



Analysis of Foundation Settlement Interaction among Multiple High-Rise Buildings

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Abstract This paper aims to develop a relatively simple approach to examining the interaction among multiple foundation systems for closely spaced high-rise structures, termed here “urban forests”, and to assess the extent to which this interaction can influence the foundation performance of a building within this “forest”. To simplify the analysis and avoid undue numerical complexity, each foundation system is modelled as an equivalent pier, representing the deep foundations, the connecting mat or raft, and the soil contained within the piled raft system. The behaviour of a single equivalent pier is considered first, with the surrounding foundations being represented by an axisymmetric smeared ring outside the pier. After examining some general behavioural characteristics, a simplified approach using the concept of interaction factors is developed to facilitate estimation of settlement interaction between multiple adjacent foundations. The accuracy of this simplified approach is assessed via comparison with the axisymmetric approach. The significance of the interaction among foundations is examined for some simple cases. It is found that the settlement interaction depends largely on the characteristics of the foundations surrounding the building being examined. When

all buildings are supported on foundations extending to a relatively stiff layer, the interaction effects tend to be relatively small. However, if one or more of the buildings is founded on a relatively short foundation system, interaction effects may be more significant. An example is provided to illustrate the application of the approach.

Keywords Analysis · Foundations · Interaction · Numerical analysis · Settlement · Tall buildings

1 Introduction

The development of urban areas to accommodate burgeoning populations has led to the construction of high-rise buildings that are concentrated in relatively close proximity. This trend appears to be accelerating, and may result in the formation of what may be termed “high-rise urban forests”, consisting of a group of closely-spaced buildings that are tall and slender (Cardno 2022). One of many examples of such a collection of buildings is shown in Fig. 1. It is well-recognized that wind loadings on such buildings are influenced significantly by the proximity and orientation of surrounding buildings, as is the seismic response (Kato and Wang 2022), but when designing the foundations for such buildings, there has been a tendency to focus on each building as an individual isolated structure. However, there is anecdotal evidence to suggest that the foundation systems of

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Fig. 1 Example of closely-spaced high rise buildings

closely-spaced tall buildings can influence each other via interaction through the soil.

In this paper, a simplified analysis will be developed to enable a rapid estimation to be made of these inter-building interaction effects. First, an idealized axi-symmetric finite element analysis will be undertaken to try and understand some of the interaction characteristics. Then, a simplified approach will be described that relies on the concept of interaction factors among foundation systems represented by equivalent piers. It will be demonstrated that this approach provides an adequate and convenient means of assessing whether interaction effects are likely to be important, without having to do a full three-dimensional finite element analysis. It also enables the examination of the effects of progressive construction around a structure, and the evolution of differential settlements as the construction of the surrounding buildings proceeds.

Introduce the concept of multiple high-rise towers in congested urban environments and the concept of “high-rise urban forests” (see article by Catherine Cardno).

2 Approximate Analysis Via Axi-Symmetric Finite Element Simulation

In principle, the interaction among multiple foundation systems can be carried out via a three-dimensional finite element analysis in which each pile within each foundation system is modelled. However,

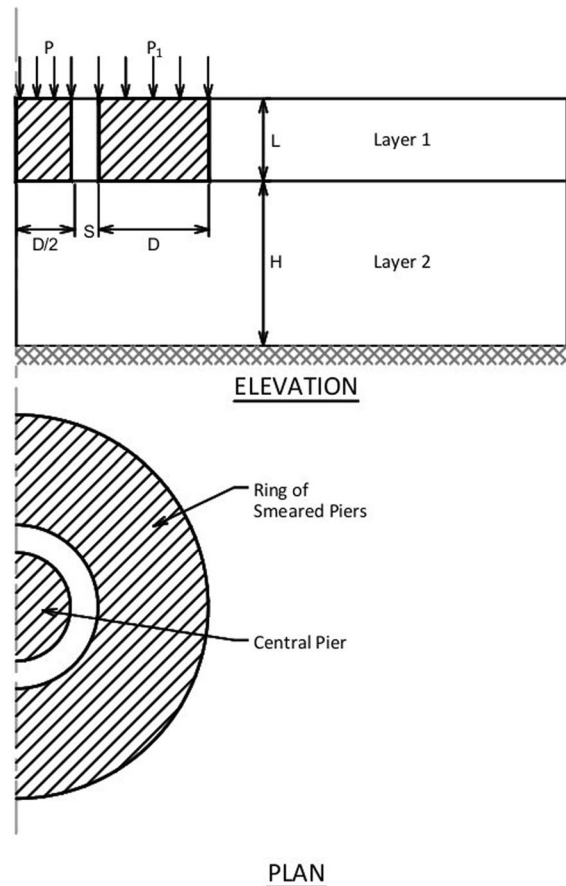


Fig. 2 Simplified model of multiple foundations (axi-symmetric)

for the purposes of understanding the behavioural characteristics of such systems, and for making preliminary assessments, it appears more efficient to simplify the problem to one in which the following assumptions are made:

1. The foundation system for the building being examined is modelled as an equivalent pier.
2. The foundations surrounding this examined system are modelled as “smeared pier rings”.

To avoid undue complexity, yet retain some element of reality, all of the foundation systems are assumed initially to be identical, and are located in a two-layer soil profile. Figure 2 illustrates this simplified representation of multiple foundations.

The Young’s moduli of the equivalent pier and the smeared pier ring can be estimated approximately

by ignoring the effect of the soil and considering the stiffness of the piles only. The equivalent modulus of the central pier, E_{p1} , is then calculated as follows:

$$E_{p1} = n_1 \cdot E_p \cdot A_p / (\pi \cdot D^2 / 4) \quad (1)$$

where n_1 =number of piles in the central group, E_p =Young's modulus of an individual pile, A_p =cross-sectional area of each pile, D =diameter of equivalent central pier.

Similarly, the equivalent modulus of the adjacent smeared pier ring, E_{p2} , is:

$$E_{p2} = n_2 \cdot E_p \cdot A_p / A_R \quad (2)$$

where n_2 =number of piles in the smeared pier ring, and A_R =area of smeared pier ring,

$$A_R = [\pi((1.5D + s)^2 - (0.5D + s)^2)] \quad (3)$$

where s =average centre-to-centre spacing between piles.

In most cases, the effect of the Young's modulus of the equivalent piers will be small, as the length of the equivalent pier in relation to the diameter will be small, typically less than 5 for most tall buildings.

2.1 Limitations of the Adopted Approach

It is important to recognize that, in an axisymmetric analysis, it is implicitly assumed that all of the adjacent piers are loaded simultaneously. In reality, this would be highly unlikely to occur, as surrounding buildings would be constructed at different times and would be likely to have different loadings. Furthermore, the foundation dimensions would be unlikely to be identical.

The effects of having unequal lengths of equivalent piers are examined subsequently in this paper after the evolution of a simplified approach.

2.2 Example Analyzed

As an example, the case described in Table 1 has been analyzed using the program PLAXIS. To avoid undue complication at this stage, both the soil strata and the piers are assumed to behave elastically. Poisson's ratio for both layers is assumed to be 0.3.

It is also assumed that there are 4 identical and equally loaded equivalent piers symmetrically

Table 1 Example analyzed

Quantity	Value
Pile length, L (m)	40
Equivalent pier diameter, D (m)	50
Spacing between central and adjacent smeared pier ring, s (m)	5
Young's modulus of layer 1 (MPa)	20
Young's modulus of layer 2 (MPa)	100
Young's modulus of piles (MPa)	30,000
Average spacing/diameter of piles	3
Applied loading on each pier, p (kPa)	300

surrounding the central pier. Each pier consists of =218 piles 1 m diameter, spaced at about 3 m centre to centre.

From Eq. (1), the equivalent Young's modulus of the central pier is 2616 MPa.

The average loading on the smeared pier ring has to take account of the fact that only the areas occupied by the 4 piers are loaded. Thus, for the smeared pier ring, the average loading, p_1 , is found to be as follows:

$$P_1 = [n \cdot p \cdot \pi D^2 / 4] / A_R \quad (4)$$

where p =average pressure on each foundation, and n =number of piers within the smeared pier ring=4 in this case.

