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Required jacking force for deviation rectification of inclined structures supported with rigid piles

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Light poles or transmission towers may become tilted over the design life, which needs rectifying considering safety and continued use. The jacking pushing method is an efficient way to rectify deviations of these inclined structures supported with rigid piles, but there is a lack of relevant engineering standards and research in this aspect. In this study, a numerical method using FLAC^{3D} is proposed to estimate the required jacking force at the pile top to plumb inclined piles in cohesive soils. Good agreements between the results obtained from the present numerical models and those taken from published experimental and numerical results suggest the reliability of the conclusion. Besides, elaborate parameter analyses including pile geometry, soil properties, and properties of the soil-pile interface are conducted to investigate their influences on the required jacking force. The results can contribute to a safer and more cost-efficient design for rectifying deviations of rigid inclined piles, especially in terms of the required jacking force.

KEYWORDS

deviation rectification, inclined piles, required jacking force, numerical models, pile geometry, soil properties

Introduction

Inclined structures or buildings are prone to instability problems, which have brought great challenges for civil engineers and researchers. The most straightforward and safest way is to demolish those inclined structures and rebuild them, but sometimes it may be inappropriate for historical and cultural architecture such as the Leaning Tower of Pisa (Burland, 2002; Wen et al., 2020; Zhou et al., 2020). Moreover, it is also unrealistic to rebuild all the inclination structures, especially those induced by human activities like neighboring excavation or filling (Shi et al., 2013; Peng et al., 2021). In these conditions, deviation rectification becomes an alternative option.

The inclination of structures is mainly caused by the differential settlement of nearby soil, which may be related to groundwater movement, soft soil, improper design, or human activities (Zhang et al., 2015; Zhang et al., 2018; Soomro et al., 2020; Wen et al., 2020). For deviation rectification, foundations in the less deformed areas can be lowered by soil excavation (Ovando-Shelley and Santoyo, 2001; Burland, 2002; Liu, 2006), water treatment (Li, 2015), or applying additional pressure (Yang, 2020). While foundations in the areas with a larger displacement can be uplifted by foundation underpinning (Wen et al., 2020), compaction grouting (Wang et al., 2011; Peng et al., 2021), jacking methods (Zhang et al., 2018), etc. For inclined structures like transmission towers or light poles supported with single rigid piles, a horizontal force can also be applied by anchor pulling or jack pushing in opposition to the inclined direction for deviation rectification (Peng, 2017). Among the abovementioned methods, the jacking pushing method is the most efficient way of rectifying inclined piles. Nevertheless, there is still no standard procedure for deviation rectification of inclined structures supported with piles. Results published on this topic are also rare.

Relevant studies on the lateral responses of batter piles can serve as a reference for deviation rectification (Zhang et al., 1999; Hazzar et al., 2017; Kim et al., 2021; Liang et al., 2022). Zhang et al. (1999) conducted centrifuge tests for square batter piles laterally loaded in sandy soils. They reported that the lateral load decreased with increasing pile inclination angle when the load was applied in the opposite direction to pile inclination. The same conclusion have also been drawn by several researchers based on numerical or theoretical analyses of batter piles in sandy soils (Rajashree and Sitharam, 2001; Hazzar et al., 2017; Ashour et al., 2020). Whereas Hazzar et al. (2017) presented a different phenomenon obtained from FLAC^{3D} that the lateral load would increase with increasing pile inclination angle in cohesive soils when the load was applied against the inclined direction of piles. Besides, the machine learning technique (Bai et al., 2021) has also been widely applied to predict lateral pile bearing capacity (Das and Basudhar, 2006; Muduli et al., 2013).

However, none of the existing publications has concentrated on deviation rectification of those batter piles, as those piles are built inclined from the beginning for a large lateral resistance. Whereas for the pile inclined during use, it is required to rectify the deviation to ensure the continued use of the building on it. Furthermore, existing studies on lateral responses of batter piles mainly focus on the evaluation of lateral bearing capacity (Zhang et al., 1999; Hazzar et al., 2017). While for the deviation rectification of inclined piles, the required jacking force at the pile top to return the inclined piles to vertical conditions is critical to guide the rectification design but has hardly been investigated in detail.

In this study, the lateral responses of rigid inclined piles in cohesive soils will be first investigated numerically with FLAC^{3D}. Then, a method of estimating the required jacking force will be described in detail when using the jacking pushing method for deviation rectification. Finally, the required jacking force will be analyzed and discussed by considering different pile and soil parameters.

Finite-difference model

The three-dimensional (3D) finite-difference numerical software FLAC^{3D} is employed to estimate the required jacking force P (kN) for deviation rectification of rigid batter piles (Itasca., 2013). It has been widely used in solving geotechnical and mining problems (Hazzar et al., 2017; Chai, 2020; Chai, 2022).

Model details

Figure 1A shows a cross section of a typical physical model for deviation rectification of an inclined pile. The pile is previously built to support a 20-m-high light pole. The vertical load F_V (kN) and horizontal load F_H (kN) at the pile top are calculated at 36 and 26.2 kN, respectively. α (°) is the inclination angle of the pile foundation. D (m) and L (m) are the diameter and the length of the inclined pile, respectively. During the rectification process, a constant velocity v (m/s) is applied at the top of the inclined pile until the pile becomes vertical.

