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Lateral pile analysis based on subgrade reaction and comparison with other methods

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ABSTRACT: Subgrade reaction method with linear soil springs is widely used in structural analysis for piles because of its simplicity. Geotechnical engineers are often required to provide subgrade modulus for evaluation of the soil spring stiffness. However, subgrade modulus is not an inherent soil property and highly dependent on structure geometry and magnitude of deflection. Due to the limitation of the linear spring model, it is not unusual for the validity of the analysis result to be questioned. This paper provides a review of the subgrade reaction method and the various approaches in determining subgrade modulus. Effect of the variation of subgrade modulus on pile analysis is studied using structural software Space Gass. Lateral pile analyses based on the p-y curve and finite element methods are also carried out using software packages LPile/Group and Plaxis 3D. Analysis results are compared and the reliability of the subgrade reaction method is discussed.

1 INTRODUCTION

Pile foundations are frequently designed to support both vertical and lateral loads. Typical examples include pile-supported bridges, buildings and offshore structures. Lateral pile analysis is one of the key design issues. Pile deflections and design actions (bending moments, shear forces) are assessed from lateral pile analysis and used in pile design.

Various methods are available for lateral pile analysis, like Broms method, Brinch Hanson method, subgrade reaction method, p-y curve method, elastic method, finite difference and finite element methods, and so on. Among the various methods the subgrade reaction method is probably the most convenient method for structural modelling, and thus widely used by structural engineers. The theory of subgrade reaction assumes that the unit soil reaction (p) for a laterally loaded pile increases linearly with the lateral deflection (y), as expressed in the following equation (Terzaghi 1955) .

$$p = k_s y \tag{1}$$

In various publications k_s is called by many different names such as coefficient of subgrade reaction, modulus of subgrade reaction, subgrade reaction, subgrade modulus, etc. To avoid confusion k_s is called coefficient of subgrade reaction in this paper, while k_s multiplied by structure size (pile diameter for instance) is called subgrade modulus (K).

In structural analysis, piles are commonly incorporated into the analysis model with surrounding soils modelled as uncoupled linear springs. Geotechnical engineers are requested to provide subgrade modulus for evaluation of the soil spring stiffness. Although soil spring model is convenient to use, there is difficulty in deriving appropriate spring constant. Subgrade modulus is not an inherent soil property but load and deflection dependent. A lot of research has been undertaken, and quite a number of approaches have been proposed for assessing K. Those approaches generally correlate K with other soil parameters such as elastic modulus or shear strength, and give highly variable K values.

This paper provides a review of the various approaches in determining subgrade modulus. Effect of the variation of K on analysis is studied using the software package Space Gass. Lateral pile analyses based on more sophisticated methods, i.e. p-y curve and finite element methods, are also carried out using software packages LPile/Group and Plaxis 3D. The Space Gass analysis results are compared with the LPile/Group and Plaxis to study the reliability of the subgrade reaction method in lateral pile analysis.

2 SUBGRADE MODULUS CORRELATIONS

As discussed above, subgrade modulus is a conceptual parameter for lateral pile analysis, and various approaches have been proposed to determine K by correlation with other soil parameters. Some correlations are shown Table 1 based on Sadrekarimi & Akbarzad (2009) and CIRIA Report 103 (2004).

Table 1. Common correlations proposed for k_s ($K=k_sB$)

Investigator	Suggested Expression
Biot	$k_s = \frac{0.95\,E_s}{B(1-v_s^2)}\left[\frac{B^4 E_s}{(1-v_s^2)EI}\right]^{0.108}$
Bowles	$k_s = \frac{E_s}{B'(1-v_s^2)mI_sI_f}$
Jamiolkowski	$k_s = 500\ to\ 700c_u/B$
Klopple and Glock	$k_s = \frac{2E_s}{B(1+v_s)}$
Meyerhof and Baike	$k_s = \frac{E}{B(1+v_s)}$
Selvadurai	$k_s = \frac{0.65}{B}.\frac{E_s}{1-v_s^2}$
Skempton	$k_s = 80\ to\ 320c_u/B$
Terzaghi	For sand $k_s = k_{s1}(\frac{B+1}{2B})^2$ For clay $k_s = k_{s1}\frac{1}{B}$
Terzaghi	For sand $k_s = n_h z/B$ For clay $k_s = 67c_u/B$
Vesic	$k_s = \frac{0.65E_s}{B(1-v_s^2)}\sqrt[12]{\frac{E_sB^4}{E_pI}}$
Vlassov	$k_s = \frac{E_s\,(1-v_s)}{(1+v_s)(1-2v_s)}(\frac{\mu}{2B})$