In this case, p_1 is found to be 136 kPa.

The number of piles in the pier ring is $n_2 = 4 \cdot 218 = 872$, and from Eq. 2, the Young's modulus of the smeared pier ring is 1189 MPa.

2.3 Example Results—Equal Pier Lengths

Figure 3 shows the finite element mesh developed for the example analysis. It contains 32,087 nodes and 3957 elements. The lateral extent of the mesh is 250 m and the vertical extent is 200 m. The upper layer is divided into two sections to enable later consideration of piers of unequal length.

The analysis involved simulation of two stages:

1. Loading of the central pier, giving the settlement of the building of interest under its own loading;
2. Subsequent loading of the adjacent smeared pier ring, giving the settlements of the central pier and

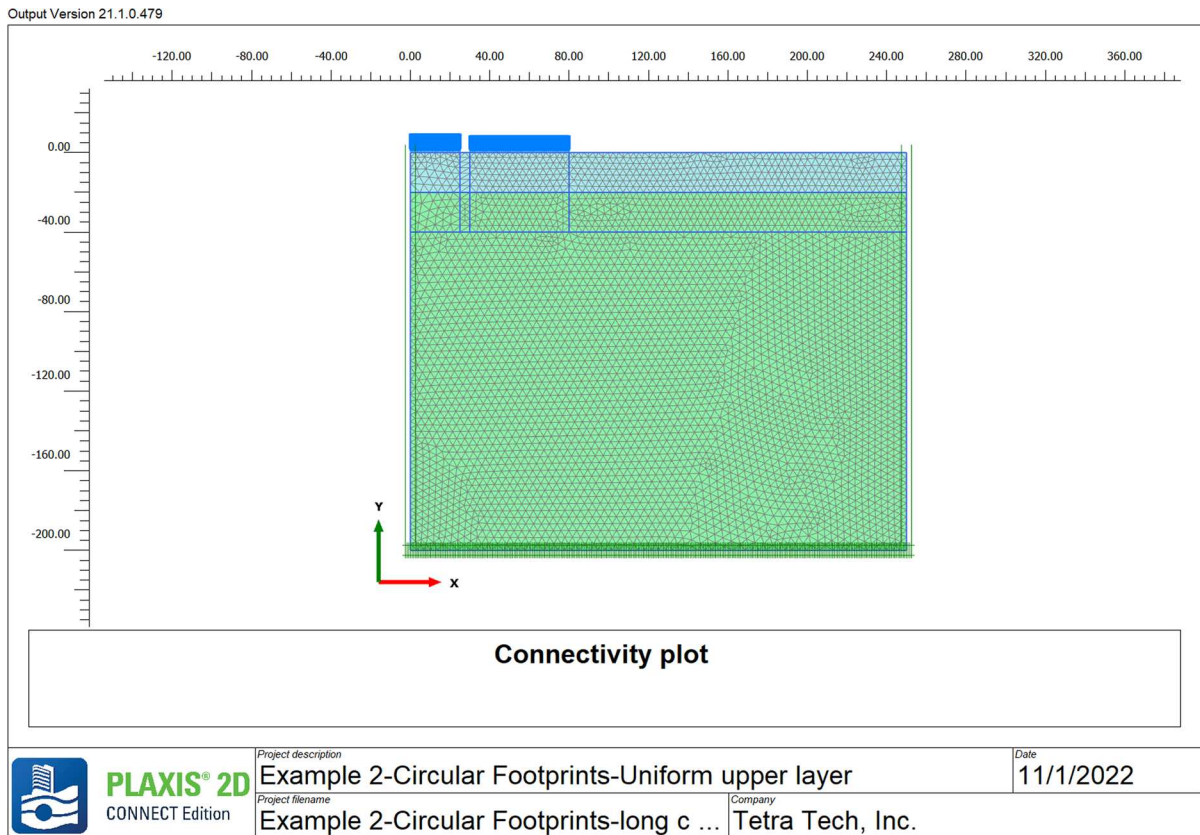


Fig. 3 Finite element mesh

the smeared pier ring at the end of load application.

For the case where the central pier and the adjacent smeared pier ring are of equal length, referred to here as Case 1, Fig. 4 shows the computed settlement profile when the centre pier is loaded, while Fig. 5 shows the profile of additional settlements after the adjacent smeared pier ring is loaded.

From these figures, the following points can be noted:

1. Under its own loading, the central pier settles about 75 mm and the settlement profile away from the pier reduces rapidly with increasing distance.
2. Under the loading of the adjacent smeared pier ring, a very significant increase in settlement of the central pier occurs, with the additional settlement being about 140 mm. Thus, the loading of

the adjacent buildings has resulted in an increase in settlement, in this case, of almost 200%. Thus, the overall final settlement of the central pier is about 215 mm.

3. The settlement of the smeared pile ring is not uniform, but tends to be larger adjacent to the central pier and smaller at the outer edges. This result is surprising, as it might be expected that the presence of the central pier would tend to inhibit the settlement of the smeared pier ring.

2.4 Effect of Unequal Pier Lengths

To obtain some indication of the effects of having interacting equivalent piers of different lengths, two additional analyses have been carried out:

1. Case 2: a shorter central pier (20 m long) adjacent to a longer (40 m) smeared pier ring.

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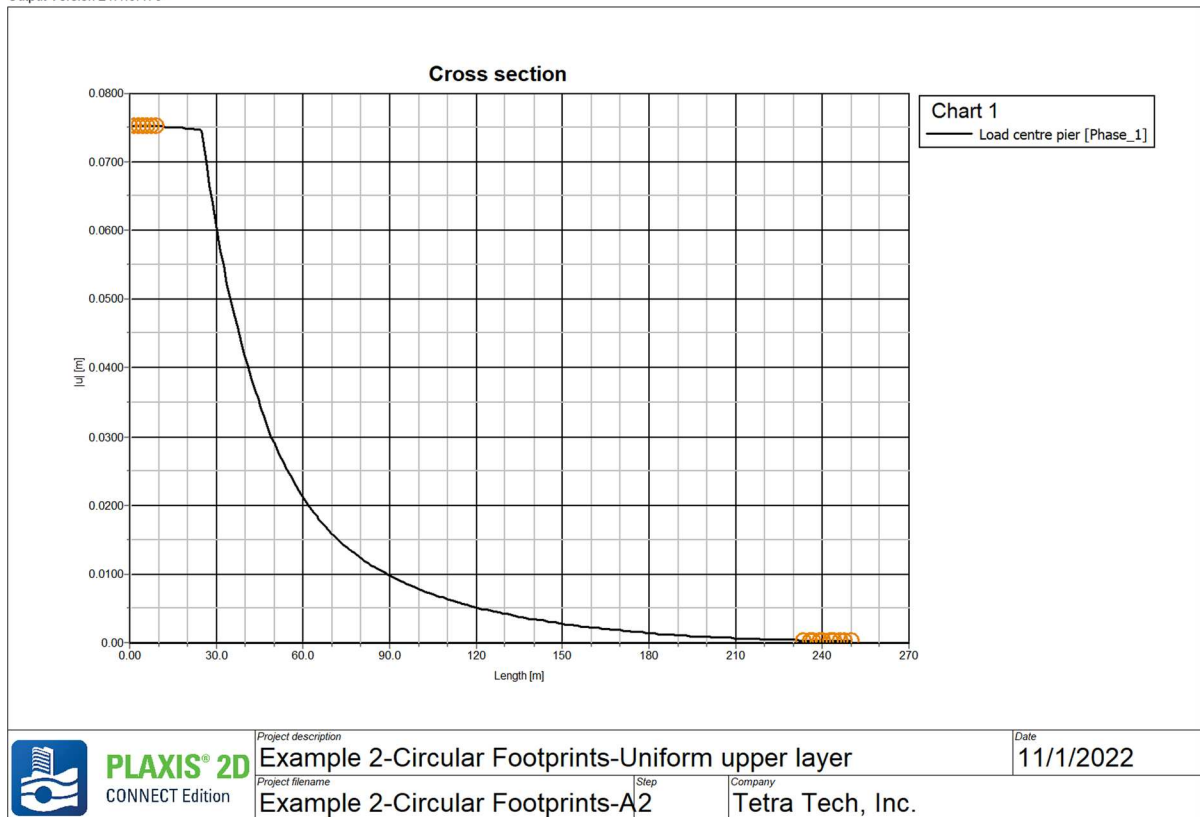


Fig. 4 Case 1: settlement profile when 40 m long centre pier loaded

- Case 3: a longer (40 m) central pier adjacent to a shorter (20 m) smeared piled ring.

