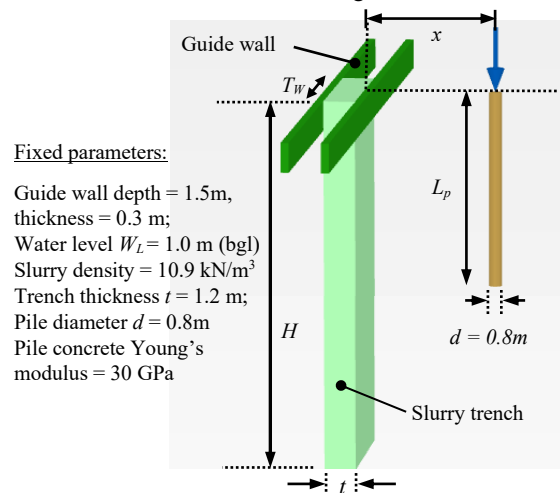


Figure 1. Problem Definition / 3D Finite Element Geometry

The trench excavation problem adjacent to the existing pile was simulated through a 3D finite element analysis in PLAXIS 3D. The soil was modeled using strain hardening soil model with small strain stiffness (HS Small). Table 1 lists the HS Small model parameters adopted for loose, medium dense and dense sand in this study.

For many sands and silts, experimental data and literature (e.g., Duncan and Chang, 1970) show that the unload–reload modulus E_{ur}^{ref} is typically 2–4 times the secant modulus E_{50}^{ref} . In PLAXIS, this ratio was set to 3 at the reference stress of 100 kPa. The oedometric modulus (or the constrained tangent modulus) E_{oed}^{ref} was calculated from the E_{50}^{ref} based on $E_{oed}^{ref} = aE_{50}^{ref}$ where $a = (1 - \nu)/(1 - 2\nu)/(1 + \nu)$ and ν = Poisson’s ratio. The small-strain stiffness E_0 was estimated using the empirical relationship proposed by Alpan (1970), as shown in Figure 2. In this chart, Alpan’s static modulus E_s and dynamic modulus E_d were interpreted as E_{ur}^{ref} and E_0 , respectively. The resulting E_0/E_{ur}^{ref} ratios for various sand densities are summarized in Table 1. The $\gamma_{0.7}$ is the shear strain level at which the shear modulus G decayed to $0.722G_0$. For sands, Wichtmann and Triantafyllidis (2004) reported typical values around 2×10^{-4} , with limited sensitivity to density indices. Based on triaxial and oedometer test data in sands from Jeffries & Been (2006) and others, Brinkgreve et al. (2010) proposed a formula of $\gamma_{0.7}$ in terms of relative density (RD): $\gamma_{0.7} = (2 - RD/100) \cdot 10^{-4}$. Benz (2007) applied the Mohr–Coulomb failure criterion to Hardin and Drnevich’s (1972) hyperbolic model to derive $\gamma_{0.7}$ in terms of small-strain shear modulus G_0 , coefficient of earth pressure at rest K_0 , soil friction angle ϕ' and vertical effective stress σ'_v :

$$\gamma_{0.7} = \frac{1}{9G_0} [\sigma'_v(1 + K_0)\sin(2\phi')] \quad (1)$$

This study adopted $\gamma_{0.7}$ values from Equation (1) at $\sigma'_v = 100$ kPa, aligning with those assessed by Brinkgreve et al. (2010).

Table 1. Adopted parameters for HS Small model

Parameter	Unit	Loose	Medium dense	Dense
E_{50}^{ref}	(MPa)	10	20	40
E_{oed}^{ref}	(MPa)	13.5	27	54
E_{ur}^{ref}	(MPa)	30	60	120
E_0/E_{ur}^{ref}	(-)	4.8	3.5	2.6
G_0	(MPa)	55	80	120
$\gamma_{0.7}$	(-)	2.5×10^{-4}	1.8×10^{-4}	1.2×10^{-4}
m	(-)	0.5	0.5	0.5
ϕ'	(degrees)	30	34	38

