

Analysing Soil-Pile Interaction under Lateral Soil Movements: Case Studies and Parameter Sensitivity

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Abstract

Pile foundations are essential to transmit structural loads to the underlying soils and rocks. Piles may functionally or accidentally be subjected to lateral soil movements, most often due to the slope's failing nature, deep excavation, soil liquefaction and seismic activities, which significantly affect its stability and safety. This study uses PLAXIS 3D software to predict the response of pile foundations subjected to lateral soil movements. Two case studies were analysed to validate the predictive ability of the software, to test the sensitivity of the input parameters, and to serve as a practical guide for the selection of the parameters in case of lack of availability of complete in-situ information. The behaviour of soil-pile interaction in different types of soils, particularly clay soils, was also considered. The results underline the importance of advanced modelling and accurate parameter selection for the stability and reliability of pile foundations under passive loading and lateral soil movement conditions.

Keywords

lateral soil movements, Pile foundations, PLAXIS 3D, Soil-pile interaction.

I. INTRODUCTION

In some situations, piles are not designed to resist soil that moves laterally without advance planning, which may occur accidentally due to natural or man-made activities, such as piles supporting bridge abutments next to embankments, existing piles adjacent to pile driving or excavations, and piles subjected to slope movements. In other instances, the piles are initially designed against lateral movements caused by soil for specific purposes of its application, such as the stabilization of unstable slopes or landslide potentials. In this respect, lateral soil movements have potential effects on the stability of piles and safety of structures; hence, this issue is often significant and need to be taken in consideration in the design of pile foundations.

Various methods have been developed for analysing laterally loaded piles. These methods can generally be categorized as follows: analytical solutions [1–6], load transfer approaches [7], boundary element methods [8–15] and finite difference and finite element methods [16]. More recently, numerical techniques have been used, particularly three-dimensional finite element methods, whereby the need to include interface elements to model probable slippage between pile and soil, and incorporating advanced models to

represent the nonlinear behaviour of soils has been emphasized.

Understanding such pile behaviour conditions becomes crucial in designing safe and efficient foundations. In this respect, two case studies, previously analysed using the PLAXIS 3D program, are elaborated in this paper. The objectives of this study include testing the capabilities of PLAXIS 3D to predict full-scale test data; investigating the sensitivity of input parameters associated with the relevant material and interface models used in the analyses; providing guidelines on selecting these parameters in practical use, notably when less than totally complete information cannot support theoretical predictions; examining more soil-pile interaction behaviour in varied soils, particularly clay soils.

The methodology adopted in this research includes a critical review of the original case studies with the theoretical assumptions, model setup and results. In each of these case studies, pile-soil interaction for stable and moving soils was modelled in PLAXIS 3D using the "embedded pile" approach for piles. Material properties, boundary conditions, and soil movement profiles have been looked at critically concerning their effects on results.

II. CASE STUDY 1 (ESU AND D'ELIA, 1974)



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A. Background and theoretical assumptions

Esu and D'Elia (1974) [17] documented a field study involving a free-head reinforced concrete pile situated against a sliding slope. The tested pile measured 30 m in length, 0.79 m in diameter, and possessed a bending rigidity ($E_p I_p$) of 360 MN.m². The upper 7.5 m of the soil moved laterally, but the extent of moving soil was not specified. It was assumed that the soil profile is mainly composed of cohesive materials. Inclinometer measurements were obtained for the pile to measure deflections and rotations. The instrumentations of the pile included pressure cells at 5, 10, and 15 m depth. This paper presents distributions of bending moments and shear force along the pile length.

A numerical solution that models piles as beam elements, the soil behaviour represented by a subgrade reaction solution, and the pile-soil interaction based on elasticity theory was developed by Chow (1996) [18]. Chow applied this hybrid method to predict a case study by [17]. In order the numerical results to be comparable with field measurements, the proposed solution required further assumptions for the missing data that were not addressed in [17]. It is assumed by default that: the in-situ undrained shear strength of clay (c_u) is 40 kPa; the ultimate soil pressure $P_u = 3c_u$ for the upper moving layer and $P_u = 8c_u$ for the lower stable soil, and Young's modulus of clay, $E_s = 500c_u$, taken as constant with depth. A flat movement profile of the soil from the top ground surface down to the sliding surface, with a value of 110 mm, was assumed. Since then, theoretical results agreed well with the measured data; these values were adopted for the present 3D analysis carried out by PLAXIS 3D. However, the uniformly distributed soil movement profile through the 7.5 m moving soil layer was set to 150 mm to better approximate numerical analysis results with measured field data.

