Numerical Modelling of Deep Shaft Excavations: Bridging The Gap Between 2D And 3D Analysis

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ABSTRACT

It is widely recognized that two-dimensional (2D) analyses for deep shaft excavations tend to be conservative, primarily due to their inability to fully account for corner effects and the arching behavior around shaft walls. Overdesign resulting from 2D analysis can lead to oversized excavation and lateral support (ELS) systems, increasing construction costs and causing greater disturbance to the surrounding environment. This paper presents a comprehensive study on the application of both 2D and 3D numerical modelling in the design and analysis of shaft excavations. The study focuses on how the dimensions, such as breath, length, and depth, influence the comparative outcomes of 2D and 3D analyses. Key outputs, including bending moments, shear forces, wall deformations, and adjacent ground settlements, are analyzed and compared.

The paper also evaluates computational efficiency, cost implications, and the trade-offs between model complexity and accuracy. Practical recommendations are provided for selecting appropriate modelling approaches in design practice. The findings support the integrated use of 2D and 3D models to enhance design reliability and efficiency for complex urban excavations.

1 INTRODUCTION

Rapid urbanization and increasing population density in major metropolitan areas have led to severe congestion in underground spaces. Consequently, urban infrastructure projects, such as water supply, drainage, electricity, and telecommunications, require deeper alignments to avoid conflicts with existing utilities and minimize disruptions to surface activities. Traditional open-cut methods for pipeline installation have become increasingly constrained due to traffic impacts, space limitations, environmental concerns, and public inconvenience. Trenchless technologies, particularly pipe jacking, have emerged as an effective alternative capable of addressing these challenges.

Pipe jacking involves the installation of pipelines through the ground behind a micro tunnelling or tunneling shield. A critical component of this method is the construction of vertical shafts, which serve multiple purposes, including entry and exit points for pipe installation, permanent inspection manholes, and maintenance access points. These shafts typically involve deep excavations supported by robust excavation and lateral support (ELS) systems, such as sheet-pile or pipe pile walls with closely spaced internal steel strutting.

Traditionally, design engineers have relied heavily on simplified two-dimensional (2D) numerical analyses to assess excavation induced soil movements, structural forces in retaining walls, and potential impacts on adjacent structures. While 2D analyses offer computational efficiency and simplicity, the assumption of plane-strain conditions neglects critical three-dimensional (3D) structural interactions. Specially, they overlook phenomena such as corner stiffening effects often referred to as "corner effects" around excavation corners and soil arching, particularly with increasing excavation depth. As a result, prediction from 2D analyses led to be overly conservative.

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This conservatism often leads to unnecessarily robust designs, excessive and/or higher grade material use, higher construction costs, and greater environmental impacts, such as noise and vibration from hard driving of sheet piles and extended construction durations. Recognizing these limitations, advanced 3D numerical modelling techniques are increasingly being adopted to better capture complex excavation behavior and optimize ELS design.

This paper systematically investigates and compares 2D and 3D numerical modelling approaches with aid of PLAXIS 2D and 3D respectively for shaft excavation design. The study emphasizes the influence of geometric factors, including shaft length-to-breadth (L/B) and breadth-to-depth (B/D) ratios, and illustrates how explicitly capturing and adopting the corner effects in the 2D analysis based on targeted 3D modelling can result in more realistic and economical designs. Furthermore, practical guidance is provided for integrating the strengths of both modelling strategies to achieve optimized, safe, cost-effective, and environmentally responsible excavation solutions, supported by theoretical insights and a practical case study.

2 TECHNICAL BACKGROUND AND THEORETICAL CONSIDERATIONS

2.1 Deep Shaft Excavation Design Considerations

Deep shaft excavations induce significant stress redistribution in the surrounding soil mass, leading to ground movements, surface settlement, lateral wall deflections, and changes in groundwater pressure. These effects can potentially impact nearby structures, utilities, and infrastructure, necessitating careful prediction and control. Accurate modelling of excavation induced stress paths and soil deformation behavior is essential for designing safe, effective, and efficient excavation support systems.

In urban areas, deep shaft excavation design is typically governed by the wall deflection and associated ground movement, especially to ensure compliance with allowable settlement limits for surrounding structures and utilities. The conservative predictions from 2D numerical analysis often necessitate the use of stiffer wall systems and closer spacing of internal steel struts to control wall deflections, resulting in over-design and less efficient excavation solutions.

2.2 Limitations of Conventional 2D Numerical Analyses

2D numerical analysis assumes plane-strain conditions, meaning the cross-section of excavation is considered uniform and infinitely long in the direction perpendicular to the section. While this assumption enhances computational efficiency, it inherently neglects key 3D phenomena and structural interactions. Specifically, 2D analyses cannot accurately represent the structural stiffening provided by perpendicular walls at corner (i.e. "corner effects") or the beneficial arching of soil that occur at excavation corners.

Several literatures have demonstrated the influence of 3D corner effects on the lateral soil pressure and their role in reducing wall deformation, bending moment and loads on shoring systems such as ground anchors or steel struts (Hsiung et al., 2018, Rabie et al., 2019 and Kosalim & Gunawan, 2023). As a result, 2D analyses typically yield conservative predictions of excavation induced wall deflections, bending moments, shear forces, and adjacent ground settlements, leading to overly robust and costly structural designs especially for deep shaft excavation whose corner effect is way more significant.

2.3 Importance of "Corner Effects" in Excavation and Lateral Support Design

In shaft excavations (see Plate 1 & 2), the perpendicular walls at corners substantially enhance the structural rigidity and reduce lateral deflections compared to plane-strain (2D) scenarios. These corner interactions facilitate the development of soil arching effects, redistributing stresses around the excavation perimeter and further reducing wall deformation and ground movements. The deeper the excavation, the broader the influence zone around the corners, with 3D effects becoming increasingly significant across the entire displacement field (Gianpiero & Marco, 2022). Accurately accounting for corner effects through 3D numerical analysis enables the designers to reliably quantify these beneficial phenomena. This improved representation typically results in significantly reduced predicted structural forces and ground movements, supporting more economical and environmentally sustainable ELS designs.