Considering the model symmetry and computing efficiency, a numerical model shown in Figure 1B with only half of the real geometry is constructed with FLAC^{3D}. For the reference case, the pile inclination angle α is 3°. The pile diameter D is 1.4 m, and the pile length L is 6.0 m with 5.9 m embedded in the soil. A linear-elastic material is considered for the pile, which is characterized by γ_p = 25 kN/m^3 (unit weight), E_p = 25 GPa (Young's modulus), and μ_p = 0.2 (Poisson's ratio). While the surrounding soil is considered elastoplastic obeying the Mohr-Coulomb criterion with a unit weight γ_s of 18.5 kN/m^3, a cohesion c_s of 20 kPa, an internal friction angle φ_s of 15°, Young's modulus E_s of 200 MPa, Poisson's ratio μ_s of 0.3, and a dilation angle ψ_s of 0°. All the parameters used in this study are either obtained in engineering practice or taken from published results (Itasca 2013; Peng 2017; Wen et al., 2020).

The axis of symmetry (the front boundary shown in Figure 1B) is fixed in the y-direction. The other three lateral boundaries (namely, the left, the right, and the back boundary) of the model keep fixed in x and y-directions. The displacements in all directions at the base are prohibited while the top surface can move freely. The mesh size and domain geometry are both determined after detailed sensitivity analyses with numerous trial numerical simulations. A uniform element size of 0.5 m is selected in the vertical direction while a radial mesh around the pile is applied in the horizontal direction. The domain geometry, the horizontal distance from the pile edge to the model edge, is 10 m for the reference case.

Interface elements are simulated between the pile and surrounding soil. In the reference case, the cohesion (c_i, kPa) and the internal friction angle (φ_i, °) of the interface elements are considered equal to c_s and φ_s, respectively. The normal (k_n, GPa/m) and shear (k_s, GPa/m) stiffnesses of the interface elements are 5.38 GPa/m, which is calculated according to the FLAC^{3D} manual (Itasca., 2013).

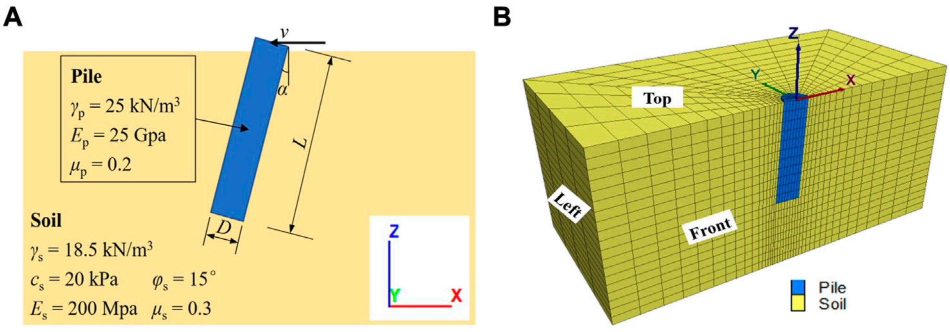

FIGURE 1
A typical model for deviation rectification of rigid inclined piles: **(A)** physical and **(B)** numerical model.

TABLE 1 A detailed program of numerical simulations (with γ_p = 25 kN/m^3, E_p = 25 GPa, μ_p = 0.2, and ψ_s = 0°).

Case	Figure(s)	Pile geometry			Soil properties					Interface properties	
		α (°)	D (m)	L (m)	γ_s (kN/m^3)	c_s (kPa)	φ_s (°)	E_s (kPa)	μ_s	c_i (kPa)	φ_i (°)
0	1, 3–6	3	1.4	6.0	18.5	20	15	200	0.3	20	15
V1	2A	0	0.06	1.2	16.48	0	35	25	0.3	= c_s	= φ_s
V2	2B	0	0.45	4.5	18	12	24	3,800	0.21	= c_s	= φ_s
V3	2C	0	0.6	5.0	12.3	30	0	100	0.3	30	20
1	7, 8	Var[a]	1.4	6.0	18.5	20	15	200	0.3	20	15
2	9A	3	Var	6.0	18.5	20	15	200	0.3	20	15
3	9B, 10	3	1.4	Var	18.5	20	15	200	0.3	20	15
4	11A	3	1.4	6.0	Var	20	15	200	0.3	20	15
5	11B	3	1.4	6.0	18.5	Var	15	200	0.3	= c_s	15
6	11C	3	1.4	6.0	18.5	20	Var	200	0.3	20	= φ_s
7	11D	3	1.4	6.0	18.5	20	15	Var	0.3	20	15
8	11E	3	1.4	6.0	18.5	20	15	200	Var	20	15
9	12A	3	1.4	6.0	18.5	20	15	200	0.3	Var	15
10	12B	3	1.4	6.0	18.5	20	15	200	0.3	20	Var

[a]Var = variable.