B. Geometry of the model

PLAXIS 3D software can deals with pile foundations by two options; volume piles and embedded piles. In the current study, embedded pile method was utilized to model the piles. In the analysis, the reinforced concrete pile was modelled as a single isolated pile with a free head. Since detailed information of the site geometry are not available, model dimensions were chosen to be large enough to ensure that the boundary conditions do not affect the numerical results (Fig.1). A uniform soil movement of 150 mm was applied to the left upper boundaries from the ground surface to a depth of 7.5 m. For this purpose, a medium-mesh generation was adequate to give accurate values regarding the deformation and structural forces. The properties of material considered for embedded pile, stable soil and moving soil are presented in Tables 1 and 2.

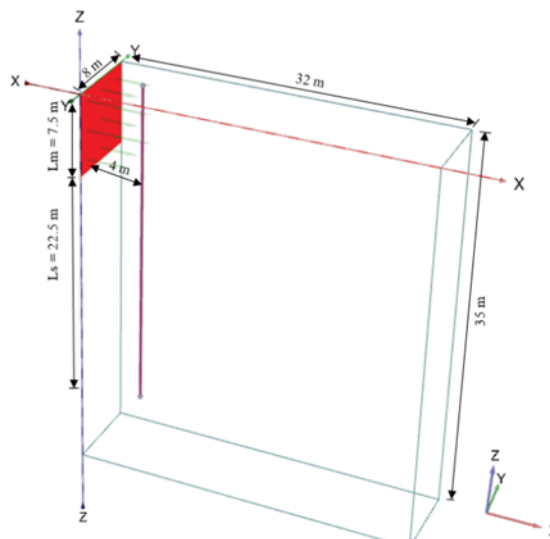


Fig. 1. Schematic diagram of the model boundary dimensions of case study 1.

C. Discussion of the results

Comparison of the bending moment, shear force, and pile deflection profiles predicted by the PLAXIS 3D with field measurements and the results from [18], as shown in Fig. 2, indicates that the expected bending moment profile fits very well with the measured one along the entire pile shaft, including the position of maximum bending moment. The estimated maximum bending moment was 770 kN.m at a depth of 11 m, which was an under-predictive value of 4%, as shown in Fig. 2(a).

The shape of the predicted profile is very close to that measured, where both the value and position of the maximum shear force are in excellent agreement. About the sliding surface, an accurate maximum shear force depth was predicted at a depth of 7.5m. However, its value was underestimated by 20%, with a maximum shear force of 275 kN observed at the level of the sliding surface.

Table 1. Material properties of moving and stable soils for case study 1.

Parameter	Value	Unit
Material model	Mohr-Coulomb	-
Drainage type	Undrained	-
Unit weight	γ	18.5 (kN/m ³)
Young's modulus	E_s	20000 (kN m ²)
Friction angle	ϕ	0 deg.
Dilatancy angle	ψ	0 deg.
Cohesion	c_u	40 (kN/m ²)

Poisson's ratio	ν_s	0.495	-
Strength reduction factor	R_{inter}	0.7	-

In this context, **Fig. 2(c)** shows the profile of pile deflection from numerical analysis compared to the field data and the results by [18]. The maximum pile deflection at the ground surface was around 142 mm, which is very close to the measured data.

Fig. 3 shows the distribution and direction of the lateral soil movement that applied directly at the left boundary of the problem. This Figure portraits, also, the deformed shape of the tested pile. The induced lateral deformation of the soil due to the boundary soil movement is illustrated in **Fig. 4**. Lateral deformations of the concrete pile and the surrounding soil for various cross-sections (at the ground surface, and 5 and 7.5m below the ground surface) showing that the relative displacement between the pile and soil was very similar at all levels (**Fig. 5**). This is also illustrated by a vertical cross-section through the centre of the pile (**Fig. 6**), which implicates that the lateral displacement increased from the sliding surface to the top of pile at the ground surface.

Pile length	L	30	m
Pile area	A	0.49	m ²
Moment of inertia	I	0.01912	m ⁴
Young's modulus	E	20*10 ⁶	kN/m ²
Unit weight	γ_p	24	(kN/m ³)
Max. skin resistance at the pile top	$T_{top, max}$	300	kN/m
Max. skin resistance at the pile bottom	$T_{bot, max}$	800	kN/m
Max. base resistance	B_{max}	1500	kN

Table 2. Material properties of the embedded pile for case study 1.