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Relying solely on 2D modeling in shaft excavations without consideration of corner effect leads to over conservatism ELS design. This often results in oversized and less constructible shoring system, with excessive preloading of struts, simply to satisfy settlement, angular distortion and serviceability criteria outlined in general specifications, codes of practice and government publications.

Plate 1: Shaft Excavation – Internal View

Plate 2: Shaft Excavation –Top View

3 NUMERICAL MODELLING AND ANALYSIS

To investigate the influence of excavation geometry on shaft performance comprehensively, a parametric study was conducted, focusing on two critical geometric parameters: the shape factor (length-to-breadth ratio, L/B) and the depth factor (breadth-to-depth ratio, B/D). Numerical analyses were conducted using both 2D and 3D finite element modelling (PLAXIS), and the results are systematically analyzed and compared between the baseline models (PLAXIS 3D) and plane-strain models (PLAXIS 2D) to highlight the significance of 3D effects in terms of maximum ground settlement, wall bending moment and strut forces.

3.1 Numerical Modelling Setup

The parametric analyses presented in this study were conducted using PLAXIS 2D and PLAXIS 3D finite element software to investigate the excavation induced ground settlement and structural responses under varying shaft geometries. Key aspects of the numerical modelling approach are summarized below:

Soil Material Model and Parameters

- The Hardening Soil (HS) constitutive model was selected to realistically represent soil stiffness, stress dependency, and unloading/reloading behavior during excavation processes. Compared to the simpler Mohr-Coulomb model, the HS model provided more accurate predictions for ground response, especially for deep excavations
- Three sets of typical soil parameters, as listed in Table 1 below, were adopted in the numerical modelling.
- The stiffness modulus for primary loading in a drained triaxial test, E_{50}^{ref} is assumed to be Young's Modulus (E_s) of soil at drained condition.
- According to Lim et al. (2010) and Calvello and Finno (2004), the reference moduli for unloading/reloading and oedometer loading were estimated to be $E_{ur}^{ref} = 3E_{50}^{ref}$ and $E_{ode}^{ref} = 0.7E_{50}^{ref}$ respectively.
- The power for stress-level dependency of stiffness (m) and reference stress for stiffnesses (p_{ref}) value are assumed to be 0.5 and 100 kPa respectively.

Table 1: Typical Soil Parameters adopted for Parametric Study

Case	Bulk Unit Weight (kN/m^3)	Cohesion, c' (kPa)	Friction Angle, ϕ′ (deg.)	Young's Modulus, E_s (kPa)

Case 1	19	0	33	10,000
Case 2	19	0	35	10,000
Case 3	19	3	33	10,000
Case 3a	19	3	33	25,000

Boundary Conditions:

- Vertical side boundaries placed sufficiently distant (typically at least 2 to 5 times the excavation depth from the shaft edges) to minimize boundary influence. Horizontal displacements normal to these boundaries are fixed, while vertical movements are allowed.
- The bottom boundary fixed against both vertical and horizontal movements.
- Ground surface boundary is free, simulating realistic surface displacement and settlement.

Groundwater Conditions:

- Groundwater table modelled at 2m below ground level.
- Hydrostatic conditions assigned to excavation faces during the staged excavation.

Excavation Sequences:

- 20kPa applied around the excavation shaft for all stages
- Excavation simulated in sequential stages, mimicking realistic construction practices, which is 500mm below strut level.
- Hydrostatic groundwater conditions are updated at each excavation stage accordingly.

The general input arrangements for PLAXIS 2D and PLAXIS 3D models are presented in Figure 1.

3.2 Effect of Shape Factor (L/B ratio)

The shape factor (L/B), defined as the ratio of shaft length (L) to breadth (B), significantly influenced the magnitude of three-dimensional "corner effects" and related ground settlement patterns. Table 2 summarizes maximum ground settlement obtained from baseline (3D) and plane-strain (2D) model analyses for varying L/B ratios under constant excavation depth of 9m (i.e. B/D = 1).

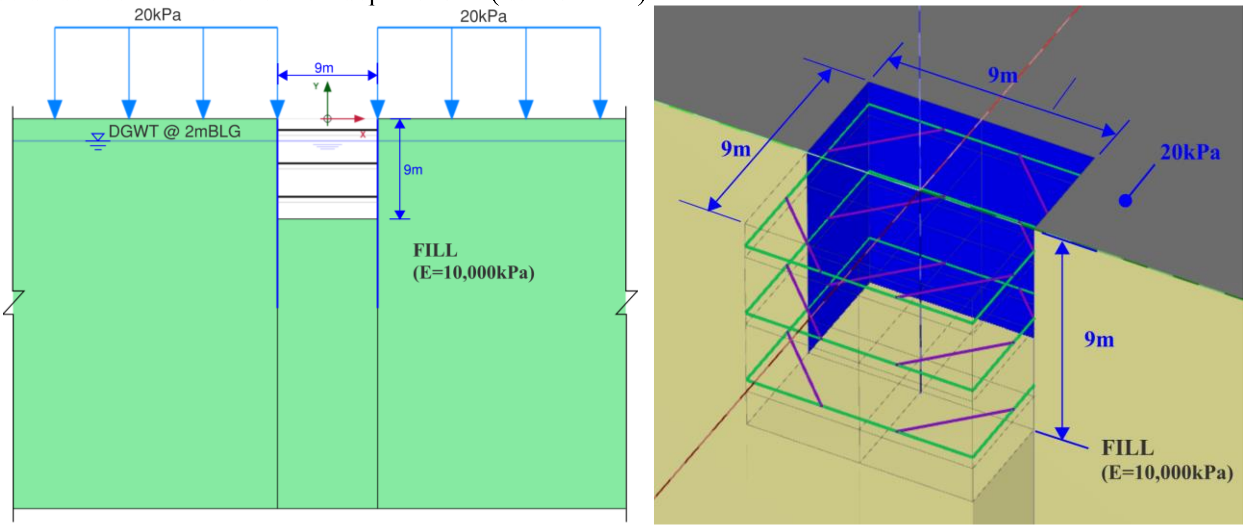


Figure 1: PLAXIS 2D (LHS) and PLAXIS 3D (RHS) Models for Shaft Excavation 9m(B) x 9m(L) x 9m(D)

Table 2: Comparison of Results from PLAXIS 3D and 2D under 3 Sets of Soil Parameters