In each case, the upper layer is 40 m deep. Thus, Case 2 represents a central foundation that may be shorter than it should be and surrounded by deeper foundations, while Case 3 represents a deeper foundation system surrounded by a series of less deep foundations. All piers are assumed to be loaded equally with an average vertical pressure of 300 kPa.

The computed settlement profile for the central pier in Case 2 is shown in Fig. 6, while the additional settlements due to loading of the adjacent smeared pier ring are shown in Fig. 7. The corresponding profiles for Case 3 are shown in Fig. 3 (the centre pier is the same as for the previous case) and in Fig. 8 for the effect of the loading of the adjacent shorter smeared pier ring.

The preceding figures suggest the following characteristics of behaviour:

- The least total settlement occurs when the central and smeared outer piers are the same length (Case 1).
- When the central pier is shorter (Case 2), its settlement (173 mm) is increased considerably as compared with the longer case (75 mm).
- When the central pier is shorter, the additional settlements due to the longer smeared pier ring are slightly larger than for the case of all piers being of equal length.
- The additional settlements due to the surrounding piers are greater when the smeared pier ring is shorter than the central pier (Case 3). In this case, the additional settlements are increased substantially, both beneath the central pier and beneath the smeared pier ring. The computed additional settlement beneath the central pier is 131 mm, as compared with 75 mm when the smeared pier ring is longer. In addition, the settlement differ-

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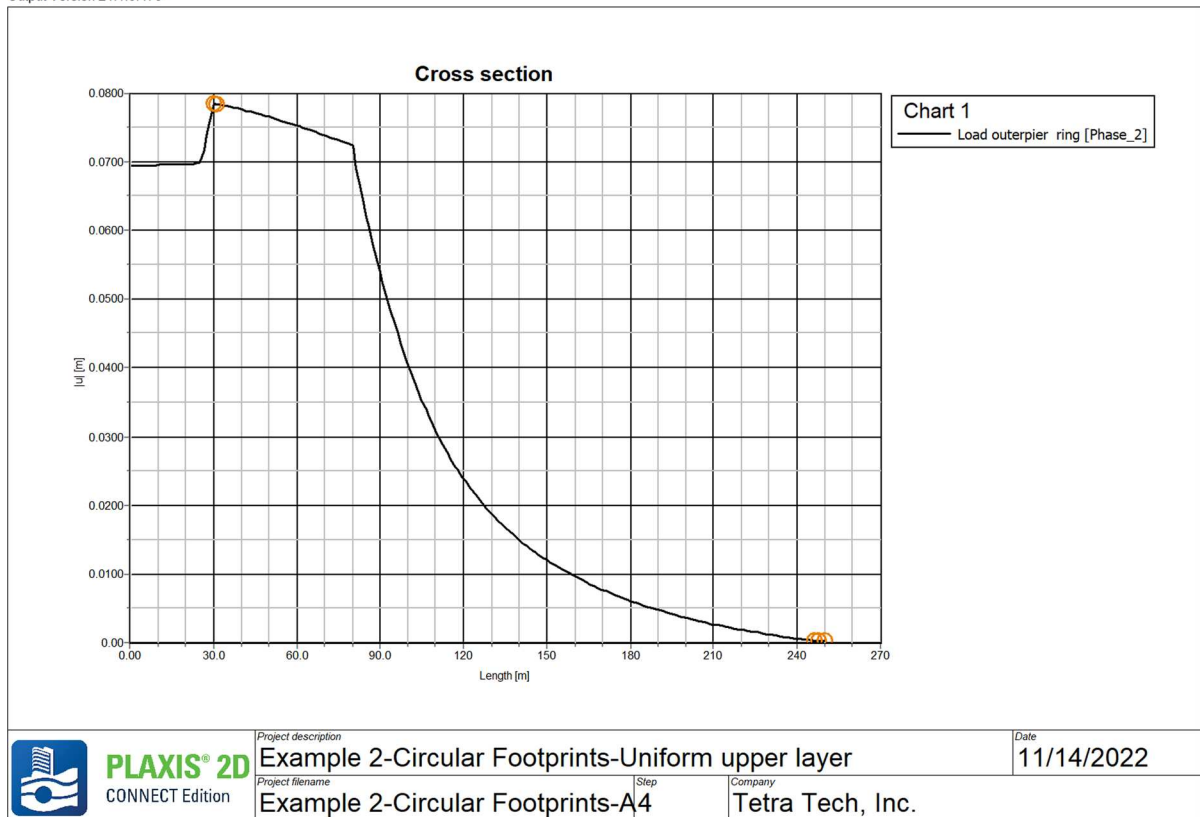


Fig. 5 Case 1: profile of additional settlements after 40 m long outer smeared pier ring loaded

ence across the smeared pier ring is significantly greater than in the other two.

5. The latter finding can be of practical importance as it implies that, even though a foundation may be relatively deep, if shallower foundations are constructed and loaded around it, the central pier may experience a significant increase in settlement. In other words, in this case at least, it appears that the stiffness of the surrounding piers tends to have the main influence on the additional settlements of the central pier.

Table 2 summarizes the computed settlements for each of the three cases.

3 Development of a Simplified Analysis Approach

While the axisymmetric finite element analyses outlined above can provide useful indications on the

consequences of multiple foundation interaction, they have significant limitations in terms of:

1. Not being able to simulate sequential loading of surrounding foundations.
2. Not being able to handle non-symmetrical arrangements of foundations;
3. Requiring all surrounding foundations to be identical, even though they can be different to the central foundation being considered.
4. Not being able to simulate the differential settlements at various points across the whole foundation footprint.

Consequently, it is desirable to seek an alternative approach that is more flexible and that can be calibrated against the axisymmetric analyses set out above. In addition, it would be desirable that the method should be implemented without the use of complex software.