Parameter	Value	Unit
Material type	Concrete	-
Predefined pile	Circular pile	-
Diameter	D	0.79
		m

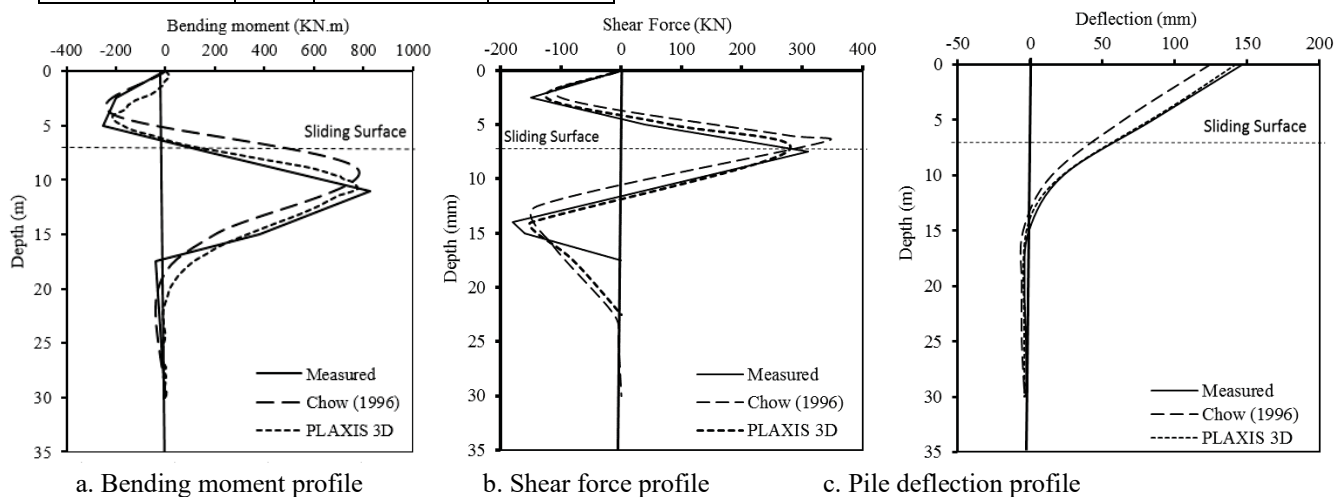


Fig. 2. Predicted versus observed pile responses for the first case study.

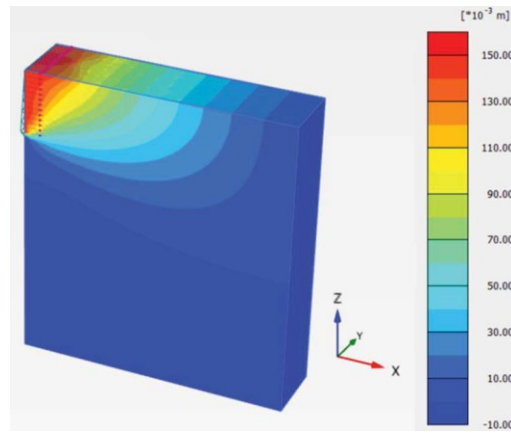


Fig. 3. Distribution of lateral deformations in the direction of soil movement of case study 1.

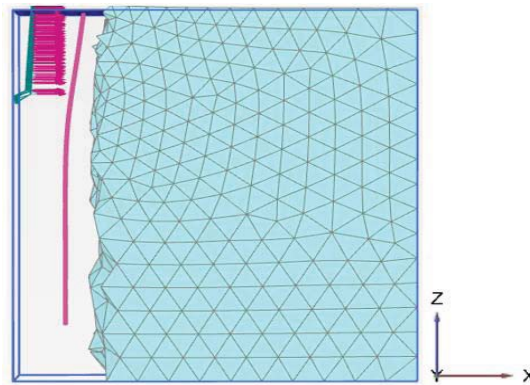


Fig. 4. The applied lateral soil movement distribution and the deformed shape of the pile.

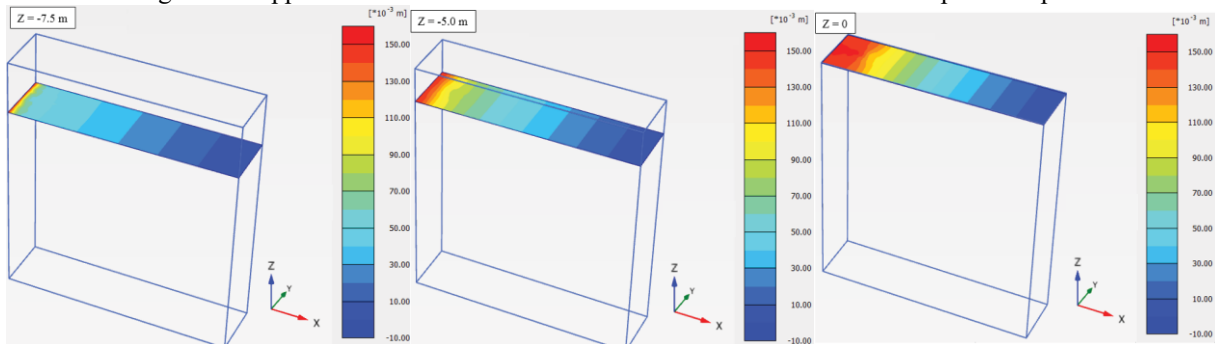


Fig. 5. Lateral deformation patterns at various horizontal cross-sections for case study no. 1.