Shaft geometry (B×L×D) m^3	**L/B ratio**	**c=0kPa, ϕ=33° (Case 1)**			**c=0kPa, ϕ=35° (Case 2)**			**c=3kPa, ϕ=33° (Case 3 & 3a*)**		
		Settlement from 3D (mm)	**Settlement from 2D (mm)**	**Settlement Reduction (3D vs 2D) %**	**Settlement from 3D (mm)**	**Settlement from 2D (mm)**	**Settlement Reduction (3D vs 2D) %**	**Settlement from 3D (mm)**	**Settlement from 2D (mm)**	**Settlement Reduction (3D vs 2D) %**
9×9×9	1.00	12.3	21.9	43.9%	11.5	19.1	39.6%	9.4 (7.4)	16.1 (11.5)	41.5% (35.7%)
9×12×9	1.33	16.5	21.9	24.7%	15.1	19.1	20.9%	12.6 (9.8)	16.1 (11.5)	21.7% (14.8%)

9×15×9	1.67	19.3	21.9	11.8%	17.4	19.1	8.8%	15.0 (10.9)	16.1 (11.5)	6.9% (5.2%)
9×18×9	2.00	20.4	21.9	7.2%	18.5	19.1	3.5%	15.8 (11.5)	16.1 (11.5)	1.6% (0.0%)

*Remark: Values in the bracket are the results from Case 3a.

3.2.1 Discussion and Interpretation:

- At low L/B ratios (approaching square shapes), significant reduction in settlements was observed in 3D analyses compared to 2D results (e.g., maximum 43.9% reduction at L/B = 1 as shown in Table 2). This indicates significant corner stiffening and soil arching effects, reducing excavation induced settlements.
- The settlement reduction diminished with increasing L/B ratios. Beyond L/B ≈ 2.00, settlement differences become insignificant (less than 10%), indicating minimal corner effects and effectively plane-strain conditions.
- The reduction in wall bending moment and strut force diminished as the L/B ratio increases, with the maximum reduction being less than 20% when L/B = 1. Beyond L/B ≈ 1.33, wall bending moment differences become insignificant (less than 5%). Benefits on the structural design from 3D analyses seem not significant as per the settlement reduction.
- The chart in Figure 2 illustrates the percentage reduction of maximum settlements (3D vs. 2D) versus the L/B ratio under different soil parameters. A similar trend is observed across all cases, indicating that the effect of the L/B ratio does not vary significantly with changes in soil parameters. However, weaker soil parameters (i.e. lower c-ϕ values) and stiffness (i.e. lower E_s) show a slightly more pronounced reduction in settlement under 3D analyses.

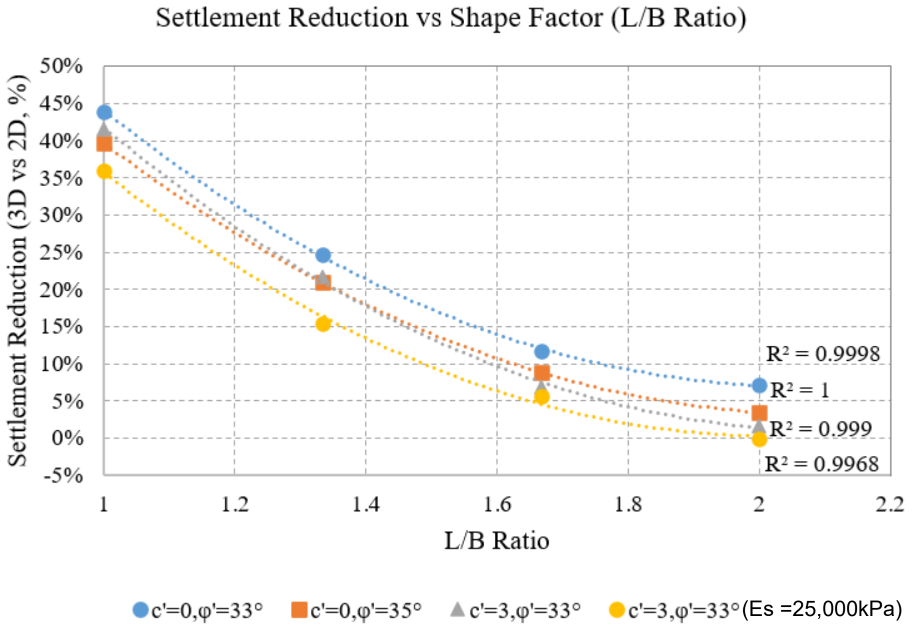


Figure 2: Settlement Reduction vs Shape Factor under different Soil Parameters (with Constant B/D = 1)

3.3 Effect of Depth Factor (B/D ratio)

The depth factor (B/D), defined as the ratio of shaft breadth (B) to excavation depth (D), critically affects excavation induced soil movements due to soil unloading and stress redistribution. Table 3 summarize numerical results from 3D and 2D analyses conducted at varying B/D ratios (constant shaft plan dimensions, i.e. B/L = 1).

Table 3: Comparison of Results from Plaxis 3D and 2D under 3 Sets of Soil Parameters

Shaft geometry (B×L×D) m³	**B/D ratio**	**c=0kPa, ϕ=33° (Case 1)**			**c=0kPa, ϕ=35° (Case 2)**			**c=3kPa, ϕ=33° (Case 3)**		
		Settlement from 3D	**Settlement from 2D**	**Settlement Reduction**	**Settlement from 3D**	**Settlement from 2D**	**Settlement Reduction**	**Settlement from 3D**	**Settlement from 2D**	**Settlement Reduction**

		(mm)	(mm)	(3D vs 2D) %	(mm)	(mm)	(3D vs 2D) %	(mm)	(mm)	(3D vs 2D) %
9×9×9	1.00	12.3	21.9	43.9%	11.5	19.1	39.6%	9.4	16.1	41.5%
9×9×12	0.75	18.5	44.3	58.2%	17.6	38.6	54.6%	15.0	36.1	58.4%
9×9×15	0.60	25.8	66.8	61.4%	24.0	57.4	58.2%	20.8	53.0	60.7%
9×9×18	0.50	33.4	94.6	64.7%	31.1	81.2	61.8%	27.2	76.4	64.4%