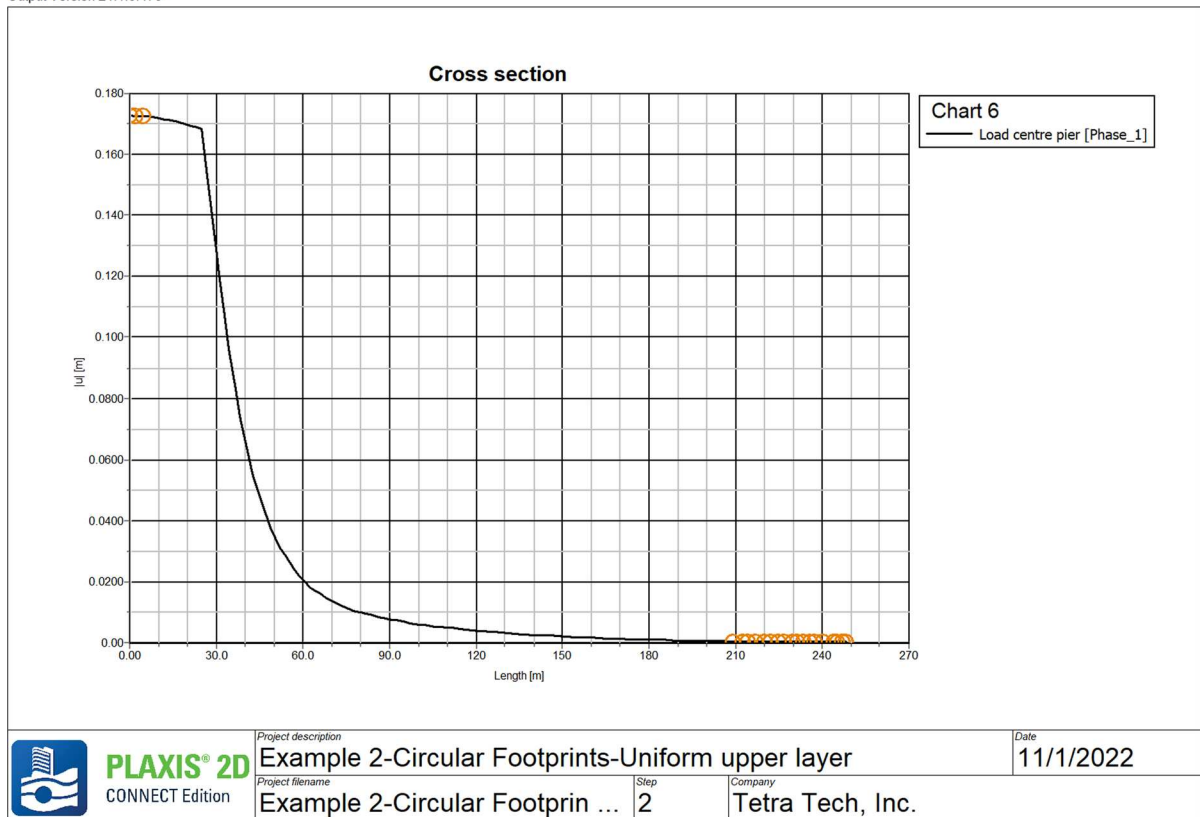


Fig. 6 Case 2: settlement profile when shorter centre pier loaded

To this end, an attempt has been made to develop a simpler method involving the use of interaction factors between foundations, an approach that parallels the interaction factor approach that is frequently used in the analysis of pile groups. In the proposed simplified analysis, the following procedure is followed:

1. The foundation system of each tower is simplified and represented as an equivalent pier.
2. The interaction between pairs of piers is considered to estimate the settlement of a pier due to loading on adjacent piers.
3. Superposition is applied in an approximate manner to consider the settlement distribution within a multiple high-rise development area.

Each of the above steps is described in more detail below.

3.1 Representation of Pile Group as an Equivalent Pier

Ideally, an equivalent pier representing a pile group should have a similar ultimate capacity and stiffness to that of the group. As discussed by Poulos (1994), in utilizing the equivalent pier approach, the following points should be noted:

1. Ideally, the diameter of the equivalent pier, D , should be such that it has an equal surface area (shaft and base) to the enclosed “block” of piles and soil. For a block of square plan of dimensions $B \times B$, D will be between $1.13B$ (for equal base area) and $1.27B$ (for equal shaft perimeter). From a practical viewpoint, it may be adequate to adopt an average $D = 1.2B$ in this case.
2. The equivalent Young’s modulus of the pier is taken as the area-weighted average value of the

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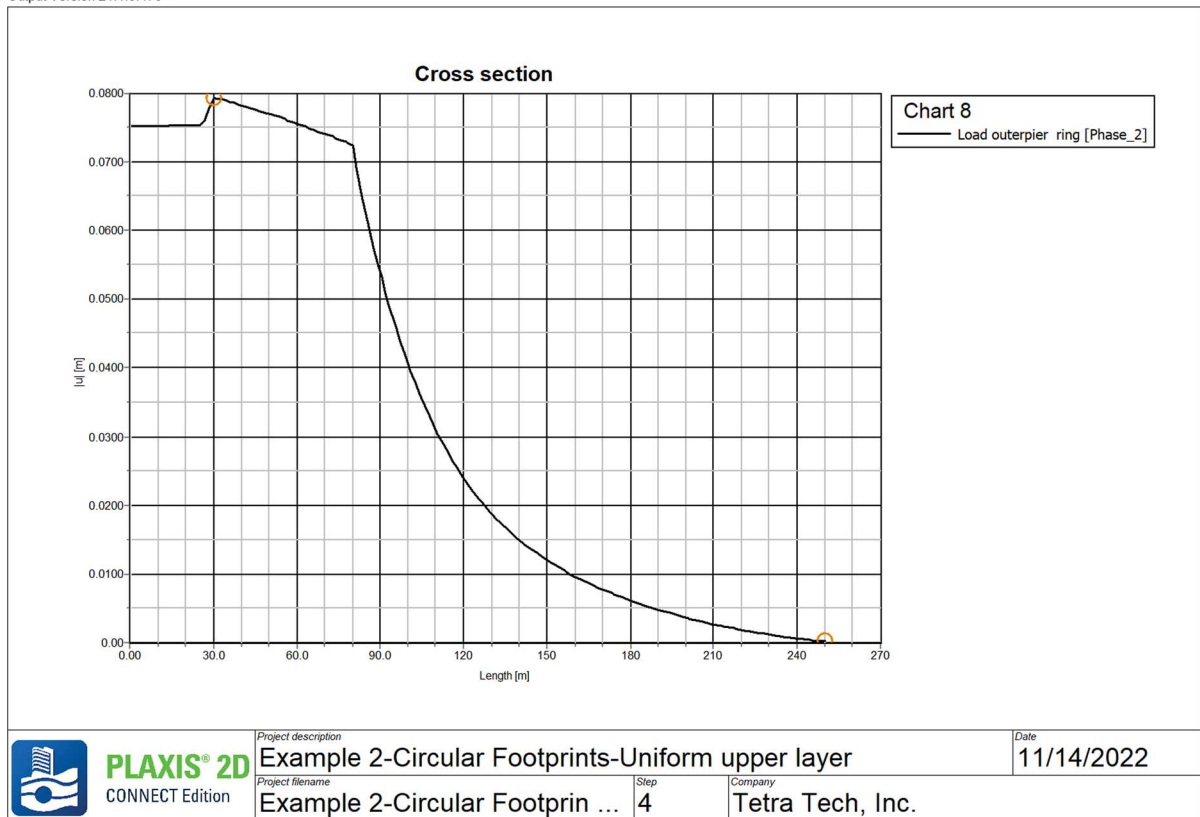


Fig. 7 Case 2: profile of additional settlements after longer outer smeared pier ring loaded

pile—soil block. If the stiffness of the soil is disregarded, and the average centre to centre spacing of the piles is s , the equivalent pier modulus, E_{pe} , is approximated as:

$$E_{pe} \approx E_p \cdot (d/s)^2 \cdot \pi/4 \quad (5)$$

where E_p = Young's modulus of the piles and d = pile diameter.

In most cases, the equivalent pier is likely to be relatively short, so that the pier is relatively rigid and the effect of E_{pe} is minor.

3. In selecting the Young's modulus of the bearing stratum, considerations needs to be given to the effects of pile installation. An average value (weighted with respect to the relative depth below the pier base) should be used.
4. For a non-linear analysis, equivalent shaft and base resistances for the pier should be computed

from the estimated ultimate shaft and base resistances of the pile group.

The axial stiffness of the equivalent pier can be readily computed from a numerical analysis or from elastic-based solutions such as those presented by Poulos (1994). These latter solutions will be reproduced later in the paper.