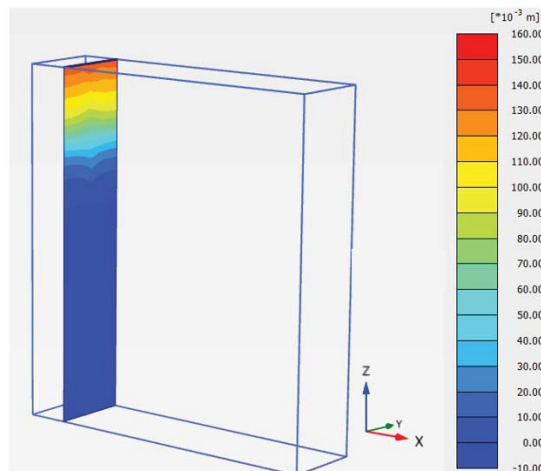


Fig. 6. Lateral Deformation Patterns for a Vertical Cross-Section through the Centre of the Pile.

D. The influence of soil elastic modulus E_s

To test the sensitivity of E_s on the pile response, two values for this parameter were considered as follows: (a) a constant value of $E_s = 100c_u = 4000$ kPa with depth, and (b) a linearly increasing value of E_s with depth starting from zero at soil surface to a specific value at the level of pile tip, say $E_s = 500z$ kPa, where z is the depth below the surface in meters, while other parameters remain constant. Theoretical results for these values E_s , along with measured values, are plotted in Fig. 7 (a and b). Although the effect of E_s on pile response was insignificant, some trends were recorded. For the assumption of linear increase of E_s with depth, the value of E_s is small at shallow depths, which induced less values of shear force and bending moment at these depths when compared to the case of constant Young's modulus. Insignificant differences in pile response were observed at deeper depths as E_s reaches to approximately the same values. On the other hand, the same deflection profiles and magnitudes were observed with no noticeable differences in both cases (Fig. 7c).

E. The influence of soil movement profile

To investigate the effect of soil movement profile, another analysis was performed assuming a linear variation of the lateral soil profile starting from a value of 150 mm at the ground surface to zero at a depth of 7.0 m. The results are shown in Fig. 8. It can be seen that the shape of the predicted bending moment profile is different from the measured, especially at the sliding layer. At this layer, the magnitudes and signs of bending moment are totally different. Moreover, the position of maximum bending moment is predicted to be higher than the measured, although the calculated value of maximum moment is less than the measured value. Furthermore, the predicted shear force, and pile deflection profiles are seen to be in poor agreement with the measured. Therefore, it is of important to input the real distribution of soil movement as unexpected response may happen.

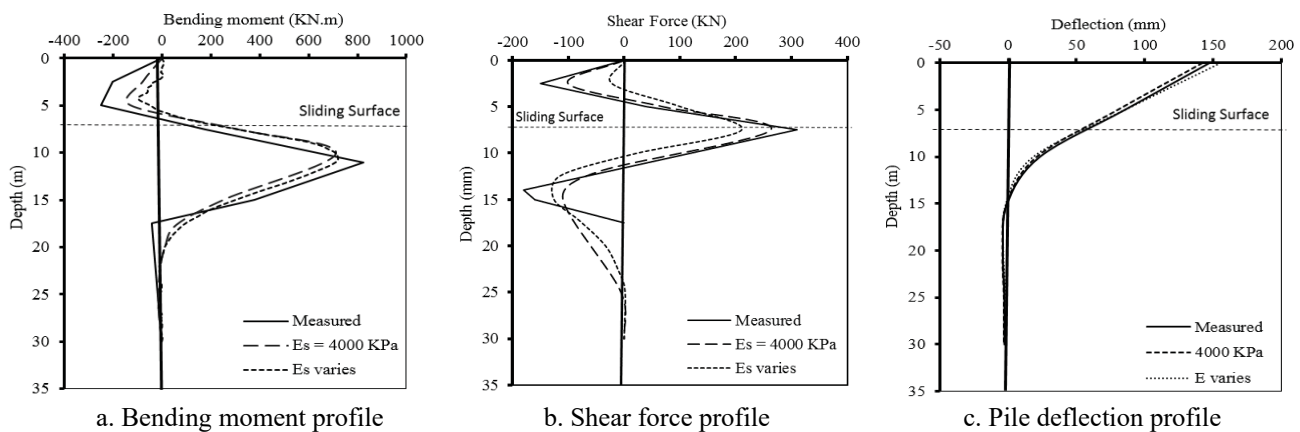


Fig. 7. The effect of E_s on pile responses of case study 1.