3.3.1 Discussion and Interpretation:

- Ground settlements predicted by both 2D and 3D analyses increased notably with greater excavation depth. However, the rate of increase in settlements predicted by the 2D model was substantially higher than that by the 3D model.
- For the model with soil parameter c=0kPa, ϕ=33˚, when B/D = 0.5, the 2D analysis predicted a settlement of 95mm, whereas the 3D analysis predicts only 33mm, a substantial difference of approximately 65%. This implies a more significant soil arching effect at greater excavation depths, which had been ignored by 2D analysis.
- There reduction in wall bending moment and strut force by 3D analyses which can be up to 25% in certain cases. However, the reduction trend with the B/D cannot be well established. Similar to shape factor discussion above, benefits on the structural design from 3D analyses seem not significant as per the settlement reduction.
- The chart in Figure 3 illustrates the reduction in maximum settlement (3D vs. 2D) versus the B/D ratio under different soil parameters. A similar trend is observed across all cases, indicating that the effect of the L/B ratio does not vary significantly with changes in soil parameters.
- A 2D axisymmetric model of a circular shaft (9m diameter and 9m deep) was also analyzed as a comparative case. The results showed that the maximum settlement predicted by the axisymmetric model fell between those of the 3D analysis and the 2D plane-strain model, highlighting the necessity for 3D modelling to achieve more accurate settlement predictions.

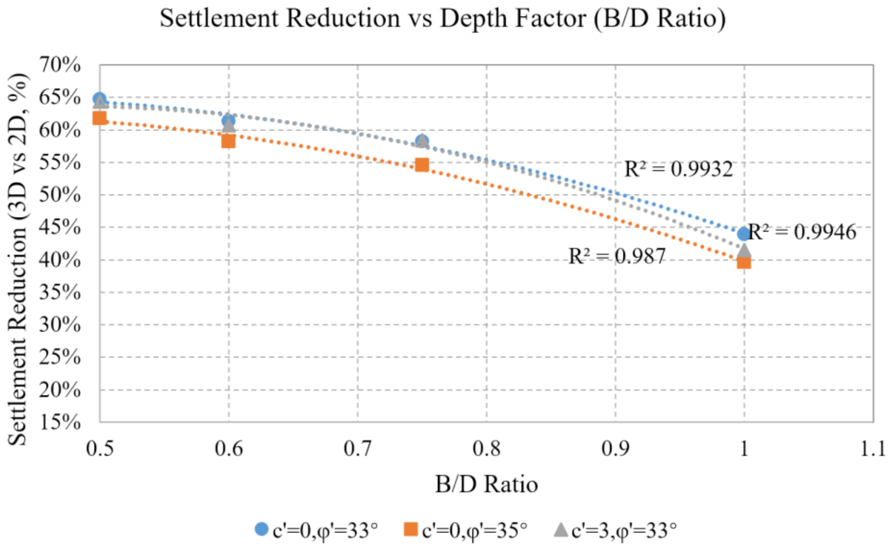


Figure 3: Settlement Reduction vs Depth Factor under different Soil Parameters (with Constant L/B = 1)

4 PARAMETRIC STUDY ON SHAPE AND DEPTH FACTORS OF SHAFT EXCAVATION

4.1 Correlation Between Enhanced Young's Modulus (E_s) and Shape Factor (L/B)

To achieve more realistic settlement results by PLAXIS 2D, an enhancement factor for the Young's Modulus (E_s) of soil is introduced to correlate the results of PLAXIS 2D and PLAXIS 3D, with reference to the shape factor (L/B). This correlation aimed at producing comparable ground settlement predictions. Since settlement is a key performance indicator of an Excavation and Lateral Support (ELS) system, the calibration of Young's Modulus (E_s) in the PLAXIS 2D model is carried out to match the settlement values estimated from the baseline 3D model.

As shown in Figure 4, the Young's Modulus (E_s) in PLAXIS 2D have to be increased by up to five times compared to the original Young's Modulus (E_s) in PLAXIS 3D to achieve similar settlement when the L/B =1.0, for soil with c'= 0 and ϕ' = 33°. However, as the L/B ratio increases to 2.0, the need for E_s enhancement becomes negligible. This indicates that as the shaft becomes more elongated, the 2D plane-strain assumption becomes increasingly valid. A similar trend is observed for soils with varying strength parameters, suggesting consistent behavior in response to changes in shaft geometry.

A lower-bound curve for the enhanced Young's Modulus (E_s) is proposed in Figure 4. The curve illustrates that enhancement is not recommended when L/B exceeds 1.60, as the influence of corner effects becomes minimal and the 2D plane-strain assumption provides sufficient accuracy.

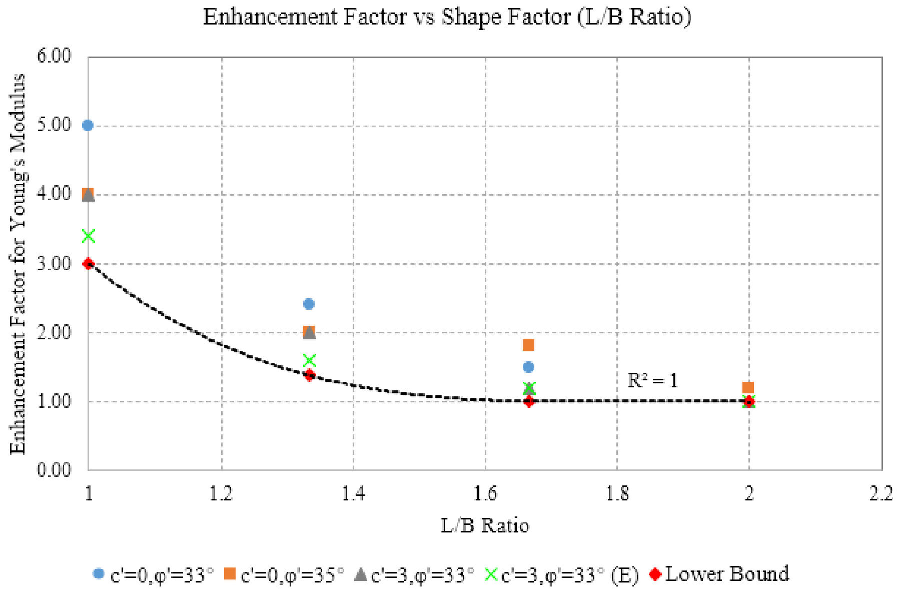


Figure 4: Enhancement Factor for Young's Modulus (E_s) vs L/B ratio (with constant B/D = 1)

