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TECHNICAL NOTE

Simplified Settlement Model for a Shallow Foundation on Composite Ground with Rigid Piles

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ABSTRACT

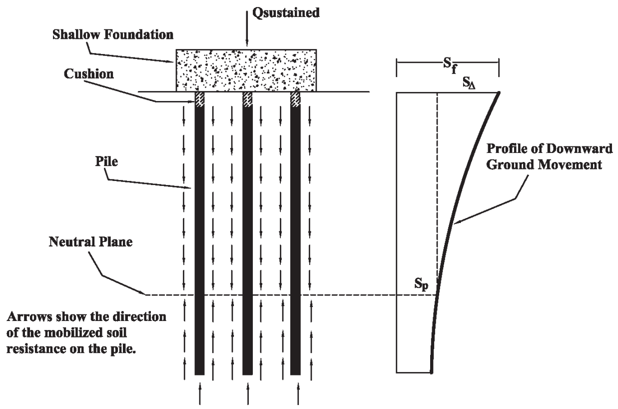
A piled raft refers to a shallow foundation that is structurally connected to the piles, while composite ground refers to a soil-pile matrix where the piles are not structurally connected. The design objectives for both a piled raft and composite ground are (excluding special considerations such as expansive soil): (1) to provide a sufficient ultimate resistance and (2) to distribute the load into the soil-pile matrix so that the settlement experienced by the shallow foundation is within tolerable limits. A simplified model is proposed for a shallow foundation on composite ground where the foundation settlement is estimated as the sum of the downward movement of the piles plus the downward movement of the shallow foundation relative to the pile head. The proposed simplified model is applied using conventional geotechnical analyses for two hypothetical examples of shallow foundations undergoing compression settlement.

INTRODUCTION

As part of the continuing evolution of foundation engineering and construction, the use of piles beneath shallow foundations to partially resist the structural load and/or to reduce the settlement has received increasing interest. The terms piled raft, pile enhanced raft, and settlement reducing piles have been applied when the structural load is shared between a shallow foundation and piles that are structurally connected (Poulos, 2001). The terms composite ground, column-type reinforcement, rigid inclusion, and disconnected pile have been applied to the piles when they are not structurally connected to the overlying shallow foundation (Zheng *et al.*, 2009; Paniagua *et al.*, 2008; Choi *et al.*, 2009; Eslami *et al.*, 2008). The overall design objectives for the piled raft and composite ground are (excluding special considerations such as expansive soil): (1) to provide a sufficient ultimate resistance and (2) to distribute the load into the soil-pile matrix so that the settlement experienced by the structure is within tolerable limits. In an effort to better understand the performance of composite ground, a simplified model for settlement is proposed that considers the interaction between the shallow foundation and the components of the composite ground.

SIMPLIFIED SETTLEMENT MODEL

A two-dimensional illustration of the proposed design model for composite ground is presented in Fig. 1. The figure illustrates that a sustained compressive load ($Q_{sustained}$) on a shallow foundation will exert a stress on the subgrade resulting in compression of the soil and the cushions. The piles are assumed to be rigid. The resulting downward ground movement is greatest immediately below the shallow foundation and decreases with depth. The sustained load will be shared between the soil at the shallow foundation subgrade and the piles as a function of the stiffness of the soil and cushions. At a certain depth, known as the neutral plane, the piles move downward the same magnitude as the adjacent soil (Fellenius, 1989). Negative skin friction develops along the portion of the piles above the neutral plane as the soil tends to move downward relative to the piles (Hanna and Tan, 1973; Cao *et al.*, 2004; Plomteux *et al.*, 2004). Positive side resistance and an upward pile toe reaction develop below the neutral plane. The shallow foundation-composite ground system will be in equilibrium when the negative skin friction plus the portion of the sustained load that is resisted by the piles is balanced by the positive side resistance and upward toe resistance. The settlement of the foundation (S_f) will be equal to the downward movement of piles (S_p) plus the downward movement of the shallow foundation relative to the pile head (S_Δ).



[FIG. 1] Conceptual Model of Composite Ground

APPLICATION OF THE PROPOSED SETTLEMENT MODEL TO DESIGN

The initial step in the application of the proposed settlement model is the selection of a trial value of S_Δ. The portion of $Q_{sustained}$ resisted by the shallow foundation subgrade is then approximated by the stress that corresponds to a settlement of S_Δ. The remaining portion of $Q_{sustained}$ is then expected to be resisted by the piles. The settlement of the piles, S_p, is estimated by the equivalent pier method (NAVFAC, 1986) at the neutral plane according to the unified design of piles. The settlement of the shallow foundation, S_f, is estimated as the sum of S_p and S_Δ. If the calculated value of S_f is either too conservative or not conservative enough, then another value of S_Δ is selected and the calculations are reiterated. This settlement model is a simplification of a complex soil-structure interaction. However, it is expected to provide a reasonable estimate provided that the neutral plane that develops within composite ground is below the zone of influence of the stress induced on the shallow foundation subgrade.