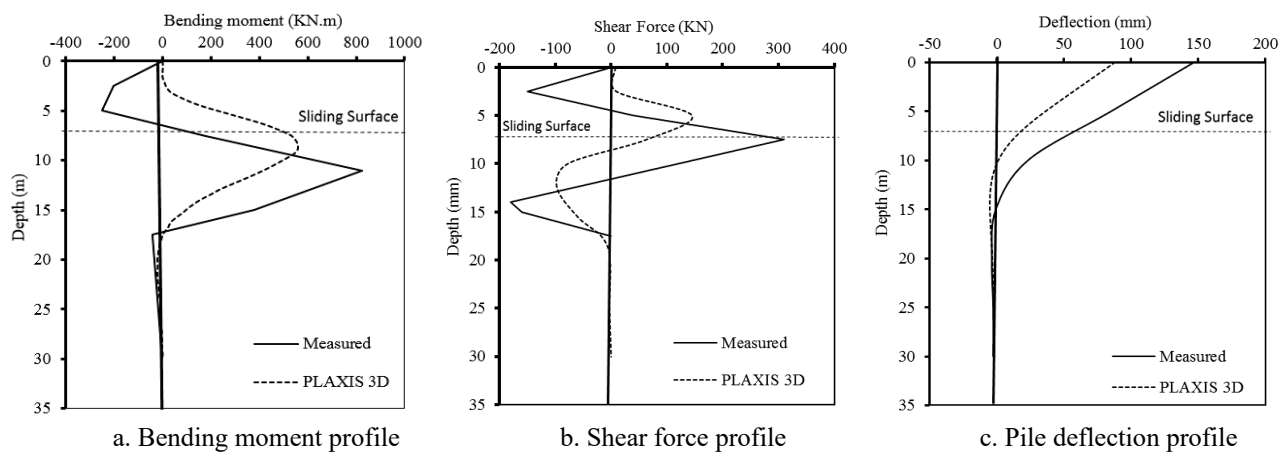


Fig. 8. The effect of soil movement profile on pile responses of case study 1.

III CASE STUDY 2 (Carrubba et al, 1989)

A. Background and theoretical assumptions

Carrubba et al. (1989) [19] presented details of a full-scale test involving a reinforced concrete pile to stabilize a sliding slope. The test pile is 22 m long and 1.2 m in diameter, fitted with pressure cells along the shaft and an inclinometer at the centre. The inclinometer data showed that the pile was installed on a sliding slope with a sliding surface located 9.5 m from the ground surface. Undrained shear strength, c_u , of soil for both moving and stable layers was estimated to be 30 kPa based on unconsolidated undrained triaxial tests. Field measurements over five months showed that pressures on the pile increased progressively before forming a plastic hinge 12.5 m below ground level. No details were given of any soil movement profile leading to the failure of the pile.

To fit the measured bending moments, Chen and Poulos (1997) [20], using the PALLAS boundary element program, assumed that the elastic modulus of soil, $E_s = 500 c_u$, is 15000 kPa, and constant with depth. The ultimate soil pressure, P_u , was taken as 3 c_u for the upper moving soil layer and 5 c_u for the lower stable layer. It was assumed that the movement of the soil is uniform from ground level down

to a depth of 9.5 m with a magnitude of 95 mm. E_p , Young's modulus of the pile was taken as 20×10^6 kPa.

B. Geometry of the model

According to the data provided, three-dimensional models for the reinforced concrete pile were analysed. As in case study 1, specific data was unavailable for site geometry; therefore, as depicted in Figure 10, the model dimensions were large enough to minimize boundary condition effects on numerical results. A uniform soil movement of 95 mm was applied to the upper left boundaries, extending from the ground surface to a depth of 9.5 m. All boundary conditions and mesh type were similar to case study 1, except pile head and tip conditions, where both assumed to be free. The stiffness properties of the soil profile and the pile embedded in it were undertaken concerning the assigned data and assumptions made by [20]. Since no differences between moving and stable soils were considered, the same material properties were used. The assigned material properties for the moving soil, the stable soil, and the pile embedded are shown in Tables 3 and 4.