4.2 Correlation Between Enhanced Young's Modulus (E_s) and Depth Factor (B/D)

To assess the influence of excavation depth, a similar approach is applied by adjusting the Young's Modulus (E_s) in PLAXIS 2D to match 3D settlement results. As shown in Figure 5, for c'=0 & ϕ' = 33°, the E_s in PLAXIS 2D is increased up to nine times when B/D = 0.6. This reflects the significant 3D confinement effect in deeper excavations. However, as B/D increases beyond 1.5 (i.e. relative shallower excavation), the effect of excavation depth on soil stiffness becomes less pronounced.

Accordingly, a lower-bound enhancement curve is proposed and applied only when B/D ≤ 1.5, as illustrated in Figure 5. Beyond this threshold, 2D modelling without enhancement may adequately reflect the excavation response.

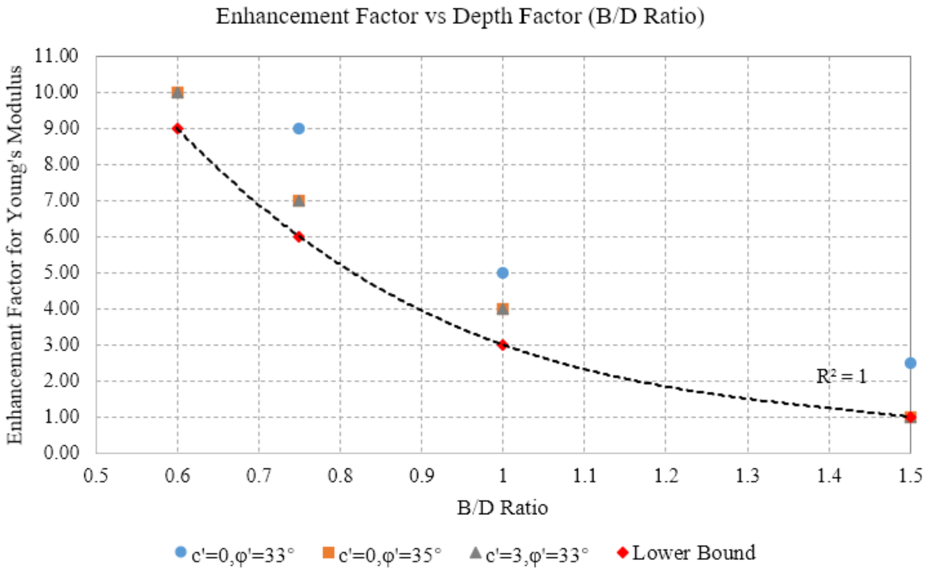


Figure 5: Enhancement Factor for Young's Modulus (E_s) vs B/D ratio (with constant L/B = 1)

4.3 Combined 3D Effects of Shape and Depth on Enhanced Young's Modulus (E_s)

To account for the combined 3D effects of shaft geometry, design lines are proposed in Figure 6, offering enhancement factors for Young's Modulus (E_s) based on the ratios of shaft length, breadth and depth. Analysis revealed that soils with varying strength parameters show consistent deformation trends relative to shaft geometry.

Among the geometric factors, depth factors (represented by B/D or L/D) are found to be the dominant contributor to increase soil stiffness, while shape factors (represented by L/B) play a secondary role. Based on this, it is recommended to apply enhanced Young's Modulus (E_s) in 2D modelling when L/B ≤ 1.6 and L/D ≤ 1.5.