Modeling procedures

The deviation rectification of inclined piles is simulated by the following four steps:

(1) Simulation of initial equilibrium state. In this step, the pile zones are assigned the same material properties as the soil.
(2) Installation of the pile. The actual material properties are assigned to the pile zones and the model is then brought to an equilibrium state.
(3) Application of loads. The vertical load F_V and horizontal load F_H are added at the top of the pile foundation in the numerical model before running to equilibrium again.
(4) Deviation rectification of inclined piles. After setting the displacements to zero, a constant velocity v of -5×10^{-7} m/s in the x-direction is applied at the pile top, which is also determined by sensitivity analyses. The displacement at the pile top and pile bottom as well as the horizontal force at the pile top are monitored throughout the rectification process. The simulation stops once the pile becomes vertical.

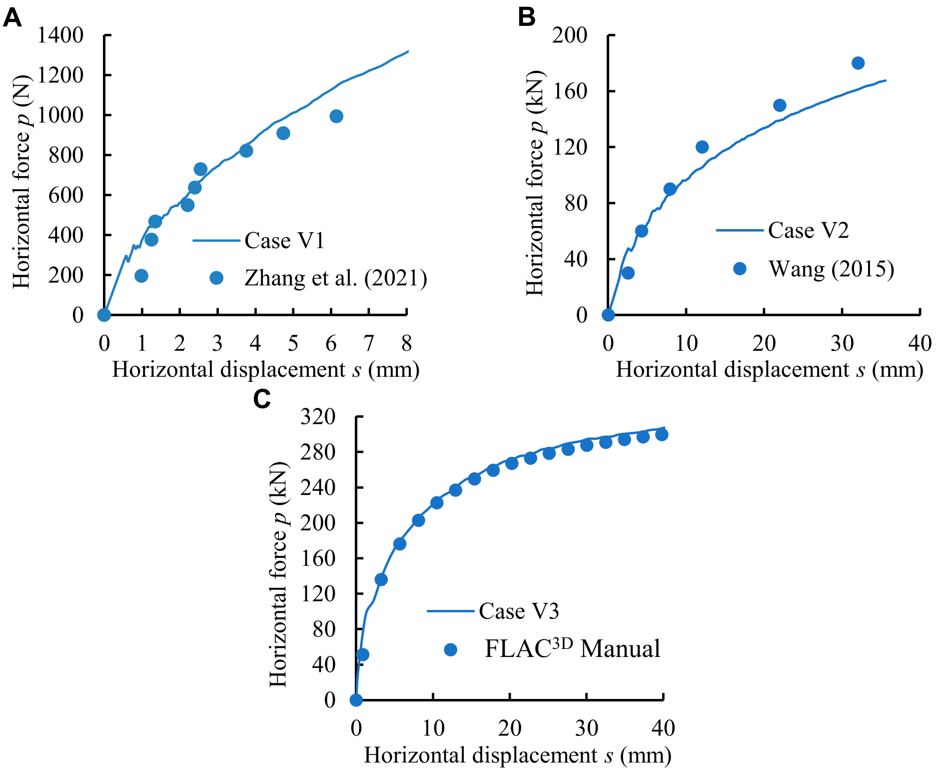

FIGURE 2
Comparisons between the numerical results obtained in the present study with experimental results of **(A)** Zhang et al. (2021) and **(B)** Wang (2015), and **(C)** numerical results in FLAC^{3D} Manual.

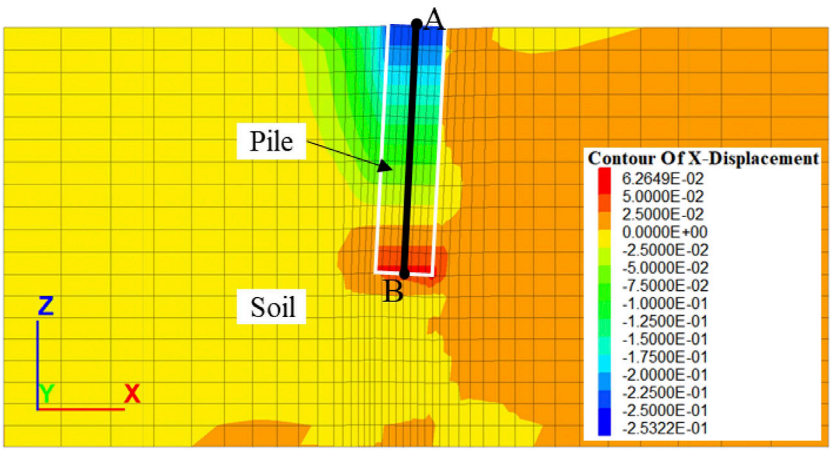

FIGURE 3
Contour of *x*-displacement for the reference case.

Model configuration

To investigate the required jacking force *P* for deviation rectification of rigid inclined piles, a series of numerical simulations shown in Table 1 are conducted with FLAC^{3D}. The reference case (Case 0 in Table 1) is used to show the modeling procedures and how to obtain the required jacking force for deviation rectification of rigid inclined piles in detail.