The table shows that K ($=k_sB$) is generally correlated with the following parameters: a) measurement from field testing such as plate-load test; b) elastic property of soil; c) undrained shear strength; d) ground depth; and e) bearing capacity. Structure size is included in all the correlations, while flexural stiffness is included in some correlations. The table also indicates a high variation of K value. Due to the fact that K is load and strain dependent, it is thought that each correlation has its rationality and limitation, and is applicable in a certain scenario. Acknowledging the limitation of the correlations, geotechnical engineers normally provide a range, not a single value of K to account for the variation.

3 STUDY CASE 1: SINGLE PILE

3.1 *Analysis cases*

A 20 m long, 0.9 m diameter concrete pile fully embedded in ground is assumed in the study. Two soil types are considered, i.e. stiff clay and medium sand. Properties of the two soils are shown in Table 2.

Table 2. Soil parameters adopted in the analysis

Soil	Unit weight	Cohesion	Friction Angle	Modulus
	kN/m^3	kPa	Degrees	MPa
Clay	18	75	0	15
Sand	18	0	34	30

For stiff clay, Vesic's correlation (1961) is used to evaluate subgrade modulus. Assuming modulus of pile Ep = 34500 MPa, K is calculated to be about 10 MPa. To study the effect of variation of K, K is divided by 2, and multiplied by 2, to give likely lower bound of 5 MPa, and upper bound of 20 MPa. For sand, $K=n_hz$ according to Terzaghi (1955), where n_h is the rate of increase with depth, and z is depth. For medium dense dry sand, n_h varies from 3.5 to 10.9 MN/m^3 as suggested by Terzaghi. In this study, n_h is adopted to be 7 MN/m^3, while the lower and upper bounds are adopted to be 3.5 MN/m^3 and 14 MN/m^3.

3.2 *Analysis methodology*

Single pile analysis is performed using three software packages, Space Gass, LPile and Plaxis 3D. Space Gass is commonly used in structural analysis, while the other two in geotechnical analysis.

In Space Gass model, horizontal ground reaction is simulated by linear springs at 1 m interval. Spring stiffness is obtained by multiplying K by contributive pile length. Pile is restrained vertically at base.

LPile (Ensoft 2017) analysis is based on the p-y curve method (Matlock & Reese 1960, Reese & Van Impe 2011), which adopts non-linear relationship between ground reaction and lateral deflection. In this study, built-in p-y curves and default settings in LPile are adopted. Clay is modelled by Reese's Stiff Clay without Free Water, with the Strain Factor (E50) set to be determined by the program. For sand, Reese's Sand model is used, and the rate of modulus increase (*k*) is set to Default.

In Plaxis 3D (2017), Mohr-Coulomb model is used for soil, while pile is modelled as "Embedded Beam". The embedded beam element models pile as a beam interacting with soil by means of special interface elements. Skin resistance of the embedded beam is set to be layer dependent, while ultimate end bearing pressure is set to be 1000 kPa.

3.3 *Analysis results*

Single pile is analysed for two lateral load cases applied at pile top, which are 300kN and 600kN. The analysis is undertaken using three software packages, Space Gass, LPile and Plaxis 3D. The analysis results are discussed below.

3.3.1 *Spring stiffness*

In Space Gass analysis the subgrade modulus (K) is assumed to be constant and evaluated from established correlations. LPile analysis is based on p-y curve where the spring stiffness (p/y) varies with deflection. The spring stiffness adopted in the Space Gass model and those from LPile are plotted in Figure 1 for clay and sand under the two load cases.

The figure shows that spring stiffness values from the correlations and p-y curves are comparable within shallow depth. With depth increase the difference becomes larger and is up to about 300 times for clay and 45 times for sand. As known p-y curve characterises non-linear soil pressure-deflection relationship. With increasing depth and reducing loads, deflection is smaller and soil is stiffer. Terzaghi's K for sand also increases with depth, but the rate of increase is apparently lower than that from p-y curve.