DESIGN CONSIDERATIONS

Simplification of soil-structure interaction. The calculation of S_Δ and S_p is decoupled. This assumption will introduce error where the neutral plane of the piles is within the zone of significant stress influence from the pressure from the shallow foundation. Significant error can be avoided by confirming that the neutral plane of the piles is below the zone of significant stress influence from the shallow foundation or that the neutral plane of the piles is within a stiff stratum.

Stiffness Compatibility. It is essential to the intended performance of composite ground that the value of S_Δ is compatible with the stiffness exhibited by the cushion at the pile head. The concept of controlling the axial load distribution in piles using a compressible insert between the pile cap and pile head is discussed by Poulos (2006) and Fleming *et al.* (2009). For the design of composite ground, ideally there would be a collapsible or highly compressible material at the pile head with a thickness equal to the magnitude of S_Δ so that the resistance of the rigid inclusions is engaged only after the subgrade resistance is fully mobilized. However, it may be more desirable to use a conventional construction material (such as sand) where the thickness and density are selected to achieve the desired compressibility.

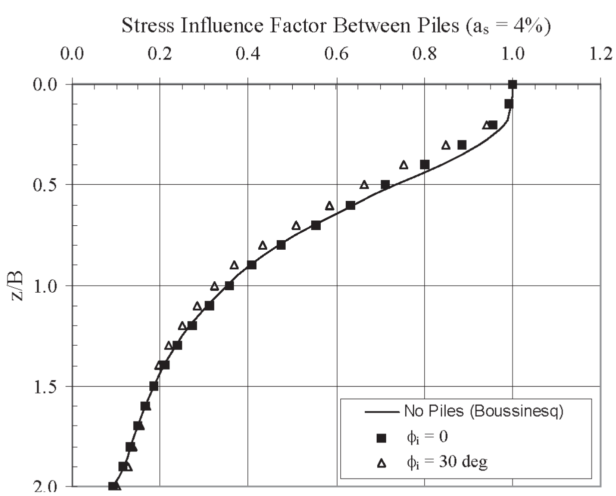
The purpose of the cushion between the shallow foundation subgrade and the pile head is to control the distribution of axial compressive load for the following reasons: (1) to avoid point loads and high stress concentrations on the bottom of the shallow foundation, and (2) so that the pile axial resistance does not have to be exceeded to begin to mobilize the subgrade resistance.

Stress distribution in soil between piles. S_Δ will depend on the stress distribution in the soil between the piles. It is anticipated that the presence of the relatively stiff piles will cause a redistribution of stress from that of an ideal homogeneous linearly elastic material. To examine the degree of stress redistribution in the soil between the piles, a numerical model was prepared in the finite difference software FLAC3D (Itasca Consulting Group, Inc., 2009) to represent a homogeneous linear elastic soil with vertical piles. The material parameters used in the FLAC3D model are summarized in Table 1. The piles in the FLAC3D model had a cross-sectional area of 0.09 m^2 (1 ft^2). Two area replacement ratios (a_s): 4% (pile spacing = 1.52 m or 5 ft) and 9% (pile spacing = 1 m or 3.3 ft) were represented in a square pile layout. These correspond to spacing-to-diameter ratios 4.4 and 2.9, respectively. A stress was numerically applied over a 3.05 m (10 ft) square area on the model boundary to represent the foundation pressure and the self weights of the soil and piles were not considered. The piles were modeled in FLAC3D as structural elements that extended from the surface of the soil model to a depth of 6.1 m (20 ft) or two times the width of the stress area.