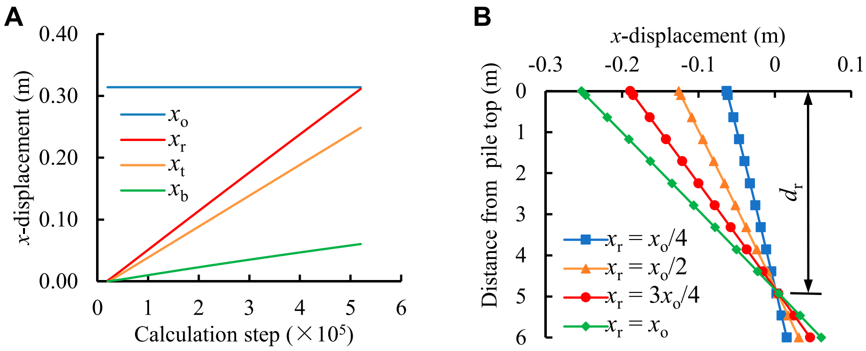

FIGURE 4
Variation of x-displacement **(A)** as a function of calculation steps and **(B)** along Line AB.

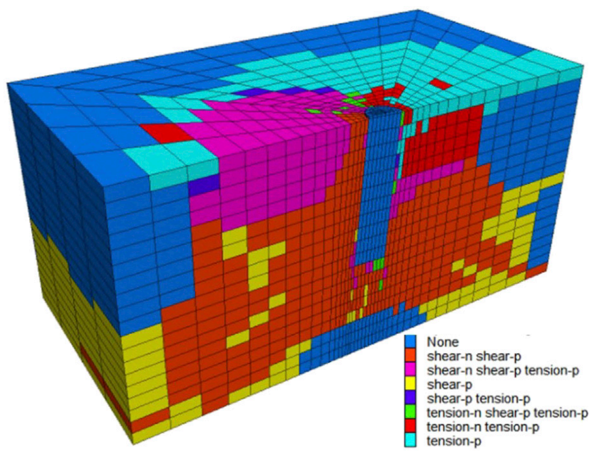

FIGURE 5
Zone state for the reference case after deviation rectification.

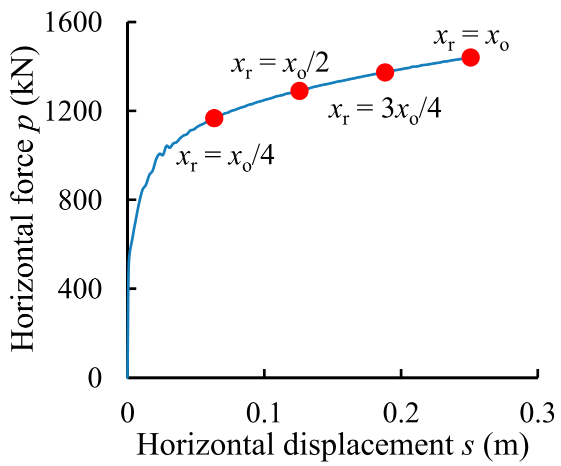

FIGURE 6
Variation of horizontal force p with horizontal displacement s at the pile top for Case 0.

Cases V1, V2, and V3 are taken from the literature and performed to validate the numerical results. The remaining cases (Cases 1–10 in Table 1) are conducted to investigate the factors which may influence the required jacking force, for instance, the pile geometry (Cases 1–3), soil properties (Cases 4–8), and interface properties (Cases 9–10).

Validation of the numerical simulations

The numerical software FLAC^{3D} is first verified with classic analytical solutions to solve cylindrical hole problems, showing good consistency, with detailed comparisons shown in Chai (2020). To further verify the reliability of the numerical results in the present study, numerical simulations (Cases V1, V2, and V3) are conducted to compare with experimental results carried out by Zhang et al. (2021) and Wang (2015) and numerical results given in FLAC^{3D} Manual (Itasca., 2013).

Zhang et al. (2021) carried out model tests to investigate the horizontal bearing behavior of piles in a model box that is 1.5 m long, 1.0 m wide, and 1.5 m high. The studied pile is 1.2 m in length with 1.0 m embedded in the sand. Other parameters are the same as Case V1 in Table 1. No vertical load (or $F_V = 0$) is applied at the pile top. The variations of the horizontal force p with different horizontal displacements s measured by Zhang et al. (2021) and obtained from numerical simulations are compared in Figure 2A. The numerical results of Case V1 are observed to agree well with the experimental results of Zhang et al. (2021).