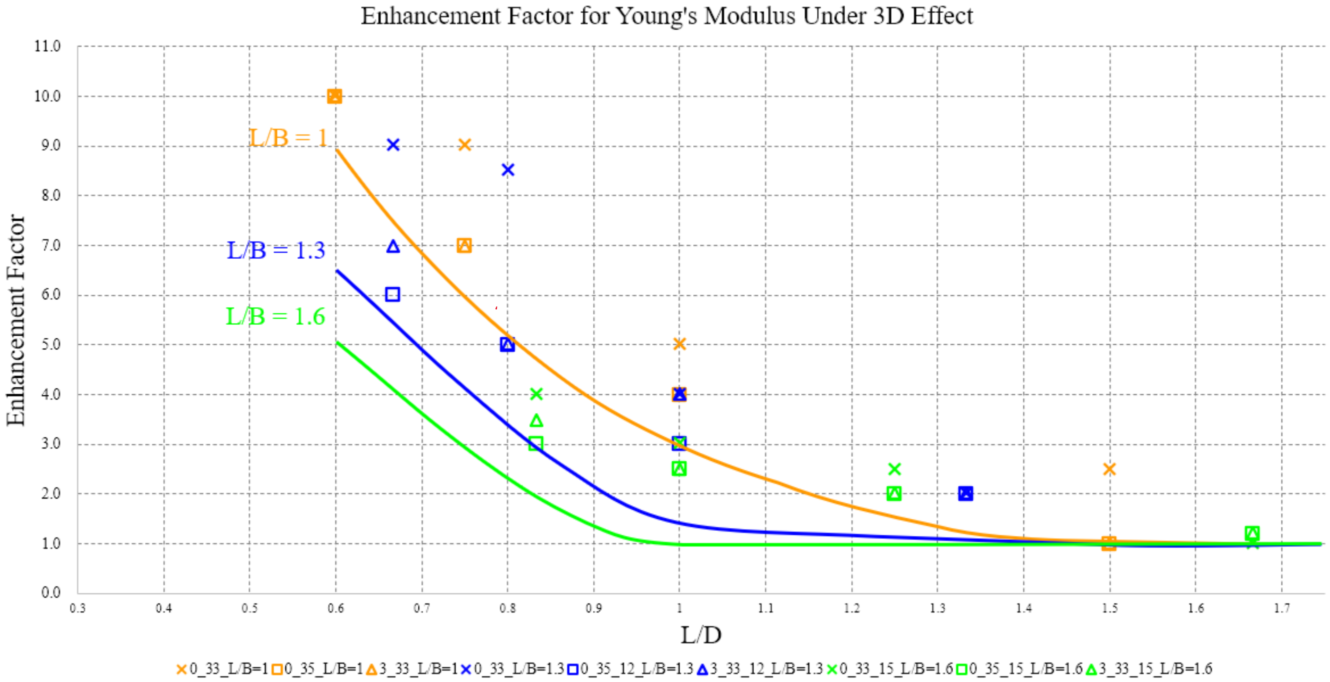


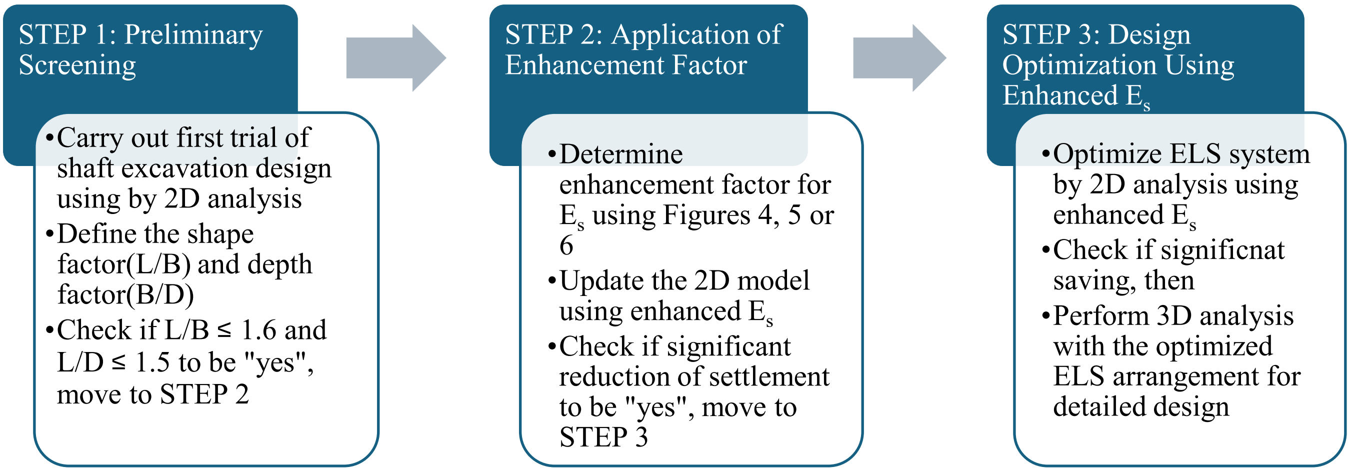
Figure 6: Enhancement Factors for Young's Modulus (E_s) under 3D Effect

5 RECOMMENDED DESIGN APPROACH USING 2D ENHANCEMENT FACTORS

The results of the parametric studies confirm that excavation geometry critically influences ground movements. Notably, 3D numerical analyses reveal that the beneficial effects of three-dimensional confinement are significant when $L/B \leq 1.6$ and $L/D \leq 1.5$. These 3D effects diminish as the excavation becomes either more elongated or shallower, reducing the influence of corner confinement.

Performing full 3D numerical simulations for every iteration of the Excavation and Lateral Support (ELS) design is not only computationally intensive but may also be inefficient, particularly when the excavation geometry lies outside the effective ranges where 3D effects are insignificant. Moreover, the complexity of 3D models makes it cumbersome to rapidly evaluate multiple design alternatives during the optimization process.

To bridge the gap between the accuracy of 3D analysis and the practicality of 2D modelling, a design framework incorporating 2D enhancement factors (as developed in Section 4) is proposed. This approach allows designers to capitalize on the benefits of 3D effects while maintaining the efficiency and flexibility of 2D modelling tools. The proposed approach advocates for the use of enhancement factors applied to the Young's modulus (E_s) of the surrounding soil strata within 2D models. This allows for a more streamlined and iterative design process, enabling engineers to explore various support system configurations while still accounting for the influence of 3D effects. The proposed design procedures are presented as follows:



STEP 1: Preliminary Screening

- Carry out first trial of shaft excavation design using by 2D analysis
- Define the shape factor(L/B) and depth factor(B/D)
- Check if $L/B \leq 1.6$ and $L/D \leq 1.5$ to be "yes", move to STEP 2

STEP 2: Application of Enhancement Factor

- Determine enhancement factor for E_s using Figures 4, 5 or 6
- Update the 2D model using enhanced E_s
- Check if significant reduction of settlement to be "yes", move to STEP 3

STEP 3: Design Optimization Using Enhanced E_s

- Optimize ELS system by 2D analysis using enhanced E_s
- Check if significnat saving, then
- Perform 3D analysis with the optimized ELS arrangement for detailed design

Figure 7: Flow Chart for ELS Design Using Enhancement Factor for Young's Modulus (E_s)

Step 1: Preliminary Screening
Identify shaft configurations with geometry falling within critical thresholds (e.g., $L/B \leq 1.6$ and $L/D \leq 1.5$). These cases are likely exhibit significant 3D effects and warrant further assessment. For configurations outside these ranges, conventional 2D analysis may be sufficient.

Step 2: Application of Enhancement Factors
Apply the corresponding enhancement factor to the Young's modulus (E_s) of the surrounding soil in the 2D model. This modification simulates the increased soil stiffness observed due to 3D confinement effects and provides an improved settlement estimate.

Step 3: Design Optimization Using Enhanced Es
Perform 2D design trial using the enhanced E_s to optimize the ELS system. Once an optimal configuration is selected, validate the final design with a single 3D numerical model to confirm performance and proceed with detailed design documentation.

It is particularly noteworthy that when the length-to-depth ratio (L/D) is less than 0.5, meaning the excavation depth is at least twice the shaft length, the 3D confinement effect becomes especially significant. In these cases, the required enhancement factors can be exceptionally high, leading to substantial reductions in surface settlement. For such configurations, full 3D modelling is strongly recommended, as the potential savings in construction materials and performance improvements justify the added modelling effort.