3.2 Interaction between Identical Piers

The concept of settlement interaction factors between two piles was introduced by Poulos (1968). Using this approach, the additional settlement, $DS_{i,j}$ at an existing pier i due to an identical newly-constructed pier j , can be expressed as follows:

$$DS_{i,j} = P_j \cdot \alpha_{ij} / K_j \quad (6)$$

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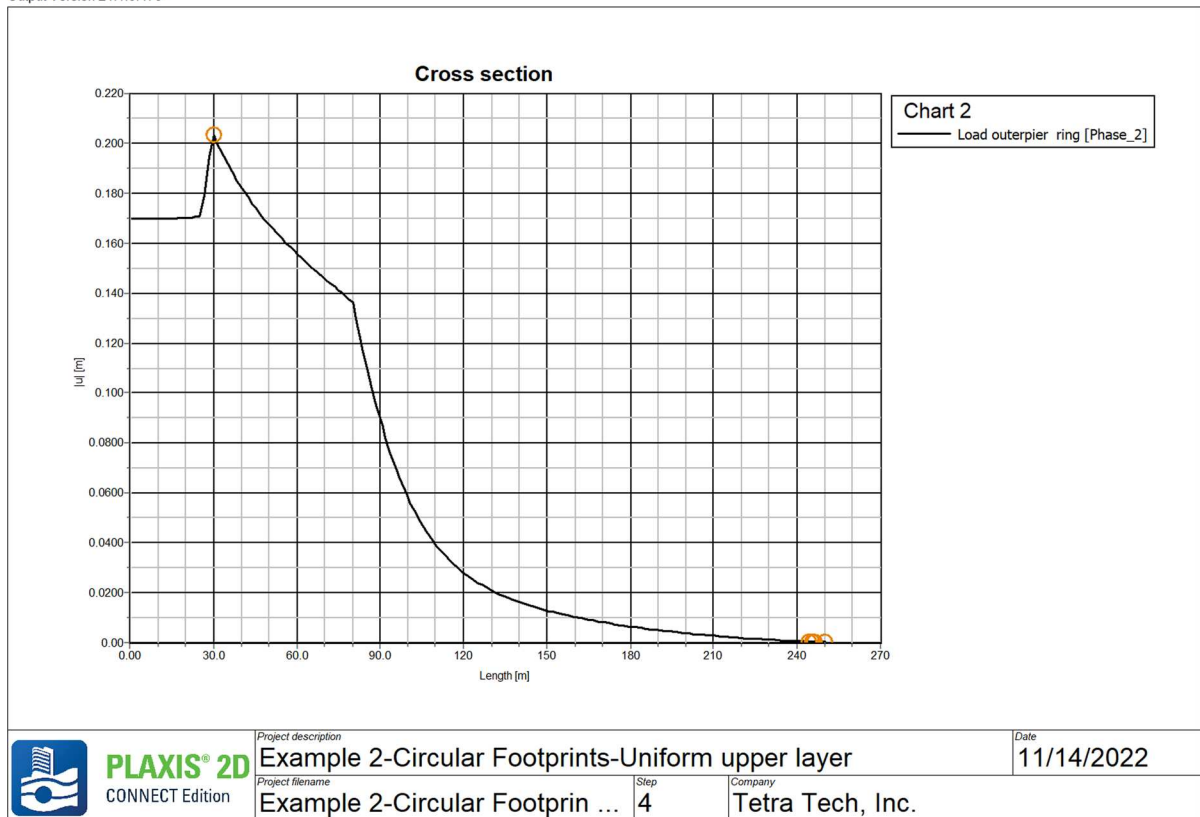


Fig. 8 Case 3: profile of additional settlements after shorter outer smeared pier ring loaded

Table 2 Summary of computed settlements from PLAXIS analyses (all piers loaded equally)

Case	Computed settlement mm				
	Central pier			Inner edge of smeared pier ring	Outer edge of smeared pier ring
	Settlement when centre pier loaded	Additional settlement when smeared ring loaded	Total settlement	Settlement when smeared ring loaded	Settlement when smeared ring loaded
Case 1: all piers of equal length	75	69	144	78	72
Case 2: centre pier shorter than smeared ring	173	75	248	79	72
Case 3: centre pier longer than smeared ring	75	131	206	202	132

where P_j = load on pier j

α_{ij} = interaction factor for spacing between centre of pier j and a point A on pier i .

K_j = stiffness of pier j .

The effects of diffraction described by Mylonakis and Gazetas (1998) were not considered because of the relatively short length of the equivalent piers.

As discussed below, such effects did not appear to be significant.

3.3 Superposition of Settlement Increments

If all the equivalent piers are identical, then the overall settlement of pier i , S_i , after the construction of a number (n) of adjacent piers is the summation of the settlement of Pier i under its own load, S_0 , plus the additional settlements due to each of the adjacent piers, i.e.:

$$S_i = S_0 + \sum P_j \cdot \alpha_{ij} / K_j \quad (7)$$

where S_0 = settlement of pier i under its own load

$$= P_j / K_j \quad (7a)$$

and P_j = load on Pier j and K_j = stiffness of pier j .

3.4 Estimation of Interaction Factors

The interaction factor α can be computed via a boundary element analysis similar to that employed by Poulos (1968). Alternatively, it may also be estimated from an axisymmetric finite element analysis finite element analysis such as PLAXIS, using the following approximation:

$$\alpha = \Delta S / S_0 \quad (8)$$

where ΔS = soil settlement at a distance r from the loaded pier, at mid-depth of the pier, and S_0 = settlement of the pier under its own load.

For the case of piers of identical dimensions considered above (length = 40 m, diameter = 50 m), both approaches give very similar relationships between

interaction factor α and the distance, r , from the pier, as shown in Fig. 9, thus indicating that the effects of diffraction are not significant. The curve labelled as “CLAP” has been obtained from a pile group analysis program based on DEFPIG (Poulos 1990), while the curve labelled “PLAXIS” has been obtained from the computed settlement profile shown in Fig. 3.

The following approximate expression for the interaction curves in this case can be derived from curve fitting:

$$\alpha \approx 1.15 \cdot \exp(-1.25r/D) \quad (9)$$

For the shorter 20 m long piers, the computed interaction factors from the PLAXIS analysis are shown in Fig. 10.

The corresponding approximate expression for the interaction curves in this case from curve fitting is as follows:

$$\alpha \approx 3.1 \cdot \exp(-2.5r/D) \quad (9a)$$

4 Assessment of Superposition Approximation

4.1 Identical Piers

To assess the accuracy of the approximate superposition approach described above, a finite element analysis has been carried out of a circular pier surrounded by 4 identical and symmetrically circular piers. The additional settlement of the central pier after all piers have been loaded has been obtained from this analysis and compared with that computed from the superposition approach. Figure 11 shows the case analyzed.

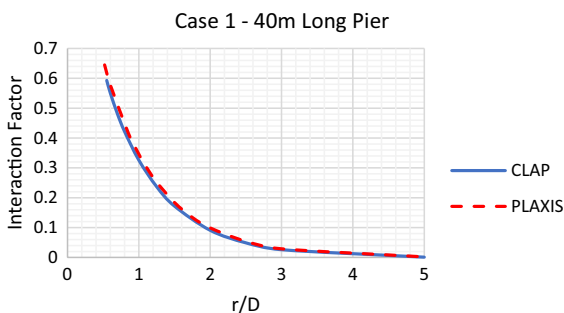


Fig. 9 Comparison of interaction factors via CLAP and PLAXIS for Case 1; 40 m long Piers

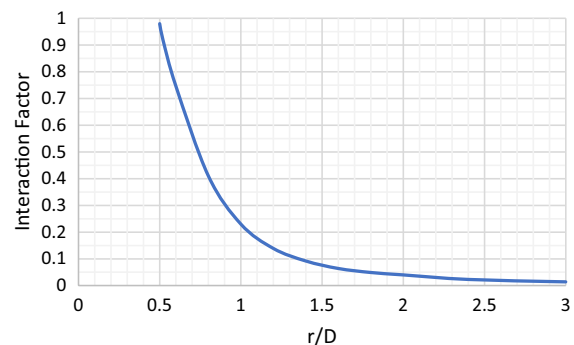


Fig. 10 interaction factors for 20 m long Piers

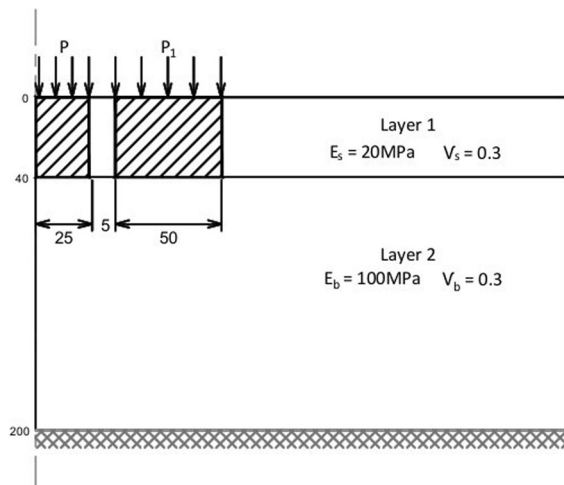


Fig. 11 Case examined (axi-symmetric)

Table 3 Comparison of computed settlements for identical piers

Analysis used	Computed settlement mm
PLAXIS axi-symmetric	69
Superposition approach	88

In the finite element analysis, the piers surrounding the central pier have been represented by a “smeared” circular pier ring. The equivalent piers representing the pile groups are all 50 m in diameter and 40 m deep. The distance between the central pier and the surrounding ring of piers is 5 m and the average applied pressure on each pier is $p = 300$ kPa (equivalent to about a 30-storey building). The axial stiffness of the pier is found to be 7820 MN/m.