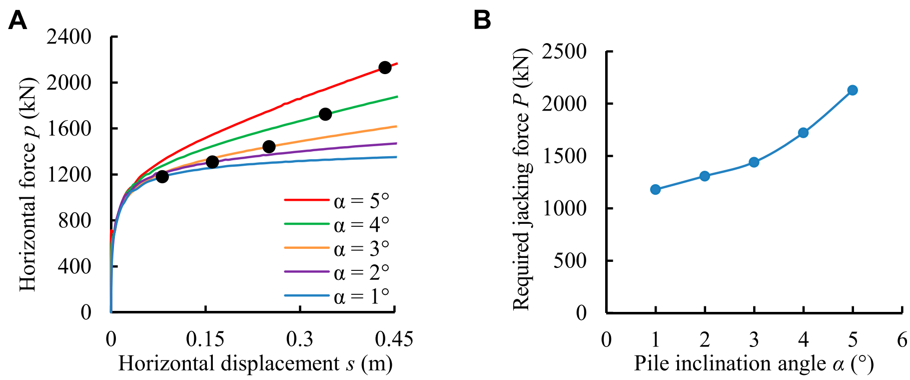

FIGURE 7
The effect of pile inclination angle α on the required horizontal force P (Case 1): **(A)** Variation of horizontal force p with horizontal displacement s at the pile top with different pile inclination angles α and **(B)** Variation of the required horizontal force P with α.

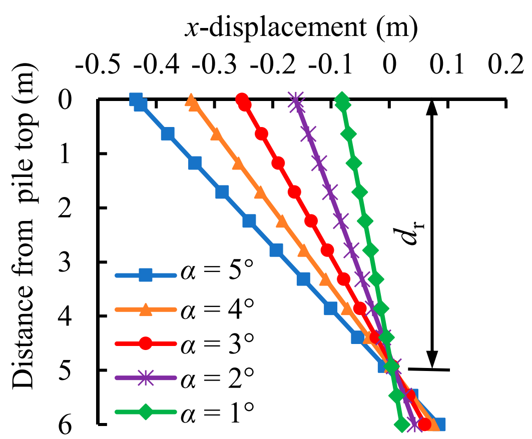

FIGURE 8
Variation of x-displacement along the pile (Line AB) after the deviation rectification of inclined piles at different values of pile inclination angle α.

Besides, the experiment results performed by Wang (2015) for the lateral response of a rigid pile in cohesive soil are also taken for validation. The studied pile is 4.5 m in length with 4.0 m embedded in the soil, and other parameters are given in Table 1 (Case V2). As shown in Figure 2B, the present numerical results correspond well with the experiment results, suggesting the reliability of the numerical models used in this study.

Case V3 is a numerical case taken from FLAC^{3D} Manual for the axial and lateral loading of a vertical pile (Itasca., 2013). A vertical load of 100 kN is applied at the pile top before applying the horizontal velocity. Figure 2C illustrates the comparisons of the horizontal forces p under different horizontal displacements s obtained from the numerical simulations. The numerical results correspond well with those shown in FLAC^{3D} Manual.

It can be concluded from Figure 2 that the numerical models and modeling procedures described in the present study are capable of investigating the pile responses. The good agreements of the numerical results in the present study with experimental and numerical results in the literature suggest the validity and reliability of numerical results.

Numerical results and discussion

Reference case (Case 0)

Figure 3 shows the contour of x-displacement for the reference case during pile deviation rectification. The top of the rigid batter pile moves left while the bottom moves right. The pile can be considered to be rectified when the relative x-displacement x_r (m) between the pile top and pile bottom is equal to the offset distance x_o (m) due to pile inclination. The corresponding horizontal force at the pile top is the required jacking force P for the deviation rectification of inclined piles. For instance, the offset distance x_o in the x-direction in Case 0 is

$$x_o = L \sin \alpha = 6 \times \sin 3° = 0.314 \, \text{m}$$

The relative x-displacement x_r can be calculated by adding together the absolute value of x-displacement x_t (m) at the center of pile top (Point A in Figure 3) and that x_b (m) at the center of pile bottom (Point B in Figure 3). In addition, x-displacement along the pile center (Line AB) shown in Figure 3 is also monitored to analyze the pile response.

Figure 4 shows the x-displacements monitored at Points A and B and Line AB. In Figure 4A, absolute values of the x-displacements of Points A (x_t) and B (x_b) are used. Both x_t and x_b increase linearly with

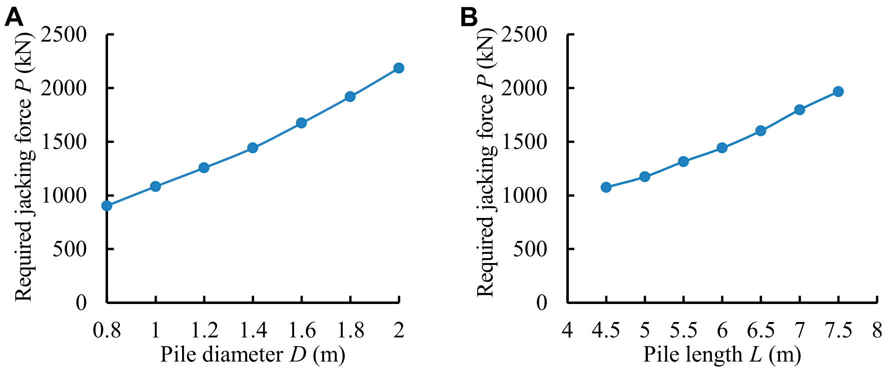

FIGURE 9
Variations of the required horizontal force P with pile geometry: **(A)** Pile diameter D (Case 2) and **(B)** pile length L (Case 3)