6 CASE STUDY: APPLICATION OF THE RECOMMENDED DESIGN APPROACH

The project involved a square-shaped excavation (size: 8m(B) x 8m(L) x 9.6m(D)) designed as a launching shaft for pipe jacking works. The subsurface profile consisted of a Fill layer overlaying a layer of Completely Decomposed Granite (CDG), with the bedrock located approximately 14m below existing ground level. The design groundwater table was assumed at 1m below ground level. The adopted design parameters for Hardening Soil (HS) constitutive model are shown in Table 4 below:

Table 4: Input Parameters for Soil (HS Model)

Soil Type	γ (kN/m^3)	c' (kPa)	ϕ' (deg.)	E_{50}^{ref} (kPa)	E_{ode}^{ref} (kPa)	E_{ur}^{ref} (kPa)
Fill	19	0	35	10,000	7,000	30,000
CDG	19	5	39	30,000	21,000	90,000

A benchmark model was developed in PLAXIS 2D as a baseline design for the optimization study. The initial ELS design employed FSP IV sheet piles with five layers of struts and walings, governed by a 25mm settlement limit especially under a high surcharge loading of 50kPa from lifting girder. The model configuration and settlement output are shown in Figure 8, with the maximum predicted ground settlement of 24.1mm.

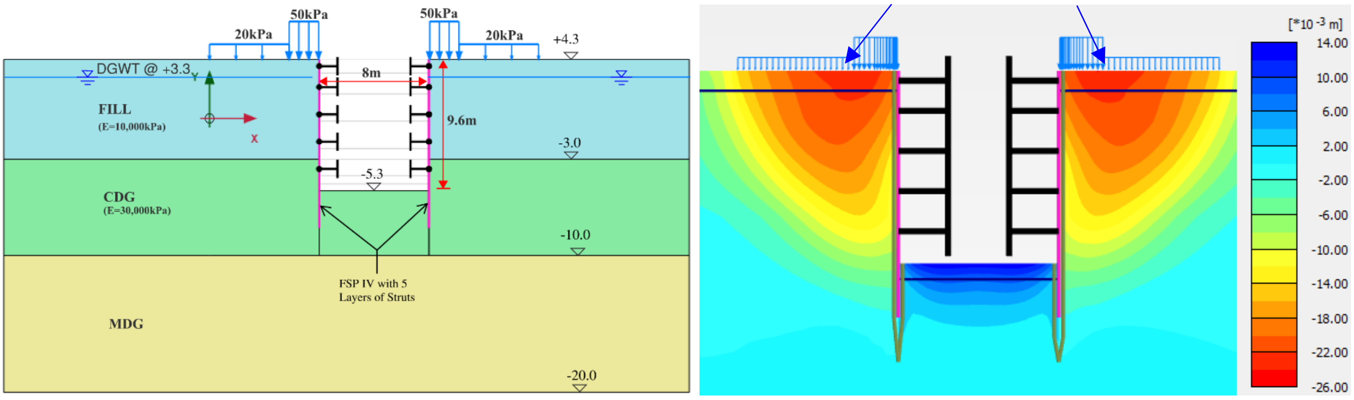


Figure 8: Original Baseline ELS Design – Input Configuration (Left) and Settlement Output (Right)

Step 1: Preliminary Screening

Both the shape factor (L/B = 1 < 1.6) and depth factor (L/D = 0.83 < 1.5) fall within the threshold ranges established in Section 5. Therefore, further exploration using enhancement factor and potential 3D effects are deemed beneficial for ELS optimization.

Step 2: Preliminary Checking with Enhanced Es

Based on Figure 6, enhancement factors for Young's Modulus (E_s) were determined according to the project's shape and depth factors. Incorporating the enhanced Young's Modulus (E_s) into the PLAXIS 2D model led to a reduction in maximum ground settlement from 24.1mm to 14.8mm, i.e. approximate 40% of reduction. This significant improvement by using enhanced E_s revealed opportunity to optimize ELS design by 3D analysis, as ground settlement was typically a critical concern in ELS design. Table 5 summarizes the baseline Young's Modulus (E_s) values and the enhanced E_s values.

Table 5: Summary of Young's Modulus (E_s) for PLAXIS 2D Analysis

Soil Type	**Baseline Design (2D Model)**		**Shape Factor (L/B)**	**Depth Factor (L/D)**	**Enhanced E_s Design (2D Model)**		
	Original E_s (kPa)	**Ground Settlement (mm)**			**Enhancement Factor**	**Enhanced E_s (kPa)**	**Ground Settlement (mm)**
Fill	10,000	24.10	1	0.83	4.6	46,000	14.60
CDG	30,000					138,000	

Step 3: Optimizing the ELS System with PLAXIS 2D with Enhanced E_s and Detailed Design in PLAXIS 3D

Several ELS configurations were assessed using PLAXIS 2D with enhanced E_s for rapid optimization. The primary focus was reducing the number of strut layers to lower construction cost and time as well as providing

more working spaces. Ultimately, the strut and waling system was reduced from five to three layers (as shown in Figure 9), while still achieving smaller ground settlement (18.6mm) compared to the original baseline (24.1mm).

Figure 9: Optimized ELS System – Input Configuration (Left) and Settlement Output (Right)

Following the 2D optimization using enhanced E_s, the proposed arrangement was analyzed in PLAXIS 3D using the original design parameters, refer to Figure 10. The maximum ground settlement was 21.7mm, which closely aligned with the result from the 2D enhanced model, confirming the reliability of the enhancement approach. From a structural optimization perspective, the strut forces in the 3D model were consistently lower than those in the 2D baseline model. Specifically, the total strut force, based on the sum of 5 strut layers in the 2D model versus 3 strut layers in 3D model, was reduced by approximately 45%. Furthermore, the maximum load on individual strut layer showed a reduction of 24%. These reductions suggest potential for further optimization in sizing of strut and waling members. On the other hand, maximum bending moment of sheet pile wall in the 3D model (i.e. 181kNm/m) were about 25% higher than 2D baseline model (i.e. 147kNm/m) due to the greater load width and longer span length between struts following reduction of the strut from 5 layers to 3 layers. Nevertheless, the maximum bending moment from 3D model still remained well within the allowable bending capacity of FSP IV sheet pile (i.e. 325kNm/m for Grade S275). The use of oversized sheet piles in the original baseline design provided additional stiffness, originally intended to control the settlement, and proved sufficient even after design optimization.