In the finite element analysis, the average pressure on the surrounding ring, p_1 , is obtained by dividing the total load on the 4 outer piers by the area of the ring, and is found to be 136 kPa.

Table 4 Summary of some possible assumptions for pile stiffness and interaction factors

Option no	Stiffness of interacting piers used	Interaction factors used
1	Influencing piers	Influencing piers
2	Influencing piers	Average for influencing & influenced pier
3	Influenced pier	Influencing piers
4	Influenced pier	Average for influencing & influenced pier
5	Mean of influenced and influencing piers	Average for influencing & influenced pier

As shown in Table 3 for Case 1, the computed additional settlement of the central pier after the outer smeared pier ring is loaded is 69 mm. In using the superposition approach (Eq. 9) and the interaction curves in Fig. 9, to allow for the stiffness of the pier, an average of the central and edge settlements has been used. The computed additional settlement of the central pier is then found to be 88 mm. Thus, in this case, the interaction factor approach is conservative and tends to over-estimate the additional settlements due to the surrounding piers.

4.2 Non-Identical Piers

The two simplified cases (Cases 2 and 3) discussed in relation to Table 2 have been considered for this evaluation. When applying the superposition approach to consider the interaction among non-identical piers, there are a number of possible assumptions that could be made in relation to the stiffness of the influencing piles and the interaction factors, and some of these are summarized in Table 4.

For each of the options listed in Table 4, the consequent computed additional settlements using the superposition approach are shown in Table 5. Also shown, for comparison, are the values from the PLAXIS analyses (shown in bold) from Table 2.

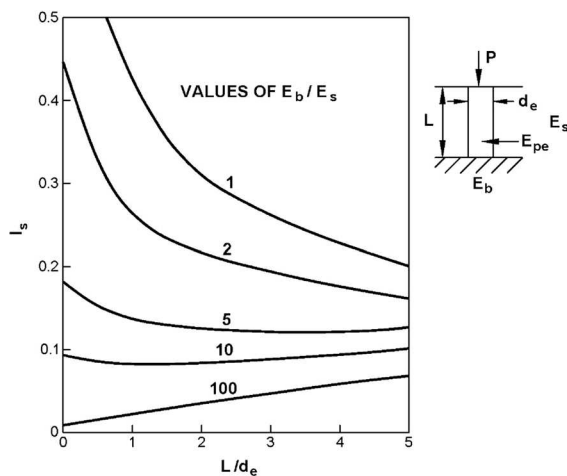
From the comparisons in Table 5, it is concluded that:

1. There is a tendency for the interaction factor approach to be conservative, except for Option 2 of Case 3;
2. For piers of dissimilar length, the influencing piers have the dominant effect;
3. The best agreement appears to be achieved when the interaction analysis uses the stiffness of the influencing piers, and the average interaction factors for the influencing and influenced piers.

Table 5 Computed additional settlements due to loading of smeared pier ring

Option no	Computed additional settlement of centre pier (mm)	
	Case 2: centre pier shorter than outer smeared ring	Case 3: center pier longer than outer smeared ring
1	88	153
2	77	177
3	153	88
4	177	77
5	107	107
PLAXIS	75	170

The bold figures are to distinguish the values from the PLAXIS analysis from the approximate analysis

**Fig. 12** Factor I_s for single pier stiffness

5 Practical Application of the Approach

To facilitate the application of the proposed approach without complex computer analyses, some solutions for single pier stiffness and interaction factors are presented below.

5.1 Axial Stiffness of a Single Equivalent Pier

In general, the axial stiffness of a single equivalent pier can be computed from a finite element analysis. If the ground profile can be idealized as a two-layer system, then the solutions developed by Poulos (1994) from finite element analyses for the settlement of an axially loaded pier within an elastic layer with Young's modulus E_s and bearing on a stratum with a Young's modulus E_b can be used. The geometry of the system and the resulting curves are shown in Fig. 12.

The average stiffness, K , of a single pier within an elastic layer and bearing on a layer of equal or greater stiffness can be expressed as follows:

$$K = D \cdot E_s / I_s \quad (10)$$

where D = diameter of equivalent pier

E_s = average Young's modulus of soil along the pier.

I_s = factor depending on L/d_e and E_b/E_s and plotted in Fig. 12

E_b = average Young's modulus of bearing stratum within two diameters below the pier base.

L = pier length.

The average settlement, S_1 , of the equivalent pier under its own load can then be calculated as:

$$S_1 = P/K \quad (11)$$

5.2 Pier Interaction Factors

PLAXIS has been used to obtain some generic interaction factors for simple cases involving a pier within an upper layer, having Young's modulus E_s , founded on a lower layer of equal or greater stiffness, with a Young's modulus E_b . Figures 13(a to d) show computed values of the basic interaction factor α versus radial distance from the centre of the pier (r/D), for four values of length to equivalent diameter (L/D) of the pier, and for four values of E_b/E_s .

Check calculations were made with the program RS2, and almost identical results were obtained for the values of α obtained from PLAXIS.

Figures 14(a to d) show corresponding plots of α versus r/D for the four ratios of E_b/E_s .

From Figs. 13 and 14, the following characteristics can be noted:

Fig. 13 Basic interaction factors for two identical equivalent piers. **a** $L/D=2.5$; **b** $L/D=1.5$; **c** $L/D=0.5$; **d** $L/D=0$

- (a) α decreases as r/D decreases, as would be expected.
- (b) α tends to decrease as the ratio E_b/E_s increases, i.e. there is less interaction between piers founded on a stiffer stratum than in a homogeneous soil.
- (c) α tends to increase as L/D increases, i.e. deeper piers experience more interaction than more shallow piers.
- (d) There is very little interaction for distances in excess of $5D$.

To simplify the use of these curves, a base case has been selected, for $L/D=1.5$ and $E_b/E_s=2$, and the relationship between interaction factor (denoted here as α_0) and r/D has been plotted in Fig. 15. Then to allow for different values of L/D , an approximate correction factor F_1 has been derived as the ratio of the interaction factor for L/D to the value for the base case, for a spacing of $r/D=1.5$. A similar correction factor, F_2 , has been derived for the effect of the base modulus ratio E_b/E_s . These correction factors are plotted in Figs. 16 and 17 respectively.