3.3.2 *Deflection and internal forces*

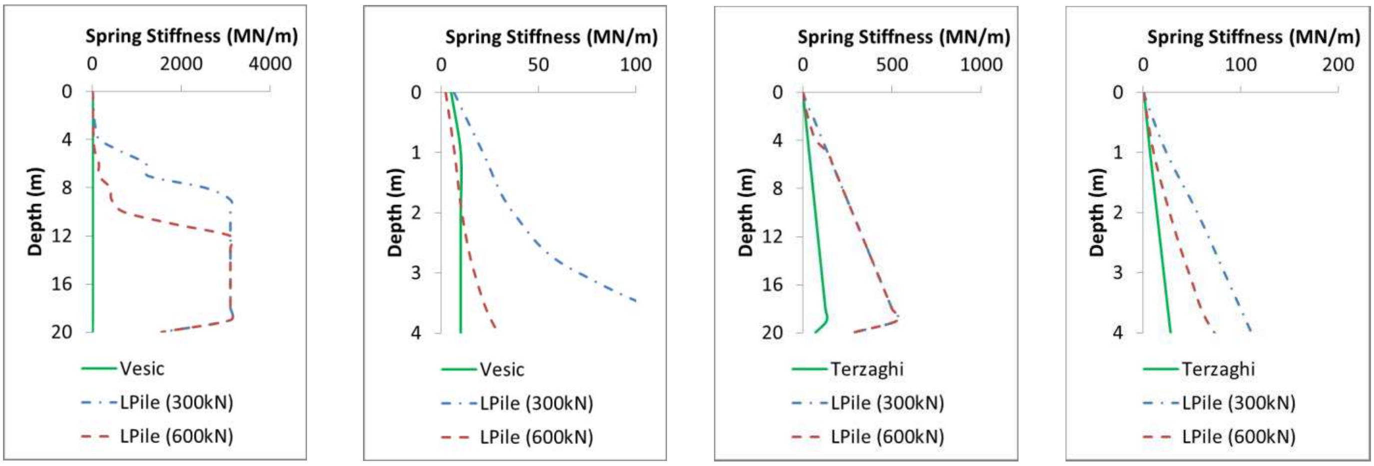
Soil spring stiffness from correlation is significantly different from that assessed from LPile. Impact of the difference on pile analysis is investigated in this paper. The Space Gass analysis results based on spring stiffness from correlations are plotted in Figures 2-3 for clay, Figures 4-5 for sand, together with the LPIle and Plaxis 3D analysis results.

It can be seen that varying soil spring stiffness in Space Gass affects lateral deflection apparently, but has less impact on bending moment, and the least effect on shear force. For pile in sand, the moment and shear force curves from Space Gass are comparable to LPile and Plaxis. For pile in clay, however, the moment and shear force curves from LPile are distinctive and the maximum values could be significantly larger. That is due to the significant difference between soil spring stiffness used in LPile and Space Gass for clay, whereas the difference is relatively small for sand, as indicated in Figure 1. Mohr-Coulomb model used in Plaxis adopts linear stress strain relationship, which would give soil stiffness comparable to the correlations. Accordingly the pile internal forces from Plaxis are similar to Space Gass. Note deflections from Plaxis are also similar to Space Gass results with base case spring stiffness being adopted. Sensitivity analysis by Space Gass shows that with reducing spring stiffness, pile deflection and maximum moment increase, maximum shear is not affected but its depth increases.

4 STUDY CASE 2: PILE GROUP

4.1 *Analysis cases*

A four-pile pile group is analysed for lateral loads. The square pile group comprises four concrete piles with rigid connection to a pile cap on ground surface. The piles are 20 m long, 1 m diameter and at 3 m center to center spacing. The pile cap is 5 m square and 1.5 m thick. Ground conditions are the same as those adopted in single pile analysis, i.e. stiff clay and medium sand. To simplify the analysis, pile bases are assumed to be on competent rock.



(a) Clay: full pile depth (b) Clay: 4m depth (c) Sand: full pile depth (d) Sand: 4m depth

Figure 1. Soil spring stiffness in Space Gass & LPile.