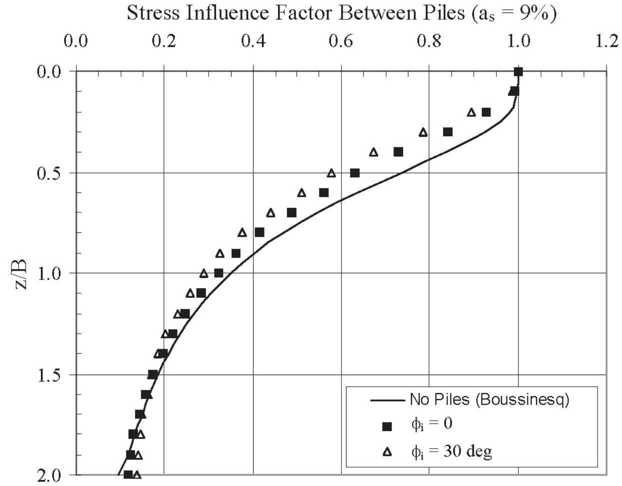
[TABLE 1] FLAC3D Model Parameters

Parameter	Value
Grid Dimensions	30.5 m x 30.5 m x 30.5 m
Soil Elastic Modulus	2.394 x 10^3 kPa (5 x 10^4 psf)
Soil Poisson's Ratio	0.49
Pile Elastic Modulus	2.394 x 10^8 kPa (5 x 10^9 psf)
Pile Poisson's Ratio	0.2
Interface Normal Stiffness	4.788 x 10^7 kPa (1 x 10^9 psf)
Interface Shear Stiffness	4.788 x 10^7 kPa (1 x 10^9 psf)
Interface Friction Angle	0 deg and 30 deg

The distributions in the vertical stress with depth at the midpoint between piles estimated by the FLAC3D analyses for soil-pile interface friction angles (ϕ_i) of zero and 30 degrees are illustrated in Fig. 2 and Fig. 3. The depth (z) is normalized to the width (B) of a square-shaped foundation pressure at the model boundary. The plot in Fig. 2 shows that the vertical stresses are generally marginally reduced at the midpoint between piles for the smaller area replacement ratio of 4%. The plot in Fig. 3 shows that the piles with a higher area replacement ratio result in a slightly greater reduction in soil stresses, except near the toe of the piles where the soil stresses are slightly increased. For both area replacement ratios, the influence of the piles was more pronounced for a ϕ_i of 30 deg than for a ϕ_i of zero (where full slip along the soil-pile interface is represented).



[FIG. 2] Stress Influence Factor Between Piles (a_s = 4%)



[FIG. 3] Stress Influence Factor Between Piles (as = 9%)

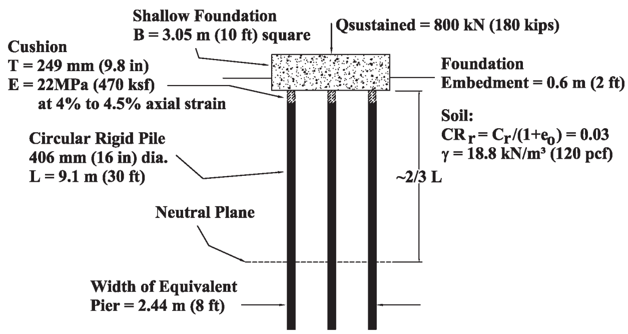
On the basis of the results of the FLAC3D analyses, it may be concluded that the Boussinesq distribution is reasonable and slightly conservative for estimating the stress change in the soil at the midpoint between piles for modest values of a_s and its use may be acceptable for preliminary design of composite ground. The Boussinesq distribution is used to determine the stresses in the soil between the piles for the two hypothetical examples included in this paper.

Separate consideration of sustained and transient loads. Only the sustained load is considered in the proposed settlement model for composite ground. A transient load, if present, is assumed to be resisted by the temporary reversal of the negative skin friction in the upper portion of the piles (Fellenius, 1989) and, to a lesser extent, by the shallow foundation subgrade which is expected to have a stiff response to a transient load. In general, the transient load is not expected to control the design but it should be considered in the evaluation of the foundation stability.

DESIGN EXAMPLES

Square Shallow Foundation on Composite Ground. The proposed settlement model is considered for a hypothetical 800 kN (180 kip) sustained column load to be supported by composite ground at a site where the ground water is very deep and the soil is heavily over-consolidated as illustrated in Fig. 4. For this example, the cushion material exhibits a secant modulus of 22 MPa (470 ksf) at an axial strain of 4% and the soil exhibits a recompression ratio (CR_r) of 0.03 and a unit weight of

18.8 kN/m_3 (120 pcf). The piles, which are considered incompressible, are located 305 mm (1 ft) from the edge of the shallow foundation. For reference, the 3.05 m (10 ft) square shallow foundation embedded 0.6 m (2 ft) in soil without any piles is computed to have a settlement of 46 mm (1.8 in). This magnitude settlement is greater than the typical acceptable maximum settlement of 25.4 mm (1 in).