Thus, the interaction factor is then expressed (approximately) as:

$$\alpha = \alpha_0 \cdot F_1 \cdot F_2 \quad (12)$$

By curve fitting of the graphs in these three figures, the following approximate relationships are derived:

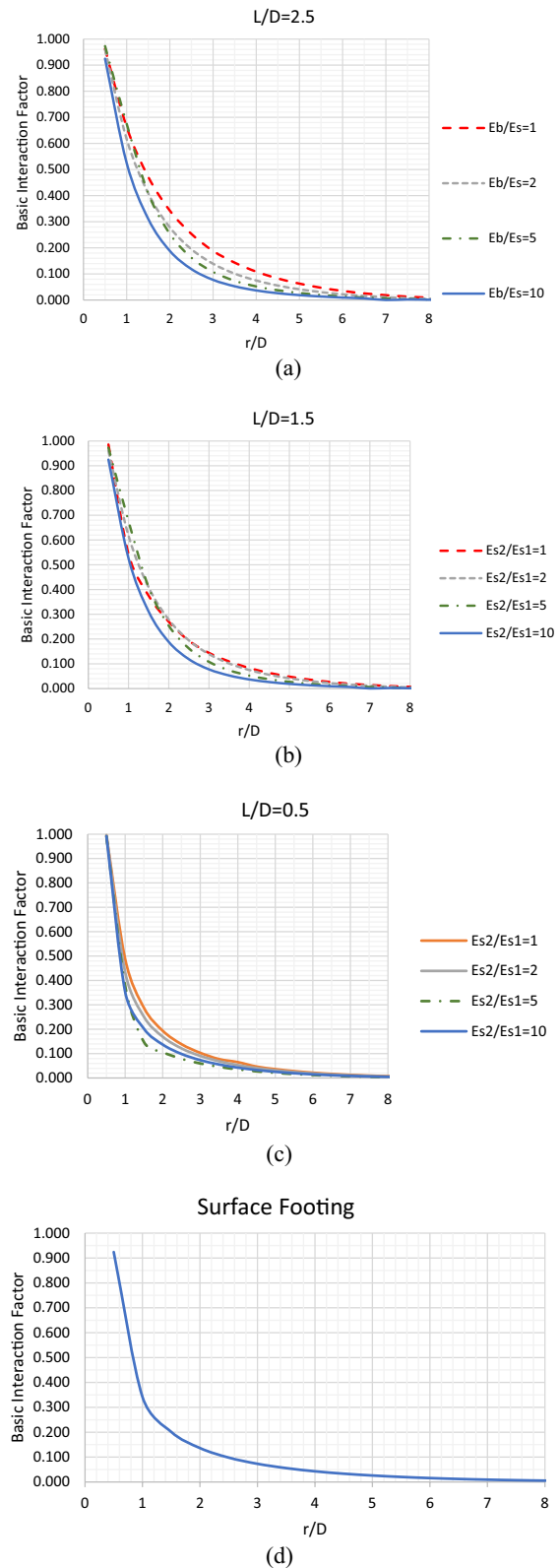
$$\alpha_0 = 1.681 \cdot \exp(-1.222r/D) + 0.038 \quad (13)$$

$$F_1 = 0.835 \cdot \exp(0.237 \cdot L/D) - 0.191 \quad (14)$$

$$F_2 = 2.337 \cdot \exp(-1.055 \cdot E_b/E_s) + 0.718 \quad (15)$$

5.3 Extension to Interaction Among Multiple Dissimilar Equivalent Piers

When the equivalent piers within the group are not all identical, the settlement of a point A on an equivalent Pier i due to load P_j on Equivalent Pier j is again given by Eq. 6. This assumes that the settlement of



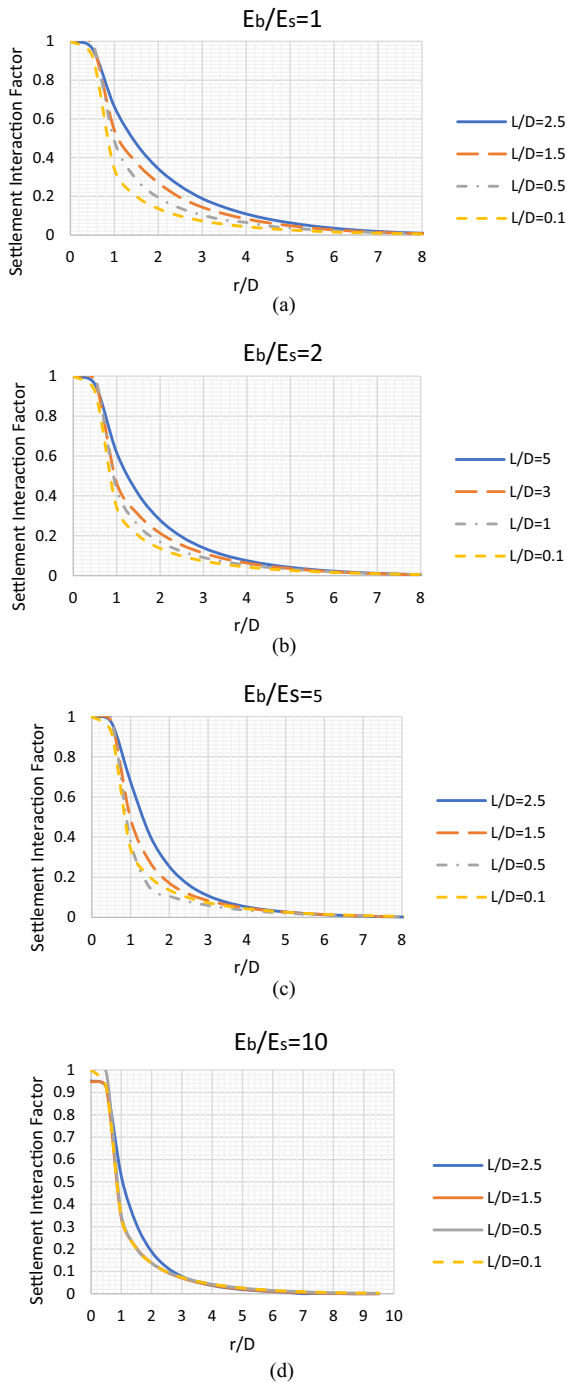


Fig. 14 Basic interaction factors for two identical equivalent piers. **a** $E_b/E_s = 1$; **b** $E_b/E_s = 2$; **c** $E_b/E_s = 5$; **d** $E_b/E_s = 10$

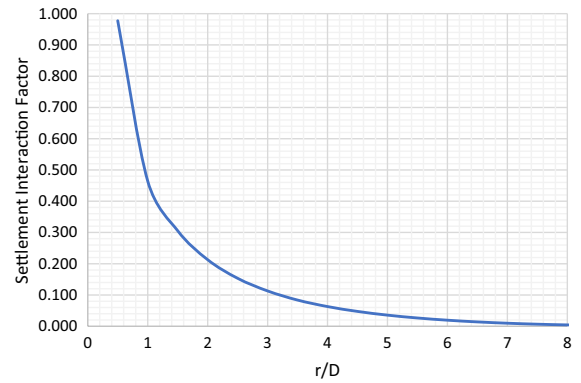


Fig. 15 Basic interaction Factor α_0 for base case ($L/D = 1.5$, $E_b/E_s = 2$)

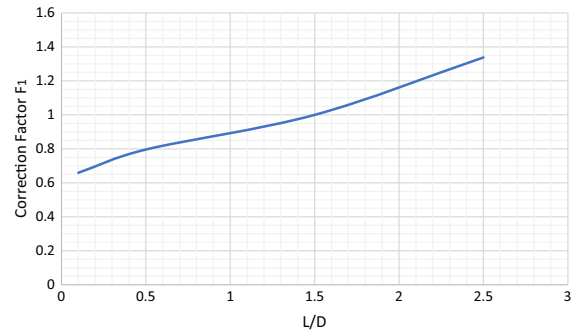


Fig. 16 Correction factor F_1 for L/D

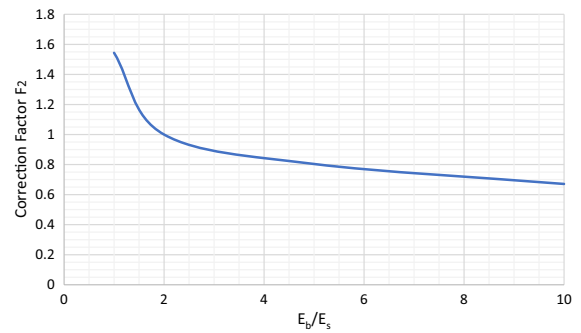


Fig. 17 Correction factor F_2 for base modulus ratio E_b/E_s

Pier i depends on the stiffness of the influencing pier and the average interaction factor for the influencing and influenced piers.

For the entire group, the settlement of point on pier i is then given by Eq. 7. This is of course an approximation, but probably adequate for a first estimate.