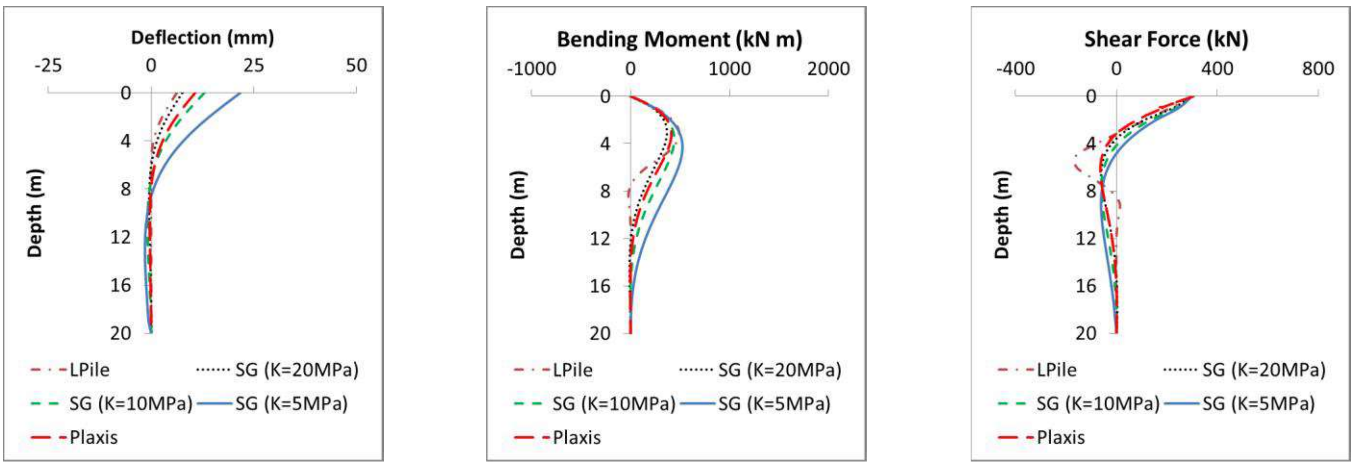


Figure 2. Analysis results of single pile in clay (lateral load = 300 kN).

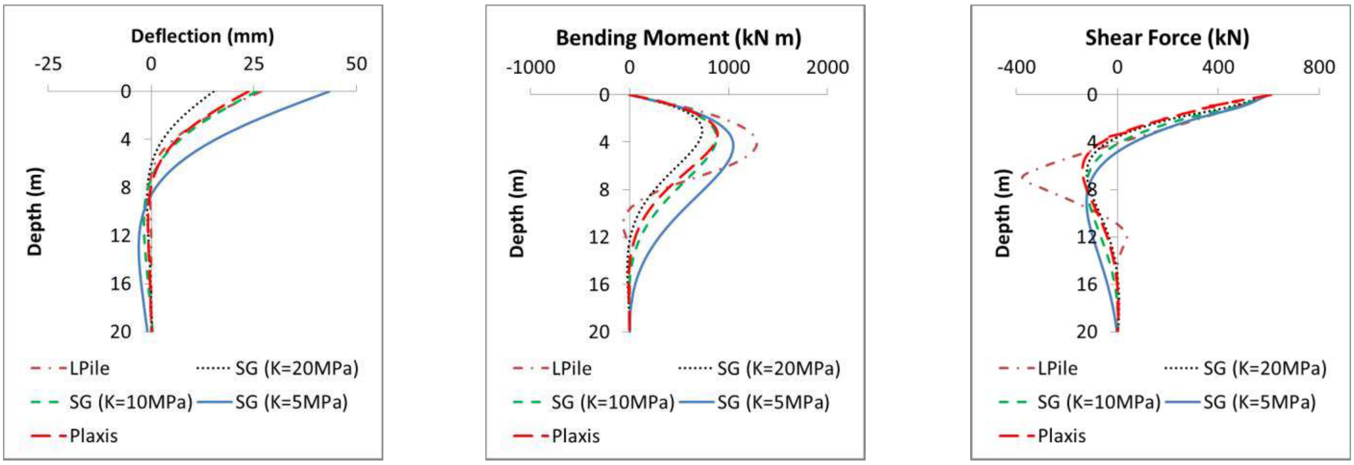


Figure 3. Analysis results of single pile in clay (lateral load = 600 kN).