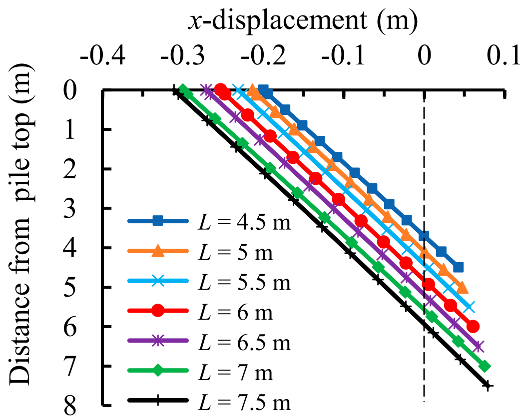

FIGURE 10
Variation of x-displacement along the pile (Line AB) after the deviation rectification of inclined piles at different values of pile length L.

increasing calculation steps. The offset distance x_o (= 0.314 m) and relative displacement x_r between Points A and B are also calculated and plotted together, which can help judge whether the deviation rectification procedure has been completed. Figure 4B presents the x-displacements along Line AB at different stages of the deviation rectification procedure. The x-displacement is observed to vary linearly along the pile length in any stage. The x-displacement at a distance d_r (m) of about 5.03 m from the pile top remains 0, suggesting that the pile rotates counterclockwise around the position. Furthermore, the zone state for the reference case after deviation rectification is presented in Figure 5. Together with the results shown in Figure 3, it suggests that no obvious pile failure occurs during the deviation rectification process.

Figure 6 shows the variation of horizontal force p with the horizontal displacement s at the pile top for the reference case. The horizontal force has been doubled considering the symmetry of the numerical model. P increases with the increase of s, but the growth rate becomes smaller and smaller, the trend of which agrees well with previous experimental and numerical results (Hazzar et al., 2017; Li et al., 2018; Zhang et al., 2021). As shown in Figure 6, when $x_r = x_o/4$, $x_o/2$, $3x_o/4$, and x_o, the horizontal forces are 1,168 kN, 1,294, 1,374, and 1,441 kN, respectively. The required jacking force P is 1,441 kN for the reference case.

Effect of pile geometry

Figure 7 shows the effect of pile inclination angle α on the required jacking force P as α increases from 1° to 5°. The variation of horizontal force p with the horizontal displacement s at the pile top is plotted in Figure 7A. It indicates that p increases with α at the same s, agreeing well with the pile responses in clayey soils reported by Hazzar et al. (2017). It may be partially due to the higher passive Earth pressure applied on the left of inclined piles caused by a larger inclination angle. The position when the pile becomes vertical is marked in Figure 7A, and the required jacking force P with the variation of pile inclination angle α is plotted in Figure 7B. It indicates that P increases by 80% from 1,180 to 2,129 kN as pile inclination angle α increases from 1° to 5°.

For all the five cases when pile inclination angle α varies, the pile rotates around a point throughout the rectification procedure. The variation of horizontal displacement along Line AB after deviation rectification is presented in Figure 8. It indicates a linear variation of the x-displacement along the pile. The rotating point of the pile decreases slightly from 5.13 to 4.83 m away from the pile top as α increases from 1° to 5°.

The influences of other parameters regarding pile geometry including pile diameter D (Case 2) and pile length L (Case 3) on the required horizontal force P are portrayed in Figure 9. One can see from Figure 9A an increase in P from 903 to 2,186 kN as D increases from 0.8 to 2.0 m. As shown in Figure 9B, an increase in