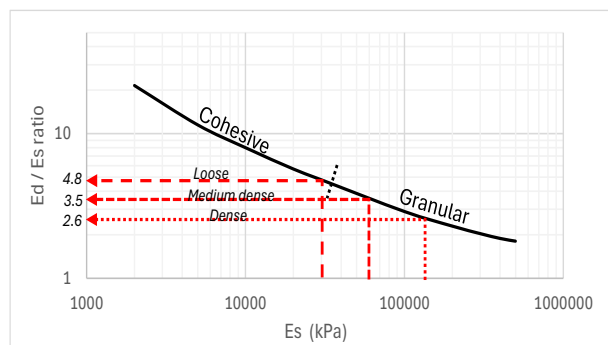


Figure 2. Relation between E_d ($\approx E_0$) and E_s ($\approx E_{ur}^{ref}$) - Alpan (1970)

3 RESULTS FOR LOOSE SANDS

3.1 Surface settlements

Ground surface settlement is often related to distance from the trench, normalized by trench depth. Figure 3 shows such normalized settlements from Cowland and Thorley (1984) at seven diaphragm wall sites in Hong Kong, along with results from this study across the centerline of a 30 m-deep slurry trench (with $T_W = 6$ m and $S_L = -0.5$ m bgl) in loose sand, using

the HS Small (with small strain stiffness) and HS models (without small strain stiffness). The HS Small model predicts a narrower, sharper settlement trough that falls well within the range of the measured data, whereas the HS model gives a broader profile with a greater peak settlement that exceeds the upper bound of the field measurements. This difference arises because the HS model does not capture the increased stiffness at small strains, leading to overestimation of deformation.

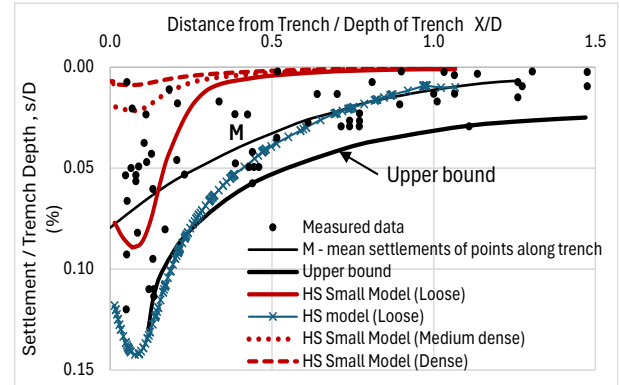


Figure 3. Ground settlement due to adjacent slurry trench excavation

Figure 4 shows that varying the trench depth produces only minor changes in the predicted surface settlement. This indicates that trench depth has limited influence on settlement in an effective stress analysis for sands. The settlement troughs exhibited in the predicted curves are mainly associated with a wedge-shaped zone of deformation concentrated within the upper 10 m adjacent to the slurry trench, or Zone A in Figure 5. As demonstrated later in this paper (Sections 4 and 5), this wedge is more strongly influenced by factors such as soil friction angle, slurry level, and trench width, rather than trench depth. Consequently, trench depth is not an appropriate parameter for normalizing settlement for sand.