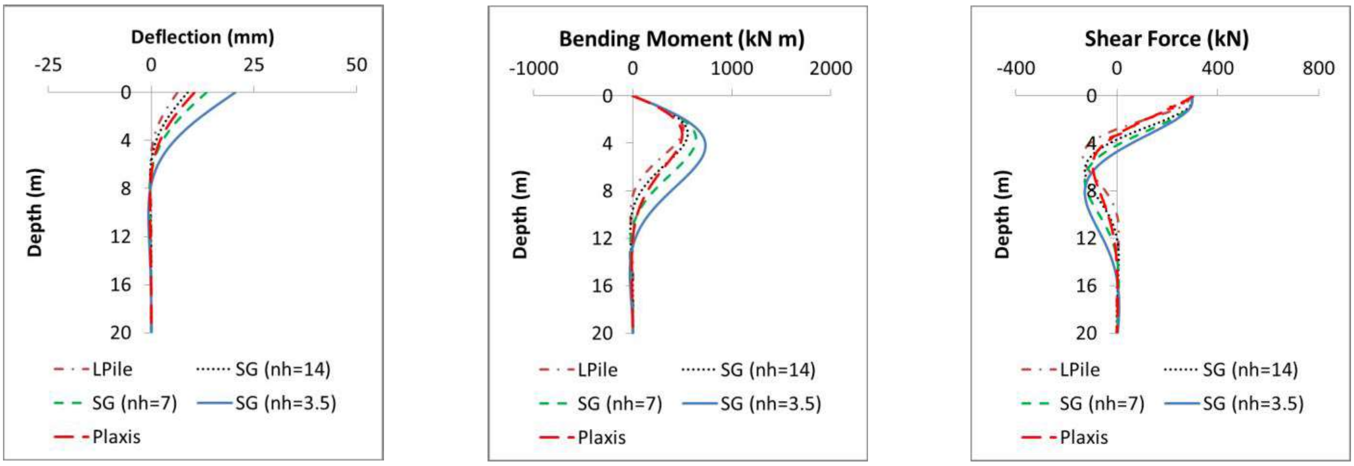


Figure 4. Analysis results of single pile in sand (lateral load = 300 kN).

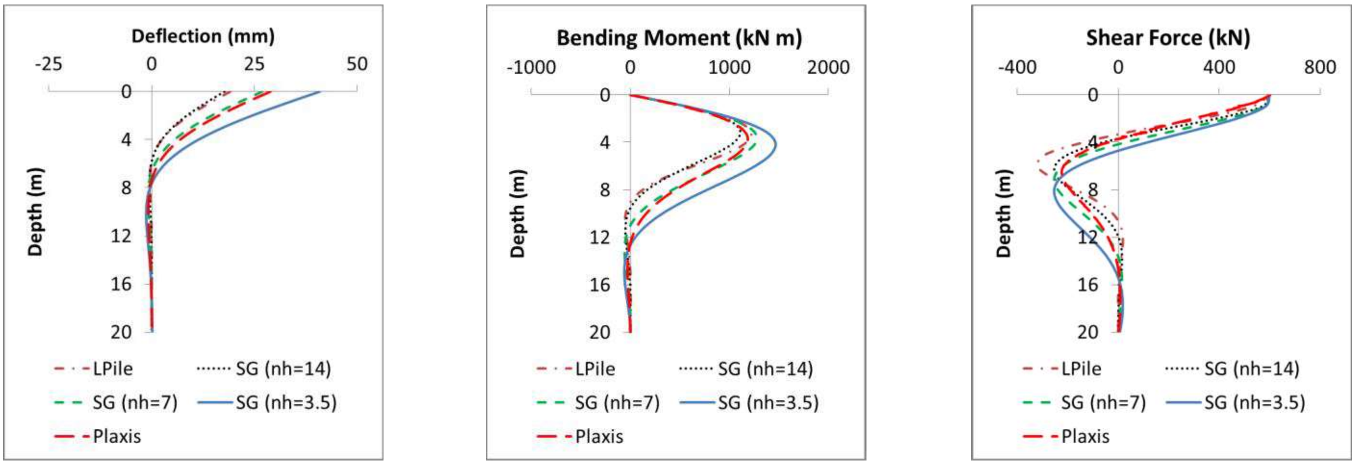


Figure 5. Analysis results of single pile in sand (lateral load = 600 kN).

4.2 *Analysis methodology*

Pile group is analysed using Space Gass, GROUP and Plaxis 3D. In Space Gass analysis, only the base case soil springs (K = 10 MPa for clay and n_h = 7 MN/m^3 for sand) are considered. Piles are modelled in the same way as that for single pile. Group effect is not considered in the analysis. Pile cap is modelled as a frame with rigid connection with piles.