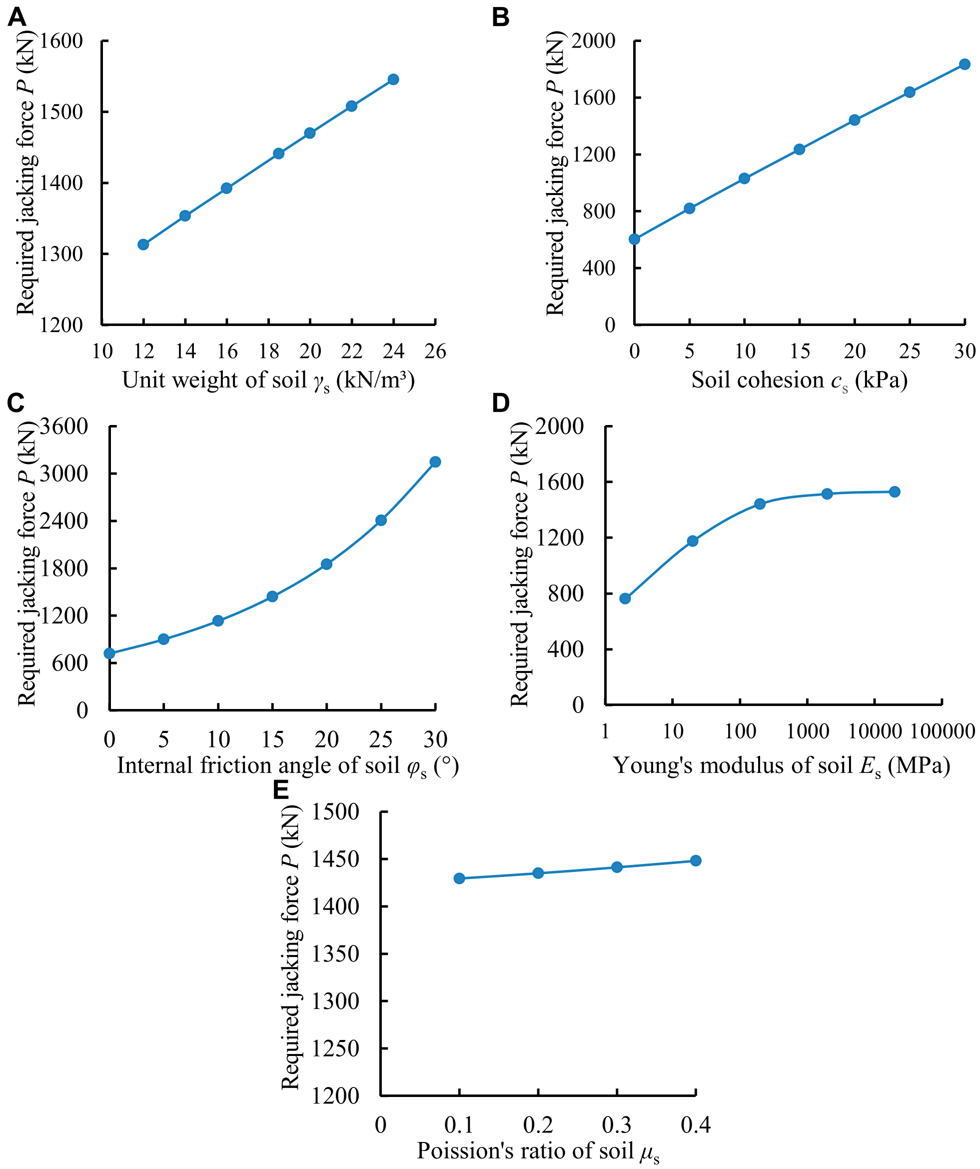

FIGURE 11
Variations of the required horizontal force P with soil properties: **(A)** Unit weight of soil γ_s (Case 4), **(B)** soil cohesion c_s (Case 5), **(C)** internal friction angle of soil φ_s (Case 6), **(D)** Young's modulus of soil E_s (Case 7) and **(E)** Poisson's ratio of soil μ_s (Case 8)

L from 4.5 to 7.5 m also causes the increase of P from 1110 to 1966 kN. The tendency is straightforward as the increasing contact area due to increasing D or L contributes to a larger P.

Besides, a linear variation of x-displacement along the pile and a rotation of the pile can also be observed for Cases 2 and 3. The position of the rotating point is nearly insensitive to the variation of pile diameter D, and the distance d_r between the point and pile top remains around 5.03 m. Figure 10 illustrates the horizontal displacement along Line AB after deviation rectification for cases with different values of pile length L. With an increase of L from 4.5 to 7.5 m, the rotating point of the pile increases from 3.69 to 6.37 m away from the pile top. It is worth mentioning that the ratio of d_r over L stays almost unchanged at about 0.84.

Effect of soil properties

Figure 11 presents the effects of surrounding soil properties, including unit weight γ_s (Case 4), cohesion c_s (Case 5), internal friction angle φ_s (Case 6), Young's modulus E_s (Case 7), and

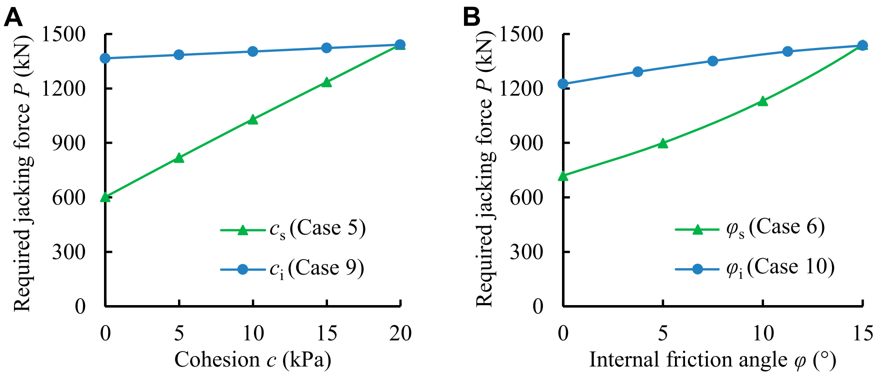

FIGURE 12
Variations of the required horizontal force P with the shear properties of soil-pile interface and soil: **(A)** Cohesion c (Cases 5 and 9) and **(B)** internal friction angle φ (Cases 6 and 10).

Poisson's ratio μ_s (Case 8), on the required horizontal force P for deviation rectification of rigid inclined piles.