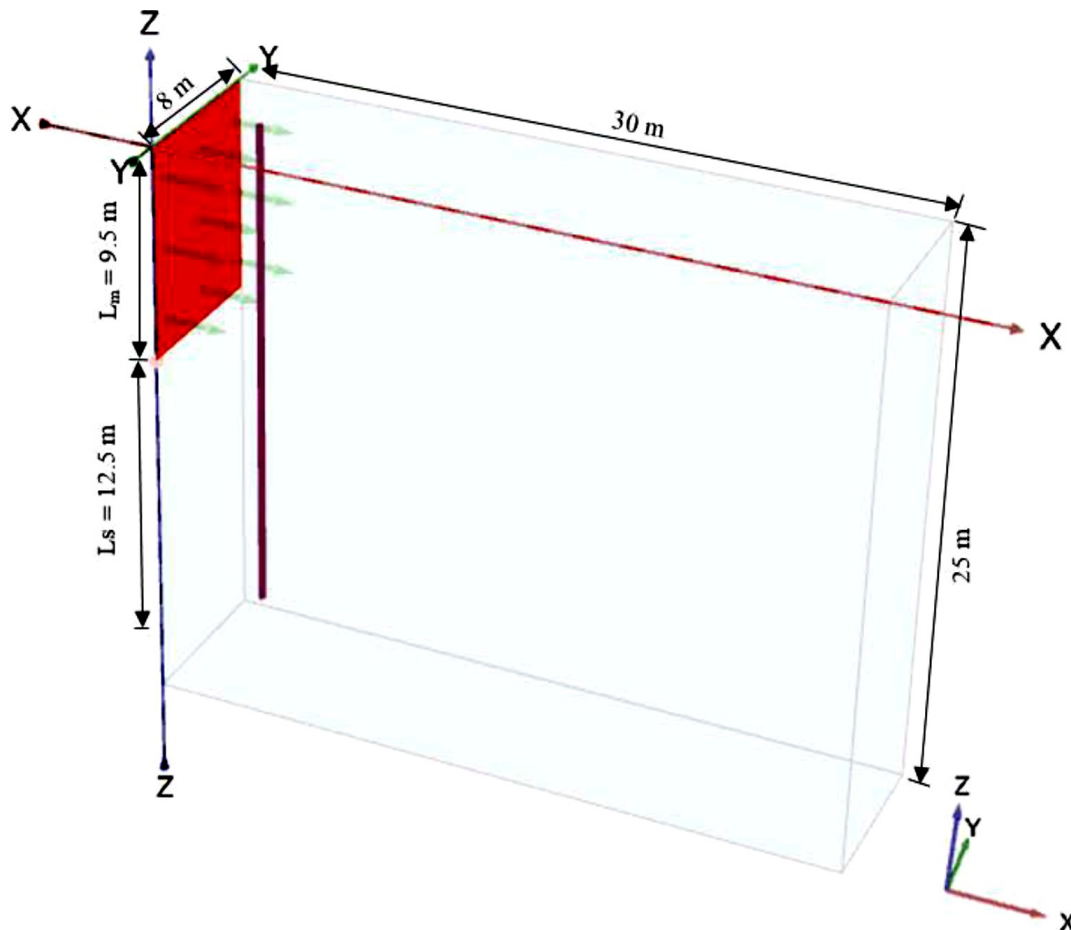


Fig. 9. Schematic illustration of the model boundary dimensions of case study 2.

Table 3. Material properties of moving and stable soils for case study 2.

Parameter		Value	Unit
Material model		Mohr-Coulomb	-
Drainage type		Undrained	-
Unit weight	γ	18.5	(kN/m ³)
Young's modulus	E_s	15000	(kN m ²)
Friction angle	ϕ	0	deg.
Dilatancy angle	ψ	0	deg.
Cohesion	c_u	30	(kN/m ²)
Poisson's ratio	ν_s	0.495	-
Strength reduction factor	R_{inter}	0.7	-

Table 4. Material properties of embedded pile for case study 2.