GROUP analysis is undertaken using the same p-y curves as used in the single pile analysis. Piles are assumed to have 0.5 m socket in rock. Rock is simulated by the Strong Rock model in GROUP (Ensoft, 2015) with 15 MPa UCS. Group effect is set to be automatically determined by the software. Fixed connection between pile and pile cap is adopted.

Plaxis analysis is also undertaken with the same soil models as for single pile analysis except that a 0.5 m rock layer at the base is included. Rock is modelled as a Mohr-Coulomb material with c = 200 kPa, ϕ = 40° and E = 800 MPa. Pile cap is modelled as "Plate" with rigid connection with piles modelled as "Embedded Beam".

4.3 *Analysis results*

Pile group is analysed for two lateral loads, 2000kN and 4000kN acting at pile top (bottom of pile cap). The analysis results are presented in Figures 6-9. In Space Gass analysis, the four piles behave the same as group effect is not considered. For GROUP and Plaxis, group effect is automatically considered in analysis, and the front (F) pile and rear (R) pile behave differently as indicated in the plots.

The figures show that Space Gass gives smaller deflection than Plaxis, which may be due to group effect being ignored in Space Gass analysis. Deflection from GROUP is the smallest under a small load, but increases quickly with load due to the non-linear

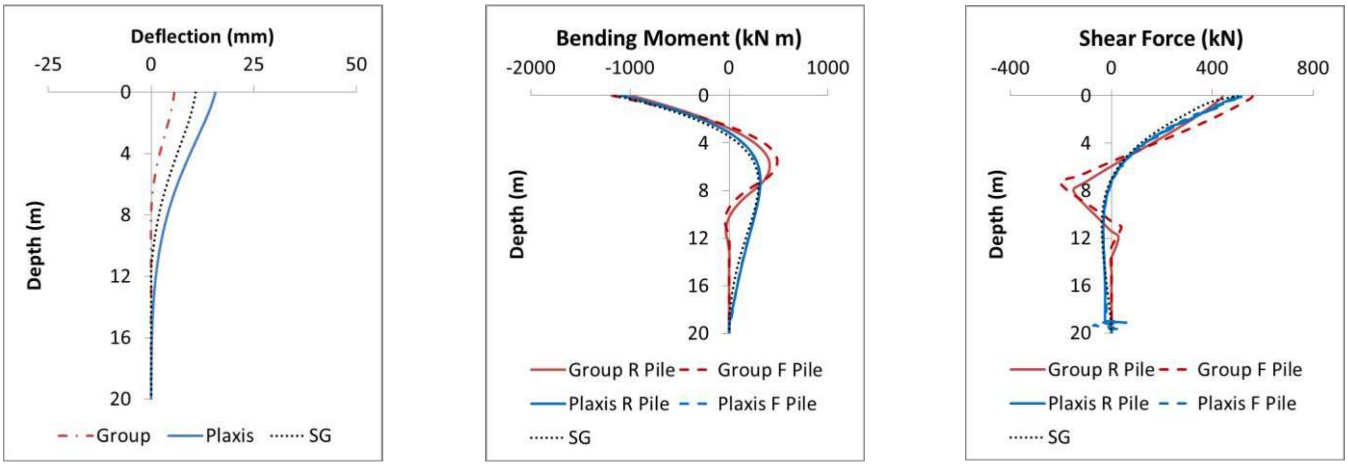


Figure 6. Analysis results of pile group in clay (lateral load = 2000 kN).