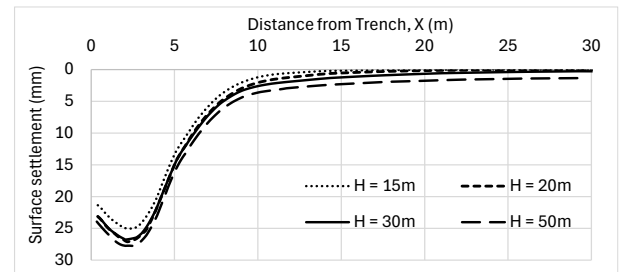


Figure 4. Effect of trench depth on assessed ground surface settlement

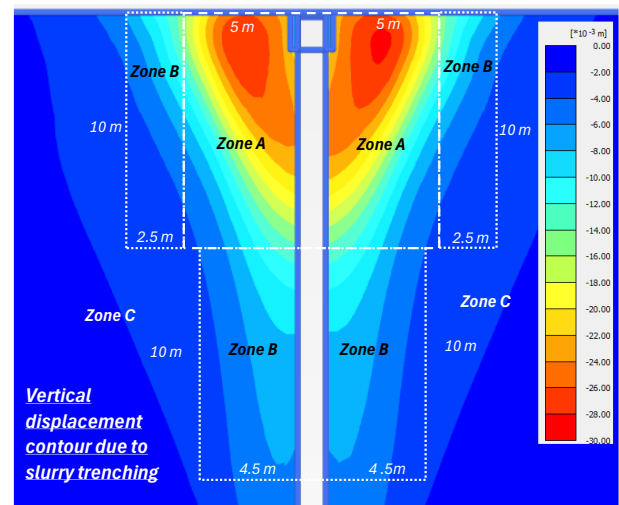


Figure 5. Settlement wedge identified in the loose sand case

3.2 Settlements of piles under sustained loads

For a non-loaded pile near a slurry trench, the pile head settlement decreases relative to the free-field surface settlement as pile length increases, due to greater mobilization of shaft resistance. This behavior is illustrated by the numerical results in Figure 6. Under sustained loading, however, the pile head settlement may exceed the free-field surface settlement, depending on the pile's relative position to the settlement wedge. Zones A, B, and C in Figure 5 represent areas that are, respectively, most critical, intermediate, and least susceptible to settlement under sustained loading, with Zone A encompassing the settlement wedge itself. Interestingly, when mapped onto the settlement curves for the non-loaded pile in Figure 6, these zones correspond approximately to 50-100%, 30 – 50% and < 30% of the maximum free-field surface settlements.

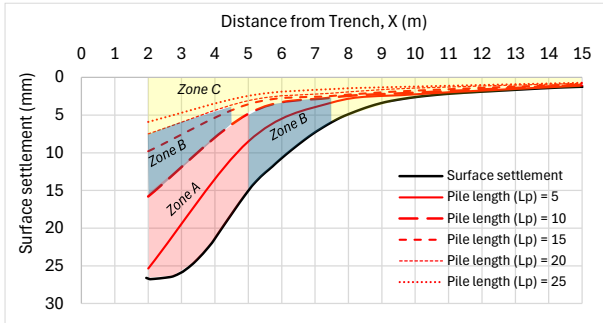


Figure 6. Pile head settlements in loose sand without applied loading

Zone A – Piles with potential plastic deformation due to soil yielding: Zone A encompasses the settlement wedge identified in the loose sand case as delineated in Figure 5. Within this zone, a high concentration of plastic points is observed in the soil elements surrounding the pile (Figure 9a), leading to a pronounced increase in pile head settlement with increasing building load. This settlement exceeds the greenfield settlement caused by trenching alone, as shown by the curves of $L_p = 5$ m and $L_p = 10$ m, founded in Zone A at $x = 2$ m and $x = 5$ m, respectively, in Figures 8a and 8b. The plastic yielding is primarily attributed to the loss of lateral confinement resulting from trench excavation. Figure 7 shows the ratio of final to initial horizontal effective stress (σ'_h) at various offset distances (x) from the trench wall for the loose sand case ($\phi' = 30^\circ$, $T_W = 6$ m, $W_L = 1.5$ m bgl, $S_L = 0.5$ m bgl). The stress ratio drops to approximately 0.37 at $x = 2$ m and 0.69 at $x = 5$ m. This substantial reduction in lateral stress lowers the soil strength at shallow depth within Zone A, promoting plastic yielding of soil surrounding the pile. While this paper focuses on the vertical pile response, it is worthwhile noting that significant horizontal displacement, approximately 60% of the settlement, also occurs at the pile toe in Zone A. This implies that the zoning framework could extend to lateral pile displacements, though the complexity of the associated pile forces places them beyond the scope of this study.