Parameter		Value	Unit
Material type		Concrete	-
Predefined pile		Circular pile	-
Diameter	D	1.2	m
Pile length	L	22	m
Pile area	A	1.13	m ²
Moment of inertia	I	0.01018	m ⁴
Young's modulus	E	20*10 ⁶	kN/m ²
Unit weight	γ_p	24	(kN/m ³)
Max. skin resistance at the pile top	$T_{top, max}$	200	kN/m
Max. skin resistance at the pile bottom	$T_{bot, max}$	700	kN/m
Max. base resistance	B_{max}	1000	kN

C. Discussion of Results

The predicted results are shown in **Fig. 10**, together with the field measurements, except pile deflection data, which were not reported by [19] and the results of [20]. It can be seen from **Fig. 10(a) and 10(b)** that there is excellent agreement between the predictions and the measurements for both the bending moment profile and the shear force profile. PLAXIS 3D provided excellent estimation for the maximum values and their positions. The pile deflection profiles were very close to those reported by [19], as shown in **Fig. 10(c)**. Deflection profile indicates that the pile head moved laterally more than the applied lateral movement of the driving soil, whereas the bottom portion of the pile moved a little backward against the soil movement.

D. The influence of E_s

E_s value was varied to be a) $E_s = 100 c_u = 3$ MPa and b) linearly increasing from zero at the surface to 11 MPa at the level of the pile tip. Theoretical results for the different E_s values are presented in Figure 11, together with the measured values. It appears that a linearly increasing E_s value tends to underestimate the bending moment and shear force along the upper pile portion of about one-third of the pile length, while it tends to give a larger pile head deflection. Comparisons also show that a smaller E_s value results in a smaller pile response.

E. The influence of the soil movement profile

A further analysis was carried out in which the uniform soil movement profile was replaced by a linearly varying profile, with a maximum value of 95 mm at the ground surface and zero at the sliding surface. Results are shown in Figure 12, and poor agreement can be observed generally between the predicted and the measured pile response, except for the maximum bending moment which is fairly well estimated by the theory. As in the previous case, a uniform distribution of soil movement with depth in the sliding zone appears to be the more relevant assumption.