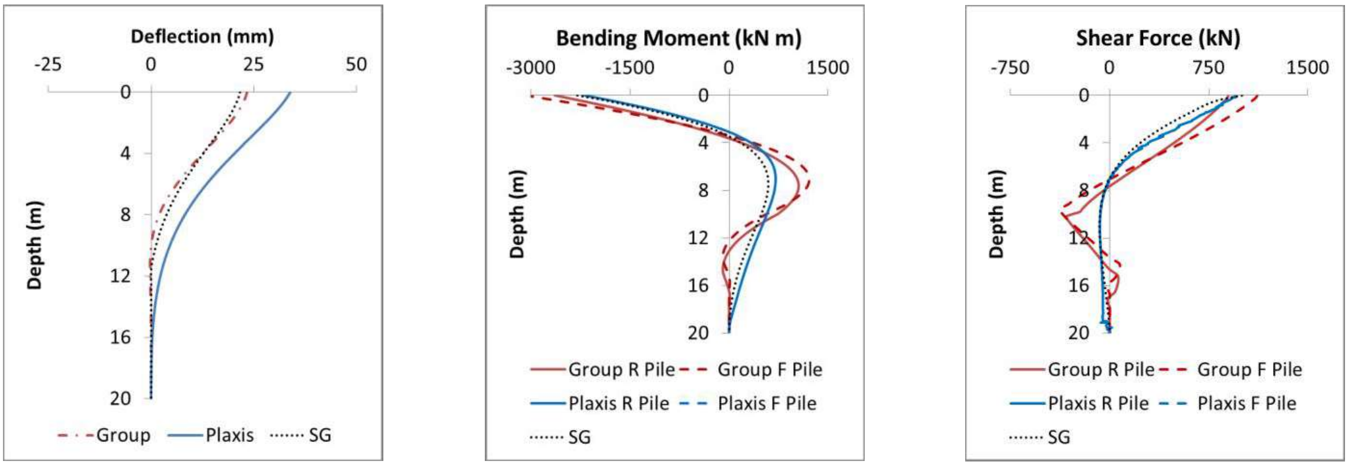


Figure 7. Analysis results of pile group in clay (lateral load = 4000 kN).

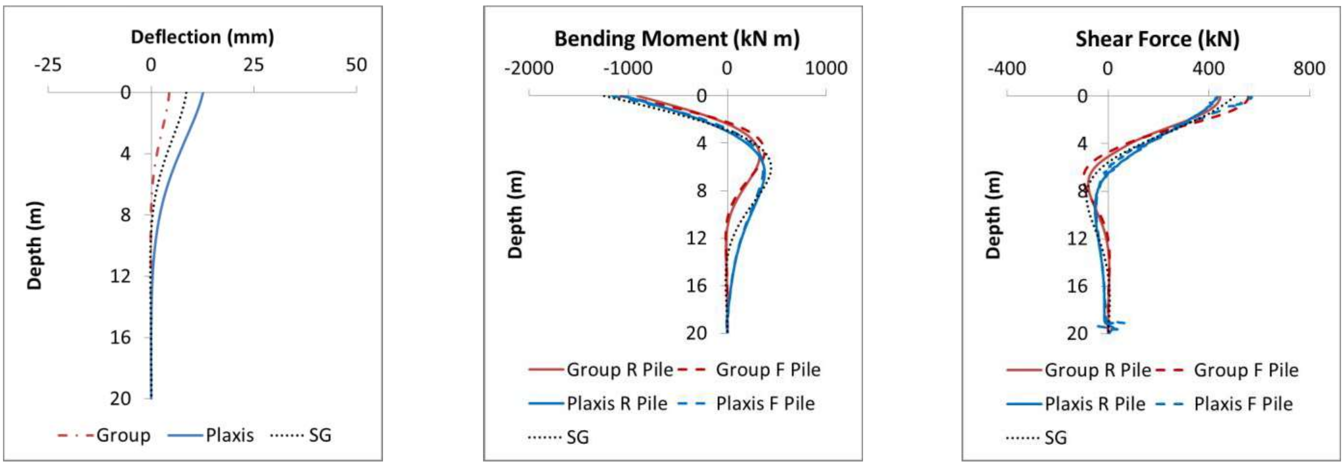


Figure 8. Analysis results of pile group in sand (lateral load = 2000 kN).