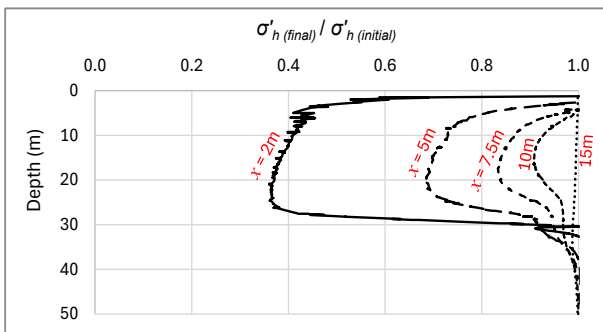


Figure 7. Assessed σ'_h (final) / σ'_h (initial) ratio for the loose sand case

Zone B – Piles subject to down-drag and reduced shaft friction: Pile toes founded in Zone B (Figure 5) experience notably smaller settlements compared to those in Zone A, primarily due to the reduced extent of plastic deformation (see the curves for $L_p = 15$ m and 20 m at $x = 2$ m and $L_p = 15$ m at $x = 5$ m, all founded in Zone B, shown in Figure 8). The settlement of Zone B piles can be attributed to three mechanisms: (i) greenfield settlement at the pile tip due to trenching; (ii) negative skin friction acting along the upper pile shaft (Figures 9b and 9c), caused by differential soil settlement with more settlement occurring near the ground surface than at depth; and (iii) greater proportion of the building load is transferred to the pile toe due to reduced overall shaft friction (f_s), which results from (a) f_s not being mobilized above the neutral axis (Figure 9b), and (b) reduced f_s below the neutral axis caused by a decrease in horizontal effective stress (σ'_h), since $f_s = \sigma'_h \times \tan \delta$ for sands, where δ is the pile–soil interface friction angle. The maximum reduction ratios of σ'_h at each x for the loose sand case, taken from Figure 7, are plotted in Figure 10 as the shaft friction reduction ratio (R_{f_s}) versus x , indicated by the solid blue curve. R_{f_s} for other combinations of W_L , S_L , T_W and ϕ' are also plotted in the figure, which will be discussed in Sections 4 and 5.

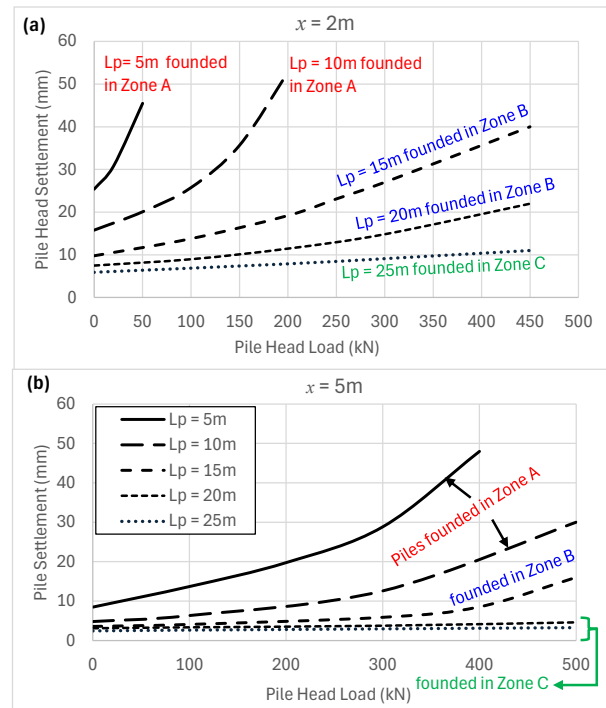


Figure 8. Assessed pile head settlements under increased pile head loads in loose sand at (a) $x = 2$ and (b) $x = 5$ m from the trench

Zone C – Piles with minimal trenching effects: For the loose sand case, pile toes located in Zone C (Figure 5) generally experience only minor settlement (5mm or less surface settlements shown in Figure 6) due to trenching. The existing pile head load has a negligible effect on the resulting pile head settlement. This is illustrated by the curves for $L_p = 25$ m at $x = 2$ m and $L_p = 20$ m and 25 m at $x = 5$ m, all founded in Zone C, shown in Figure 8.

3.3 Discussion

Based on the zoning in Figure 5, the behavior types of the pile in each zone are predominantly influenced by both the stress changes and ground movement illustrated in Figure 11. Where the piles are close to the trench (illustrated as Zone A in Figure 5), the settlements induced by trenching become more sensitive

to the pile loads. The physical mechanism driving this observation is due to the yielding of the soil, as shown in Figure 9(a). This is conceptually illustrated using Mohr-Circles in Figure 11, where the earth pressure at rest, K_0 , may reduce to the limiting active Rankine earth pressure coefficient K_a (significant impact in Figure 11).