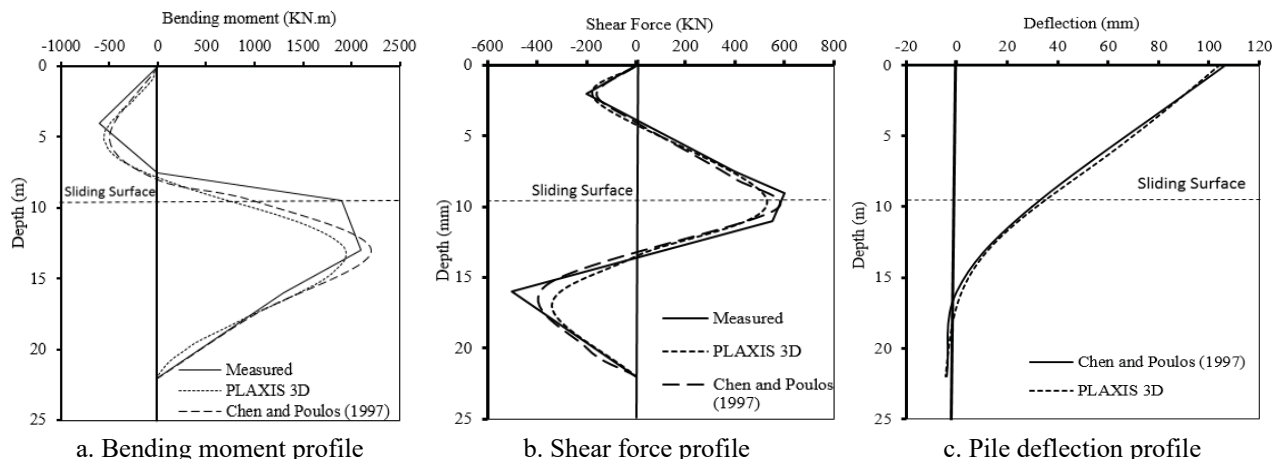
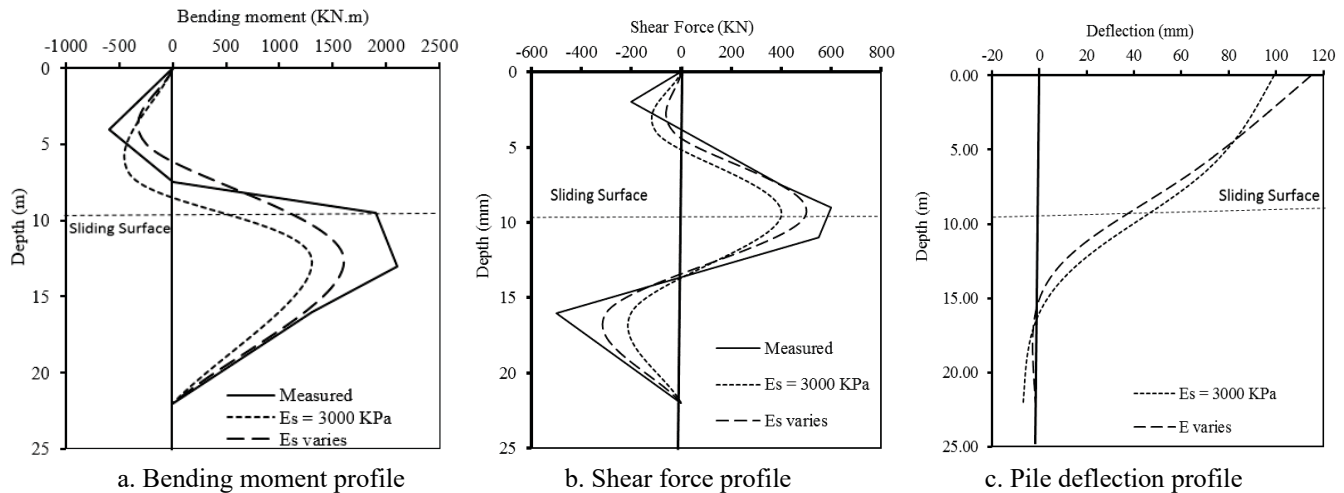
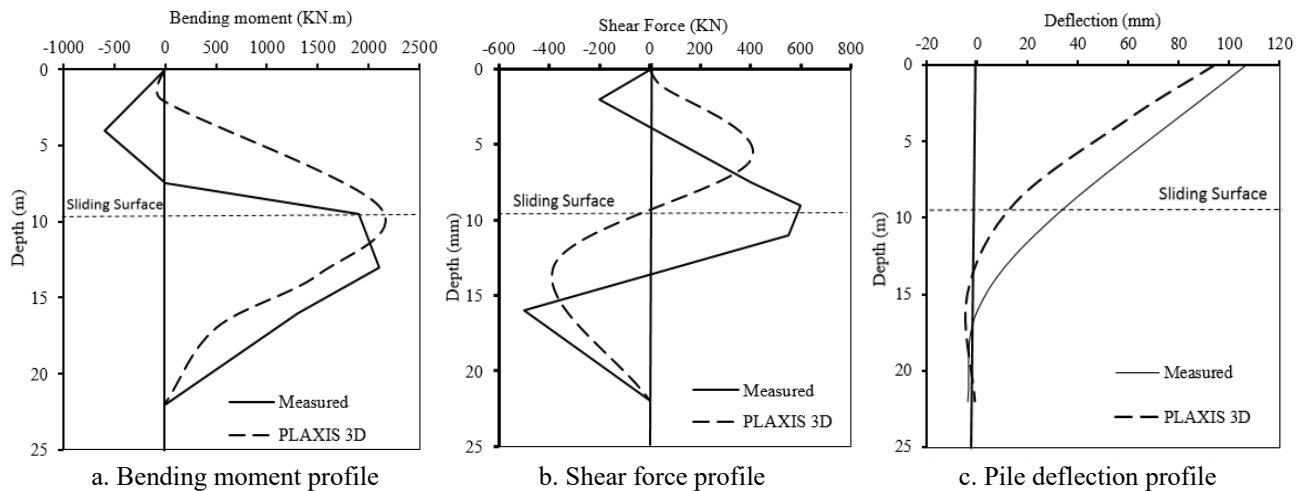


Fig. 10. Predicted and measured pile responses of case study 2.

Fig. 11. The effect of E_s on pile responses of case study 2.Fig. 12. The effect of E_s on pile responses of case study 2.

IV CONCLUSIONS

Choosing a reliable finite element software is necessary to ensure a reasonable degree of accuracy to simulate special cases of geotechnical problems. The consideration of case studies is the most constructive manner to validate numerical solutions. In the current study, a back analysis of

two case studies involving isolated piles under lateral soil movement was carried out using PLAXIS 3D. The validation of the proposed numerical analysis was conducted in terms of pile response, i.e., bending moments and deflection. A good agreement was obtained when comparing numerical results with in-situ measurements, reflecting the ability of PLAXIS 3D to predict such loading conditions. On the basis of the above analysis, the

following conclusions can be drawn for some parameters that have been studied:

1. The variation of Young's modulus, E_s , has a relatively minor effect on the passive pile response. A linearly varying E_s with depth generally tends to give rise to a somewhat lower bending moment but considerably greater deflection at the upper part of the pile than a uniform E_s .
2. The soil movement profile significantly affects the pile response. It is, of course, expected that more significant soil movements will lead to more significant pile responses. Further, a uniform distribution of soil movement with depth gives more pile response compared to a triangular distribution that has its maximum value at the pile head level.

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