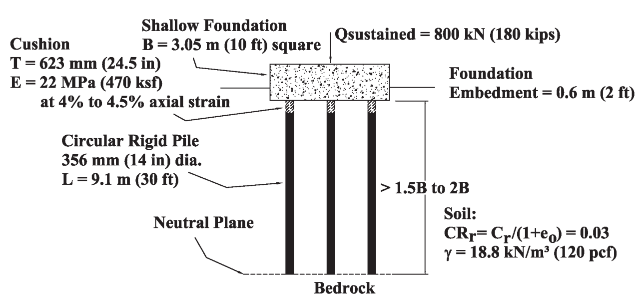


[FIG. 4] Sketch of Example 1

The settlement of the 3 m (10 ft) square shallow foundation on composite ground can be evaluated using the proposed model. For this example, the analysis is described as follows:

1. An average stress on the shallow foundation subgrade of 23.9 kPa (0.5 ksf) results in a settlement of 10.1 mm (0.4 in). The remaining balance of the sustained load of 577.7 kN (130 kips) is resisted by the piles. (Iteration may be necessary to determine the distribution of the foundation that achieves the settlement design criteria.)
2. The pile diameter and spacing and the cushion thickness is selected so that cushion compression is also equal to 10.1 mm (0.4 in) and the total load that is concentrated on the pile heads is 577.7 kN (130 kips). While there are number of acceptable combinations, one practical solution is a pattern of five piles where each pile is designed for a concentrated load of approximately 115.5 kN (26 kips) on each cushion/pile, a pile diameter of 406 mm (16 in) and a cushion thickness of 249 mm (9.8 in). The compression of the cushion is calculated by PL/AE: 115.5 kN x 0.249 m/(π(0.406 m)²/4 x 22,000 kPa) = 10.1 mm. A pile length of 9.1 m (30 ft) is selected so that the neutral plane is below the zone of influence of the stress on the shallow foundation subgrade – typically about 1.5 to 2 times the width of a square shallow foundation.
3. S_p is computed using an equivalent pier analysis where the depth of the equivalent pier is at the neutral plane located at an estimated depth of 6.7 m (22 ft) or about 2/3 of the pile length. The width of the equivalent pier is 2.44 m (8 ft) after considering the distance from the edge of the shallow foundation to the piles, and the stress induced by the equivalent pier at the neutral plane is 97 kPa (2 ksf). The computed S_p is equal to 15.2 mm (0.6 in).
4. The total settlement of the shallow foundation on composite ground, S_f, is considered to be the sum of S_Δ and S_p which is approximately 25.3 mm (slightly less than 1 inch).

Square Shallow Foundation on Composite Ground Overlying Shallow Bedrock. The proposed settlement model is considered for the hypothetical foundation described in the preceding example where the piles extend to shallow bedrock as illustrated in Fig. 5. Again there may be several suitable changes to account for the shallow bedrock, for this example the cushion and pile diameter are adjusted to allow the stress on the shallow foundation subgrade to be increased. A stress of 48 kPa (1 ksf) on the shallow foundation subgrade results in a settlement of 25.4 mm (1 in) assuming that the top of the bedrock is at a depth below the shallow foundation of at least 1.5 to 2 times the width of the shallow foundation. The total load that is concentrated on the pile heads is 446.5 kN (100.4 kips) which is 89.3 kN (20.1 kips) per pile. It can be calculated that a pile diameter of 356 mm (14 in) and a cushion thickness of 623 mm (24.5 in) will provide an S_Δ approximately equal to 25.4 mm (1 in).



[FIG. 5] Sketch of Example 2

CONCLUSIONS

The simplified model considers settlement of a shallow foundation on composite ground with the following components: (1) foundation subgrade soil; (2) piles, and; (3) cushions between the shallow foundation and the piles. One simplification of the proposed model is that the soil compression due to the stress on the shallow foundation subgrade is estimated based on a Boussinesq stress distribution for a homogeneous elastic half-space. In reality, the relative stiff piles may alter the soil stresses to some degree depending on the spacing and diameter of the piles. A second simplification of the proposed model is that the piles are assumed to be incompressible. The examples presented herein are for square shallow foundations; however, the procedure may also be applied to rectangular or strip shallow foundations provided that the neutral plane is below the zone of significant stress influence from the shallow foundation or that the neutral plane of the piles is within a stiff stratum. The proposed simplified model of composite ground should be validated by large-scale plate load testing or by another acceptable method prior to the final design.

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