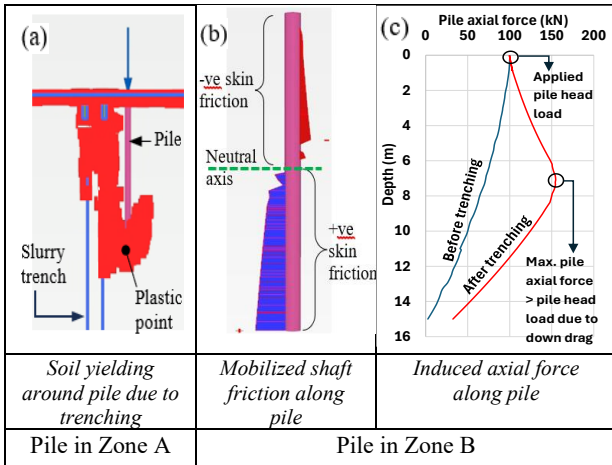


Figure 9. (a) Soil yield around pile in Zone A, (b) Mobilized shaft friction and (c) induced axial force of pile in Zone B

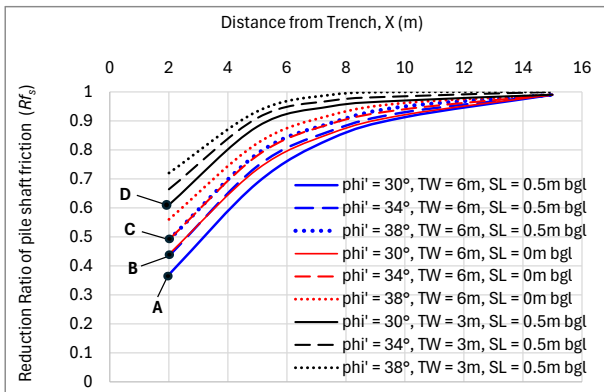


Figure 10. Reduction ratio of pile shaft friction due to slurry trenching

In Zone B (Figure 5), the main mechanism is down drag, where the soil settlement would lead to a reduction in mobilized resistance at the pile (blue line to red line in Figure 12). This is further compounded by a loss in confining stress which may reduce the geotechnical capacity of the pile, particularly in sand (moderate impact in Figure 11). Where instability is not the predominant mechanism, a load transfer analyses (Seed and Reese, 1957) would be able to provide an estimate of the settlement induced by trenching, by assigning as input the greenfield settlements of the soil caused by trenching. The pile then needs to settle to recover the working load at the pile head (red line to green line in Figure 12). Based on the authors' experience, the trends obtained from a load transfer analysis are consistent with the finite element method for Zone B and C. The advantage of the load transfer analyses is that it is more versatile than the finite element method in assigning the unit shaft resistance and end bearing stiffness and limiting values. However, this method would lead to a divergence of prediction compared with the finite element method in Zone A, as the load transfer analyses cannot assess the influence of soil yielding.

In Zone C, the change in load transfer along the pile body is minimal (minimal impact in Figure 11), and a more crude method using engineering judgement can be adopted by assessing two parameters, namely (i) the subsurface settlement at the pile toe, and (ii) the settlement commensurate with the inferred settlement of the pile at its working load, based on the

reduction in geotechnical capacity caused by a loss in confining pressure.

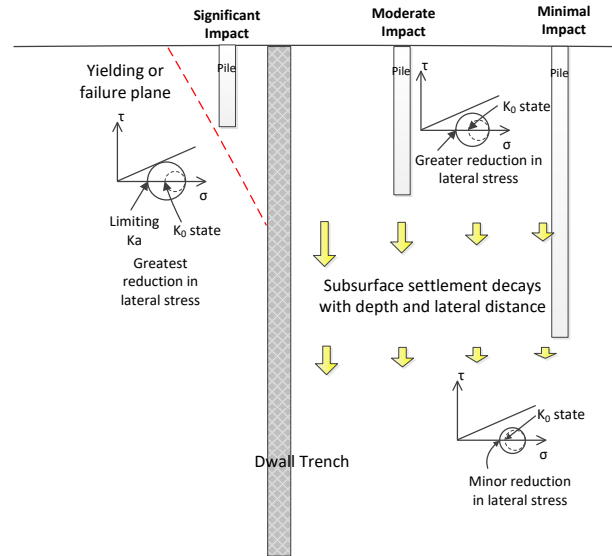


Figure 11. Impact to pile due to nearby diaphragm wall trenching arising from ground movement and stress changes. The latter is illustrated via Mohr Circles. Stress rotations are not included for simplicity.