6 Example of the Application of the Approach

To illustrate the application of the proposed approach to a somewhat more realistic case, the example illustrated in Fig. 18 has been considered. In this example, a cluster of 7 identical towers are to be constructed, with the central tower (T0) being constructed first, and then the remaining towers (T1 to T6) being constructed in turn. Each tower has an average serviceability loading of 0.3 MPa (equivalent to about a 30-storey building), and occupies a square footprint of 50 m by 50 m. The buildings are in close proximity, being spaced 5 m apart.

The ground conditions consist of a 20 m deep layer of medium clay with an average long-term Young's modulus of 20 MPa, overlying a 180 m deep layer of stiffer residual clay with a long-term Young's modulus of 100 MPa. The foundation system of each tower consists of a series of bored piles with a total length of 40 m, i.e. founded 20 m into the residual clay layer.

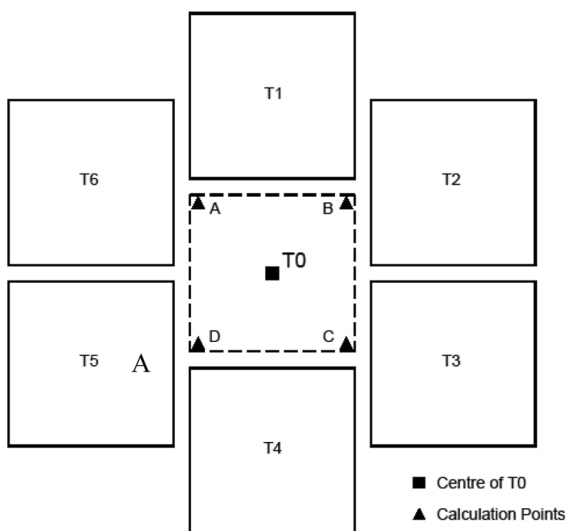


Fig. 18 Configuration of tower cluster

The evolution of settlement will be calculated at the centre and at each of the corners of T0. Because of the simplified nature of the analysis, the settlement of T0 under its own loading is (approximately) uniform, but settlements due to the adjacent towers will be dependent on the distance between the tower centre and the point in question.

The simplification of the problem proceeds as follows:

1. Developing the equivalent pier for each tower foundation: Assuming that the piles occupy the area of the tower footprint, the area is $50 \times 50 = 2500 \text{ m}^2$, so that the equivalent diameter is $(2500 \times 4/\pi)^{0.5} = 56.4 \text{ m}$. The length L is 40 m, so that $L/D = 0.71$.
2. Develop an equivalent 2-layer soil profile:

The average Young's modulus along the length of the piles, E_s , can be approximated as $(20 \times 20 + 20 \times 100)/40 = 60 \text{ MPa}$. Thus, $E_b/E_s = 100/60 = 1.67$. For the above values of L/D and E_b/E_s , from Figure 11, $I_s \approx 0.33$.

3. From the chart in Fig. 12, and Eq. 10: $K = 56.4 \times 60/0.33 = 10,255 \text{ MN/m}$.
4. The average settlement, S_0 , of tower T0 under its own loading can be estimated using Eq. 11: $S_0 = 0.3 \times 50^2/10255 = 0.073 \text{ m} = 73 \text{ mm}$.
5. The influence of the adjacent buildings can now be considered. The settlement calculations points are the centre of T0 and the four corners of that tower. The effect of Tower T1 is considered first, and the calculations are shown in Table 6 where values of the spacing from the centre of T1 to each of the calculation points are shown. The corresponding values of interaction factors, computed from Eqs. 12 to 15, are shown, and then the overall additional settlement at each of these points is computed from Eq. 7.
6. Similar tables can be set up for the effects of the other towers, T2 to T6. These calculations are carried out most effectively via a program such as MATHCAD, and Table 7 summarizes the final outcome of the calculations carried out. Figure 18 summarizes the evolution of settlements at each of the five points considered, with the load-

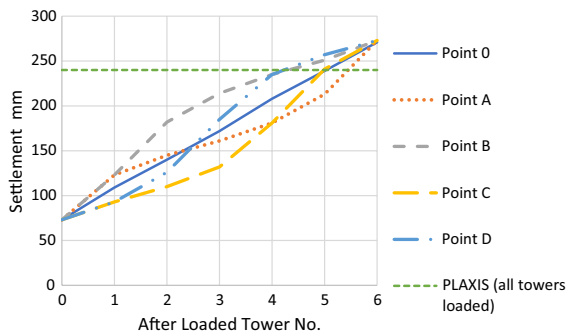


Fig. 19 Evolution of computed settlements at various points below T1

Table 6 Calculations for effect of tower T1 on tower T0

Calculation point	Distance r from centre of T1 (m)	r/D	Interaction factor α_{ij}	Additional settlement due to T2 (mm)
O (centre)	55	0.975	0.549	36
A	39.1	0.692	0.759	50
B	39.1	0.692	0.759	50
C	83.8	1.486	0.312	20
D	83.8	1.486	0.312	20

ing stages representing the loading of Towers T0 to T6 in turn.

- Also shown in Fig. 18 is the results of a PLAXIS axisymmetric analysis for the final stage after all buildings have been loaded. It can be seen that this computed settlement is about 25 mm smaller than that computed via the approximate approach, thus confirming the earlier finding that the approximate approach is likely to provide somewhat conservative results.

Table 7 Calculations for effect of all towers on tower T0

Calculation point	Additional settlement after tower loaded (mm)						
	T0	T1	T2	T3	T4	T5	T6
O (centre)	73	109	140	172	208	239	271
A	73	123	145	161	181	213	273
B	73	123	182	214	235	251	273
C	73	93	110	132	181	241	273
D	73	93	126	185	235	257	273

The following characteristics can be seen from Fig. 19:

- Significant additional settlements are induced below T0 due to loading on the adjacent towers. The final settlement is almost 4 times the settlement of T0 under its own loading.
- The settlements below T0 are uniform at the start and finish of the loading sequence, but not at intermediate stages.
- Significant differential settlements are induced below T0 during the loading process of the adjacent towers. In this example, the largest differential settlement occurs between Points D and A after Tower T3 has been constructed and loaded (82 mm between Points B and C), and is in excess of the initial uniform settlement of T0.
- In the simple case considered, where the tower configuration around the tower of interest is symmetrical, the differential settlements will eventually become zero or near-zero. However, in cases where asymmetric adjacent towers are present, or there is a marked difference between the loadings on the adjacent towers, there will be a residual differential settlement of the original tower.

7 Conclusions

This paper has set out an approximate approach of estimating the interaction among groups of tall tower foundations. This approach involves the simplification of the foundation system of each building to an equivalent circular pier, and extends the interaction factor approach initially developed for pile groups. It should be noted that the present analysis does not account for the effects of the strain level on the ground stiffness, and may therefore tend to over-estimate interaction effects. Nevertheless, it is hoped that the approach at

least provides a rational means of assessing whether multiple building interaction effects are likely to be important or not.

For the relatively short piers likely to be relevant to tall tower foundations, the interaction factors have been computed from axisymmetric analyses using PLAXIS. An axisymmetric PLAXIS analysis has also been used to assess the accuracy of the approximate approach and has revealed that the latter may provide a somewhat conservative assessment of the additional settlements. However, a more satisfactory assessment of the accuracy of the approach must await a comparison with a more rigorous full three-dimensional finite element analysis.

It seems clear that the additional settlements of the original foundation of interest are controlled largely by the following factors:

1. The loading on the adjacent foundations;
2. Their distance from the original foundation;
3. The axial stiffness of the influencing foundation.

Significant differential settlements may be induced below a tower during the loading process of the adjacent towers, depending on the sequence of construction of these towers. Where the subsurface conditions are uniform over the site and surrounding area, and the tower configuration around the tower of interest is symmetrical, and the loadings and foundation systems are identical, the differential settlements will eventually become relatively or near-zero. However, in cases where asymmetric adjacent towers are present, or there is a marked difference between the loadings on the adjacent towers, there will be a residual differential settlement of the original tower. Such a residual settlement may be significant if the surrounding tower foundations are less stiff than the original foundation.

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Data Availability Data related to this research can be made available on written request to the author.

Declarations

Conflict of interest The authors are not aware of any competing interests.

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