Figure 11A shows the required horizontal force P at the pile top is 1,313 kN when γ_s = 12 kN/m^3 while it increases linearly to 1,545 kN when γ_s = 24 kN/m^3. It can be attributed to the increased passive Earth pressure at the left of the inclined pile. Figures 11B,C illustrate the influences of shear strength parameters of the surrounding soil on the required horizontal force P for deviation rectification. P increases linearly from 603 kN for cohesionless soil to 1835 kN for cohesive soil with c_s = 30 kPa. Besides, a larger internal friction angle φ_s of the soil will also lead to a higher jacking force required for deviation rectification. For example, P is 720 kN as φ_s = 0, while it increases exponentially to 3,146 kN as φ_s = 30°. Deformation is observed in the surrounding soils during the deviation rectification procedure, especially in the soil near the left of the inclined pile, as shown in Figure 3. It suggests the failure of soils. Therefore, the higher shear strength of the surrounding soil can contribute to a more stable soil but is unbeneficial to the deviation rectification of inclined piles.

The variation of required horizontal force P with different values of Young's modulus E_s of soil is shown in Figure 11D. When E_s is relatively small ranging from 2 to 200 MPa, P increases obviously from 763 to 1,441 kN. Whereas, as E_s continues to increase from 200 to 20,000 MPa, P is observed nearly insensitive to the variation of E_s. It is partially because the soil with lower stiffness is prone to deformation, thus causing the stress easily released and reducing P. However, once the stiffness of the surrounding soil is large enough (e.g., E_s > 200 MPa for Case 7), the shear behavior of the soil may be dominant when considering deviation rectification. Besides, Figure 11E presents the effect of Poisson's ratio of soil μ_s on P. It is observed that P slightly increases from 1,429 to 1,448 kN as μ_s varies between 0.1 and 0.4.

Moreover, the pile is observed to rotate around a position in Cases 4–8 when the material properties vary. With the variation of soil properties, the distance d_r between the rotating point and the pile top keeps almost unchanged at about 5.0 m. It is probably because of the consideration of uniform soil in this study, and more efforts are required in this aspect to consider more complex soil properties (Wen et al., 2020; Peng et al., 2021; Xue et al., 2021).

Effect of interface properties

Figure 12 shows the effects of shear properties of the soil-pile interface (Cases 9 and 10) on the required jacking force P for deviation rectification of rigid inclined piles. The variations of P with soil shear properties are also plotted together for comparison. As shown in Figure 12A, P is 1,366 kN when the interface cohesion c_i = 0 and increases by 5% to 1,441 kN as c_i = 20 kPa. One can also see from Figure 12B an increase of P from 1225 to 1436 kN when the internal friction angle φ_i of the soil-pile interface varies from 0 to 15°. It is straightforward as the increased shear resistance causes the required jacking force to increase. The trends can be partially verified by Jiang et al. (2022) who found that the horizontal bearing capacity increased with the increase of the internal friction angle of the pile-soil interface.

Figure 12A also indicates that the effect of interface cohesion on the required jacking force can be nearly regarded as negligible compared to the effect of soil cohesion. Similarly in Figure 12B, the required jacking force is observed more sensitive to the variation of internal friction angle φ_c of soil rather than the internal friction angle φ_i of the soil-pile interface. The results are valuable if the engineers intend to reduce the required jacking force, and additional work on this aspect is still ongoing.

Conclusion

The study estimates the required jacking force for deviation rectification of rigid inclined piles in cohesive soils with FLAC^{3D}.

Factors of influence including the pile geometry, soil properties, and interface shear properties are analyzed numerically.

By comparing the numerical results with previous experimental and numerical results, the proposed modeling procedure is proved to perform well in estimating the required jacking force. The numerical results indicate that the required jacking force increases with increasing pile geometry parameters including pile inclination angle α, pile diameter D, and pile length L. An increasing unit weight γ_s of the surrounding soil can also contribute to the increase in the required jacking force due to a higher passive Earth pressure acting on the pile. Besides, larger shear strength parameters of the soil including cohesion c_s and internal friction angle φ_s can enhance the soil stability, thus causing the required jacking force to increase. Young's modulus E_s of the soil has a positive effect in increasing the required jacking force when E_s is below a critical value (e.g., 200 MPa for Case 7 in this study) but becomes negligible once E_s exceeds the value. Moreover, increasing Poisson's ratio μ_s of the soil can help increase the required jacking force slightly but seems insignificant compared with the aforementioned parameters. Higher interface shear strength parameters (c_i and φ_i) can increase the required jacking force, but their effects are not pronounced compared with soil shear strength parameters (c_s and φ_s).

The results will be beneficial to estimate the required jacking force for deviation rectification of rigid inclined piles, which contributes to a safer and more cost-efficient design for deviation rectification.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SC and LF conceived and designed the study; SC conducted numerical simulations, analyzed the results, and wrote the original draft. LF and HL reviewed the original draft. All authors contributed to the manuscript revision and approved the submitted version.

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Conflict of interest

Author HL is employed by Henan Province Information Consultation Designing Research Co., LTD.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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