Zone B and Zone C Concept of Settlement Prediction using Load Transfer Analyses of Piles

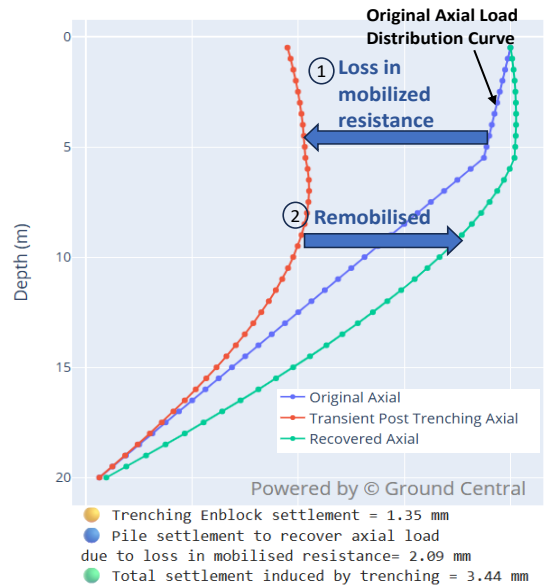


Figure 12. Illustration of the method using a load transfer analyses by taking into account soil settlement causing loss in mobilized resistance, with the python ground central platform

4 RESULTS FOR MEDIUM DENSE AND DENSE SAND

While the preceding analyses focused on loose sand conditions, the observed settlement wedge mechanism and the corresponding Zone A classification remain applicable to medium dense and dense sands, despite higher friction angles and increased soil stiffness.

The assessed surface settlements for medium dense and dense sands (Figure 3), and the corresponding pile head settlements for various pile lengths at $x = 2$ m (Figure 13), are lower than those in loose sand. However, Figure 10 shows that slurry trenching still results in significant reductions in σ'_h and R_{fs} . For example, at $x = 2$ m, the R_{fs} reduction ratio improves

only slightly, increasing from 0.37 in loose sand (Point A on the blue solid curve), to 0.44 in medium dense sand (Point B on the blue dashed curve), and 0.49 in dense sand (Point C on the blue dotted curve). These relatively modest changes indicate that even in denser granular soils, piles founded within the settlement wedge remain subject to substantial stress reduction and potential soil yielding under increased pile loading.

Accordingly, the spatial extent of the settlement wedge and the corresponding zoning framework (Zones A, B, and C), originally developed for loose sand, remain valid for medium dense and dense sands, with adjustments to account for the reduced, but still significant, magnitude of stress reduction. The extents of the zones are similar for the granular soils of different densities and friction angles.

5 REMEDIAL STRATEGIES FOR CONTROLLING TRENCH-INDUCED SETTLEMENTS

Among the various parameters examined, raising the slurry level and reducing the trench width are found to be the most effective measures for limiting potential soil yielding in Zone A. Increasing the slurry level enhances lateral support along the trench walls, thereby mitigating the extent of stress relief in the adjacent soil mass. Similarly, narrowing the trench width reduces the magnitude of unloading by decreasing the volume of soil removed, which in turn limits the relaxation of σ'_h in the critical region surrounding the trench. Together, these measures significantly reduce the likelihood of exceeding the soil yield criterion within Zone A, particularly for piles embedded near the trench and subject to increased axial loading.

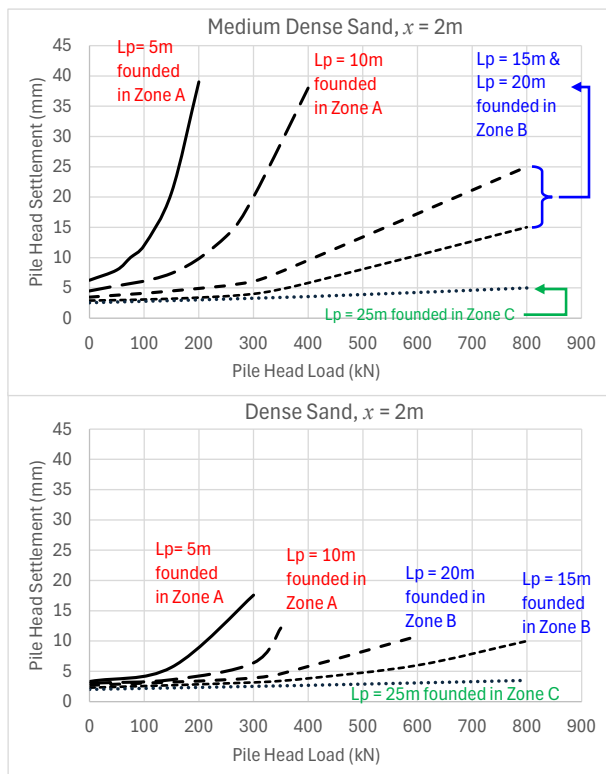


Figure 13. Assessed pile head settlements at $x = 2\text{m}$ under increased pile head loads in (a) medium dense sand and (b) dense sand

5.1 Raising slurry level

To evaluate the influence of slurry level on stress redistribution and ground deformation, additional simulations were conducted for the loose sand case with the slurry level raised from RL -0.5 m to RL 0 m . In the baseline case (RL -0.5),

significant unloading led to notable reductions in σ'_h and the development of a pronounced settlement wedge.