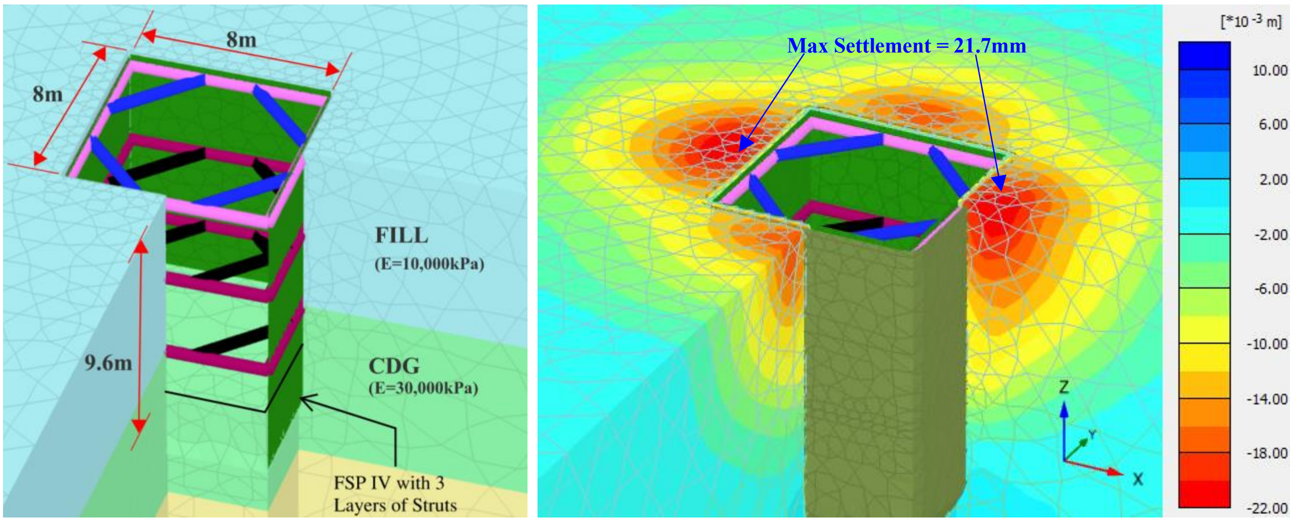


Figure 10: PLAXIS 3D Model of Optimized ELS System – Input Configuration (Left) and Settlement Output (Right)

Figure 11 presents a summary graph of the maximum ground settlements across the various design cases. As discussed, the settlement predicted by the optimized arrangement of PLAXIS 2D model using the enhanced E_s closely aligns with the results from the PLAXIS 3D analysis. This case study demonstrates how the proposed enhancement approach can effectively streamline and optimize the ELS design process for deep shaft excavations with consideration of 3D effects.

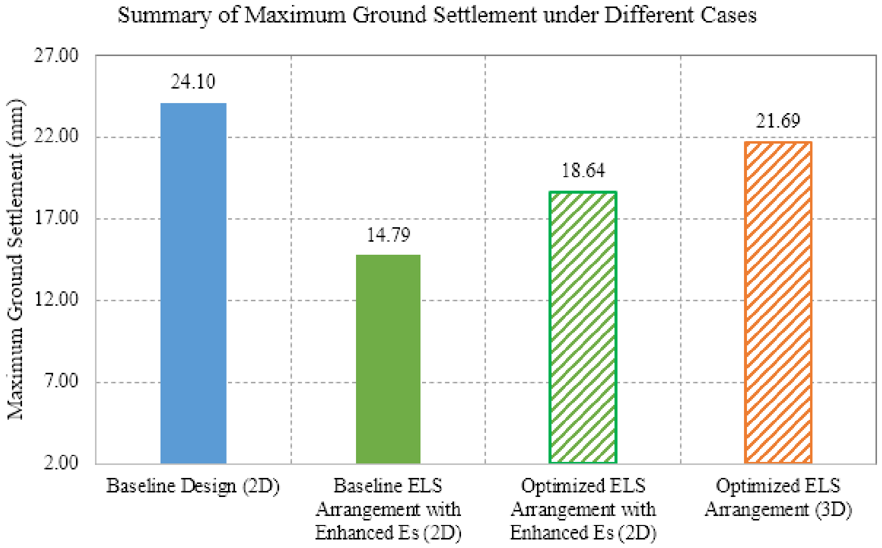


Figure 11: Summary of Settlement Results Across Various Design Cases

7 CONCLUSIONS

This paper presents a simplified and efficient methodology for the preliminary design of Excavation and Lateral Support (ELS) systems in shaft excavations. The approach is particularly beneficial during the serviceability limit state (SLS) design stage, where rapid and reliable assessment of ground movement is normally the controlling factor for ELS design. By incorporating enhancement factors into 2D numerical models to simulate 3D confinement and corner effects, designers can streamline the design process, enabling early-stage optimization of ELS systems prior to comprehensive 3D verification.

The keys findings from the study include:

1. Depth factor (L/D) is the most influential parameter affecting ground movement due to 3D confinement effects. The effect becomes particularly significant when L/D ≤ 1.5, and is most pronounced when L/D < 0.5, where the excavation depth is at least twice the shaft length. In such cases, the vertical confinement induces substantial soil arching and stiffness gains.

2. Shape factor (L/B) also plays a critical role. When L/B ≤ 1.6, the corner and buttressing effects provide additional lateral support to the retaining walls, leading to reduced lateral wall deflection and associated settlement.

3. When L/D > 1.5 and L/D > 1.6, the influence of 3D effects diminishes. Under these conditions, the plane-strain assumption in 2D modelling becomes valid, with 2D results aligning closely with those from full 3D analyses.

The integration of 2D enhancement techniques with strategic 3D validation offers a practical, cost-effective, and technically robust framework for shaft excavation design. When applied during early planning stages, this hybrid approach allows designers to efficiently evaluate multiple ELS configurations, reduce reliance on resource-intensive 3D modelling, and ultimately shorten construction timelines and reduce project costs, without compromising safety or performance. This methodology supports the development of resilient and sustainable underground infrastructure in dense urban environments.

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