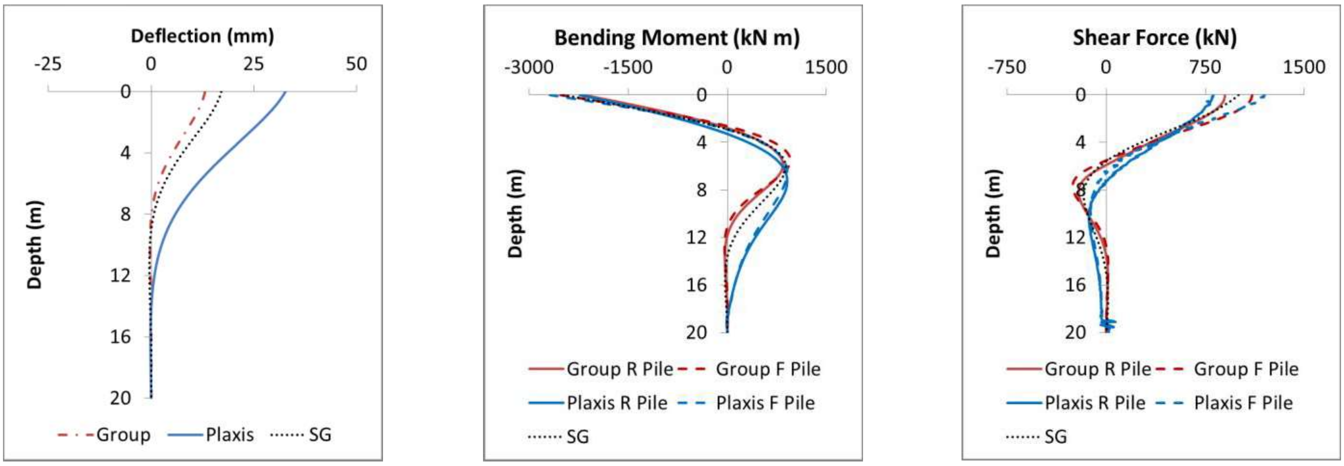


Figure 9. Analysis results of pile group in sand (lateral load = 4000 kN).

nature of p-y curve. Similar to the findings of single pile, p-y curve method (GROUP) gives significantly different internal forces for piles in clay compared with the other two methods, which is thought to be due to the large difference of soil stiffness assumed for clay. The difference is smaller for piles in sand. Pile internal forces from Space Gass and Plaxis are comparatively closer due to the similar nature of soil springs assumed (linear elastic). Group analysis shows that front piles take more loading than rear piles.

5 CONCLUSIONS AND DISCUSSIONS

This paper discussed subgrade reaction method in lateral pile analysis, and compared that method with p-y curve and finite element methods based on the analysis of a single pile and a four-pile pile group using Space Gass, LPile/GROUP and Plaxis 3D. Main conclusions drawn are discussed below.

1) Subgrade reaction method based on linear soil springs (constant subgrade modulus) is widely used in structural pile analysis. However, subgrade modulus is not an inherent soil property but load and deflection dependent. Various correlations in determining K give highly variable K values.

2) In Space Gass analysis, variation of K has great effect on pile lateral deflection, less effect on bending moment, and the least effect on shear force.

3) Soil spring stiffness assessed from p-y curve is much higher than that from K correlation. Comparatively, the difference is larger for clay than for sand.

4) Compared with p-y curve method, pile deflections predicted by the analysis with subgrade reaction method are generally larger. Moments and shear forces are relatively comparable for piles in sand, and for smaller load cases for piles in clay.

5) Plaxis analysis gives results quite different from LPile/GROUP, which is thought to be due to the difference of soil stiffness derived from the Mohr-Coulomb model (linear elastic-perfectly plastic) and the p-y curve (non-linear).

6) Front piles in a pile group take more loading than rear piles.

7) Lateral pile analysis based on the subgrade reaction method could be used with reasonable safety with K properly assessed. However, due to the high variation of K, the method is liable to under- or over-design of pile. Verification with more sophisticated approaches like the p-y curve or finite element method is recommended for detailed design, especially for piles subject to large lateral loads and structures sensitive to lateral deflection.

REFERENCES

CIRIA Report 103. 2004. Design of laterally-loaded piles.

Ensoft Inc. 2017. Technical Manual for LPile 2018.

Ensoft Inc. 2015. Technical Manual for GROUP 2016.

Matlock, H. & Reese, L. C. 1960. Generalized solutions for laterally loaded piles. Journal of the Soil Mechanics and Foundations Division, ASCE 86: 63-91.

Plaxis 3D. 2017. Material Models Manual.

Reese, L.C. & Van Impe, W.F. 2011. Single Piles and Pile Groups Under Lateral Loading. 2nd edition. Boca Raton, CRC Press.

Sadrekarimi, J. & Akbarzad, M. 2009. Comparative study of methods of determination of coefficient of subgrade reaction. Electronic Journal of Geotechnical Engineering 14E.

Terzaghi, K. 1955. Evaluation of coefficient of subgrade reaction. Geotechnique 5(4), 297- 326.

Vesic, A. B. 1961. Beams on Elastic Subgrade and Winkler's Hypothesis. Proc. 5th Int. Conf. on Soil Mechanic and Foundation Engineering, Paris: 845-850.