While stress retention improved only moderately (e.g. σ'_h reduction ratio at $x = 2\text{ m}$ increased from 0.37 to 0.44 as indicated by Points A and B, respectively in Figure 10), the impact on deformation was more substantial. Vertical displacement contours show that raising the slurry level suppressed the shallow settlement wedge (compare Figure 14 with Figure 5), leading to noticeably reduced pile head settlements across all pile lengths (compare Figure 15 with Figure 8a). However, the 5 m-long pile at $x = 2\text{ m}$ remained susceptible to soil yielding, as evidenced by the non-linear response of the $L_p = 5\text{ m}$ curve in Figure 15, indicating that heavily loaded short piles near the trench remain vulnerable.

These findings confirm that slurry level control is an effective mitigation measure for improving load-bearing performance and reducing the risk of soil yielding during trench excavation in loose granular soils, although further reinforcement may be needed for short, heavily loaded piles located near the trench.

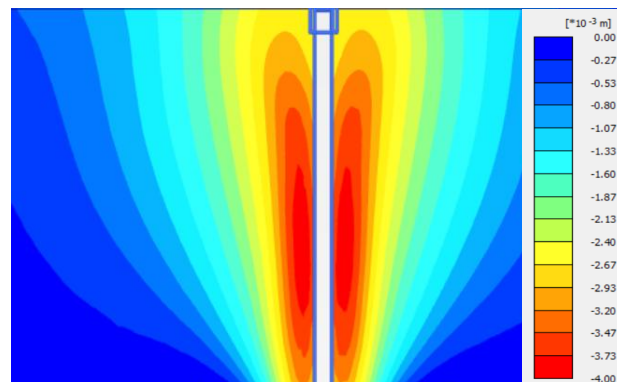


Figure 14. Vertical displacement contour from PLAXIS for loose sand case with raised slurry level

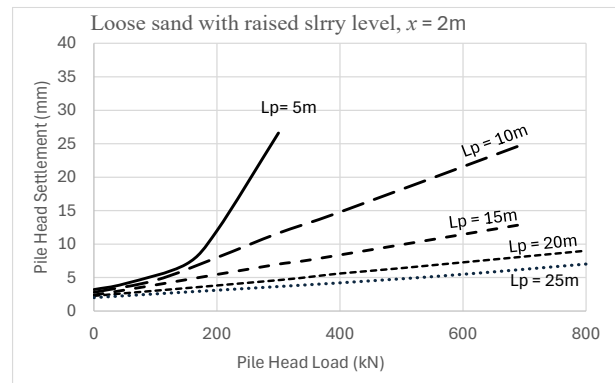


Figure 15. Assessed pile head settlements under increased pile head loads in loose sand with raised slurry level at $x = 2$

5.2 Reducing trench width

The influence of trench geometry was assessed by reducing the trench width from 6 m to 3 m in the loose sand model. This change produced a greater benefit than raising the slurry level alone. The σ'_h reduction ratio at $x = 2\text{ m}$ improved from 0.37 (6 m case; Point A in Figure 10) to 0.61 (3 m case; Point D in Figure 10), while raising the slurry level to RL0 resulted in a lesser improvement to 0.44 (Point B in Figure 10).

Figure 16 highlights that the narrower trench greatly limits ground deformation, with the settlement wedge significantly curtailed in extent and depth. Pile head settlements across all lengths are also lower compared to the raised slurry level case (Figure 17). Nonetheless, the 5 m pile at $x = 2\text{ m}$ continued to

exhibit yielding behavior, as indicated by the non-linear $L_p = 5$ m curve, suggesting that short piles near the trench remain susceptible to plastic deformation.

These results indicate that reducing trench width is also an effective mitigation strategy for controlling both stress relaxation and pile settlement in loose sandy soils, though additional measures may be necessary to safeguard short, heavily loaded piles near the trench.

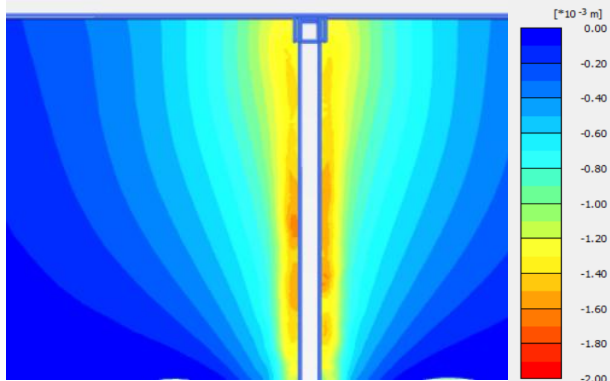


Figure 16. Vertical displacement contour from PLAXIS for loose sand case with reduced trench width

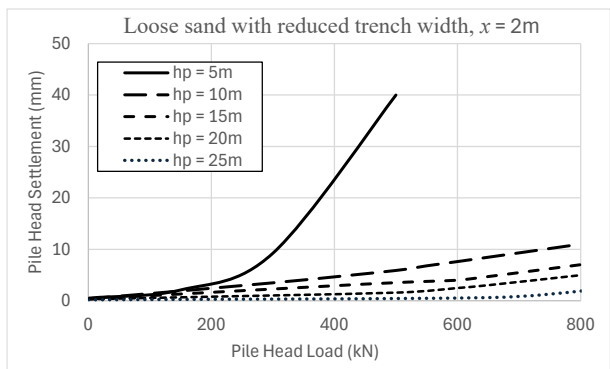


Figure 17. Assessed pile head settlements under increased pile head loads in loose sand with reduced trench width at $x = 2$

6 CONCLUSIONS

This study examined the impact of slurry trench excavation on the axial performance of existing piles in granular soils using 3D finite element analysis with the HS Small model. The results indicate that normalizing settlement by trench depth is inappropriate, as the extent of deformation is more strongly influenced by factors such as soil friction angle, slurry level, and trench width rather than trench depth. Consequently, the influence zone does not scale linearly with trench depth, reflecting the complex interplay of stress redistribution and settlement in granular soils.

A three-zone conceptual framework was developed to characterize pile responses near the trench:

- **Zone A:** Settlement wedge zone, marked by soil yielding and significant ground movement.
- **Zone B:** Transition zone with down-drag and loss of shaft resistance.
- **Zone C:** Stable zone where trenching effects on the pile are negligible.

In loose sands, piles founded within Zone A experienced pronounced plastic deformation due to substantial reduction in horizontal effective stress (σ'_h), leading to pile settlements exceeding free-field surface settlements. This behavior was

primarily driven by the loss of lateral confinement caused by trench excavation. As a result, the pile response became increasingly sensitive to the applied load and its proximity to the settlement wedge.

In medium dense and dense sands, increased stiffness and higher friction angles helped reduce overall deformation; however, a settlement wedge similar to that observed in the loose sand case remains identifiable. Significant reductions in horizontal stress and shaft friction were still observed, especially for piles located near the trench within the settlement wedge. For instance, at $x = 2$ m, the shaft friction reduction ratio (Rf_s) increased only moderately from 0.37 in loose sand to 0.44 in medium dense sand and 0.49 in dense sand. These findings indicate that the proposed zoning framework remains applicable across different sand densities, although the magnitude of impact decreases with increasing soil density.

Parametric analyses revealed that trench width and slurry level are the most influential factors in mitigating potential soil yielding in Zone A:

- Reducing trench width yielded the greatest improvement, significantly increasing the σ'_h reduction ratio and largely suppressing formation of the settlement wedge.
- Raising the slurry level provided moderate reduction of horizontal stress but effectively limited shallow ground deformation and settlement wedge formation, thereby reducing pile settlements and improving load-carrying capacity.

In summary, this study highlights the importance to consider excavation-induced stress changes in diaphragm wall design adjacent to existing piles. Although reducing trench width and maintaining a high slurry level effectively preserve shaft resistance and limit soil yielding in most cases, short, heavily loaded piles close to the trench still require special attention due to their ongoing susceptibility to deformation and localized yielding.

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