Uniform Pressure Assumptions and Simplified Design of Footings Supported by Rigid Inclusions

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ABSTRACT

In recent years, the use of rigid inclusions has become common place as an economical soil improvement option that allows shallow foundations to be used in areas where soil characteristics would otherwise require more expensive deep foundations or soil improvement designs. However, many structural engineers designing footings supported by rigid inclusions are not clear as to how to account for the varying soil stiffness parameters under the footing, particularly since the rigid inclusion design is often a delegated design performed after the structural design is complete. More specifically, some structural engineers designing footings are concerned that uniform soil pressure assumptions typically used to design footings may result in overstressing of the reinforced concrete footing due to perceived "point-loading" by the rigid inclusions or moments across the footing due to the varying reaction stiffness. This paper presents the results of a parametric study of Fuller Pile rigid inclusions. Based on parameters that include soil stiffness, rigid inclusion stiffness, pile spacings, footing thickness, and overall material properties, this paper concludes that a uniform soil pressure assumption is appropriate for Fuller Pile rigid inclusion design applications, and load transfer is appropriate. For all cases considered, the presence of Fuller Pile rigid inclusions under typical footings resulted in less than an 8% increase in design moment as compared to traditionally assumed uniform pressure models used in practice.

INTRODUCTION

Foundation design must provide adequate bearing resistance (strength check) and acceptable settlement (service check). Figure 1 presents commonly used foundation options for supporting vertical load P_u from a building or non-building structure. Where soils provide adequate bearing capacity and acceptable settlement behavior, footings (Figure 1a) are the most economical option. Conversely, deep foundations (Figure 1b), where the footing is actually a cap, found the structure in deeper competent geotechnical material to provide bearing and limit settlement. Note that for deep foundations, the pile or shaft must be physically connected to the cap. This type of foundation is always most appropriate where adequate bearing capacity is not available and significant lateral load is also a design consideration.

Where lateral loads can be resisted by sliding friction and passive pressure, but the soil cannot provide the required bearing capacity or settlement performance, rigid inclusions (Figure 1c) are commonly used. In simplified terms, by "sharing" the vertical load between the subgrade and rigid inclusions, this ground improvement alternative is often economical. The rigid inclusions transfer a portion of the load to deeper competent strata. As implied by Figure 1c, rigid inclusions (both size and length) are typically smaller than piles used for pile foundations. Unique to rigid inclusions, they are not connected to the footing but rather a load transfer platform or cushion (e.g., granular soil, stone, aggregate base course or similar layer) is installed between the bottom of the footing and the top of the rigid inclusion element as shown. For Fuller Pile rigid inclusion design, the thickness and material of the added soil/aggregate layer is designed by the geotechnical engineer to ensure that vertical compressive load is appropriately transferred from the footing to the rigid inclusion element, and is often 4 to 6 inches thick.

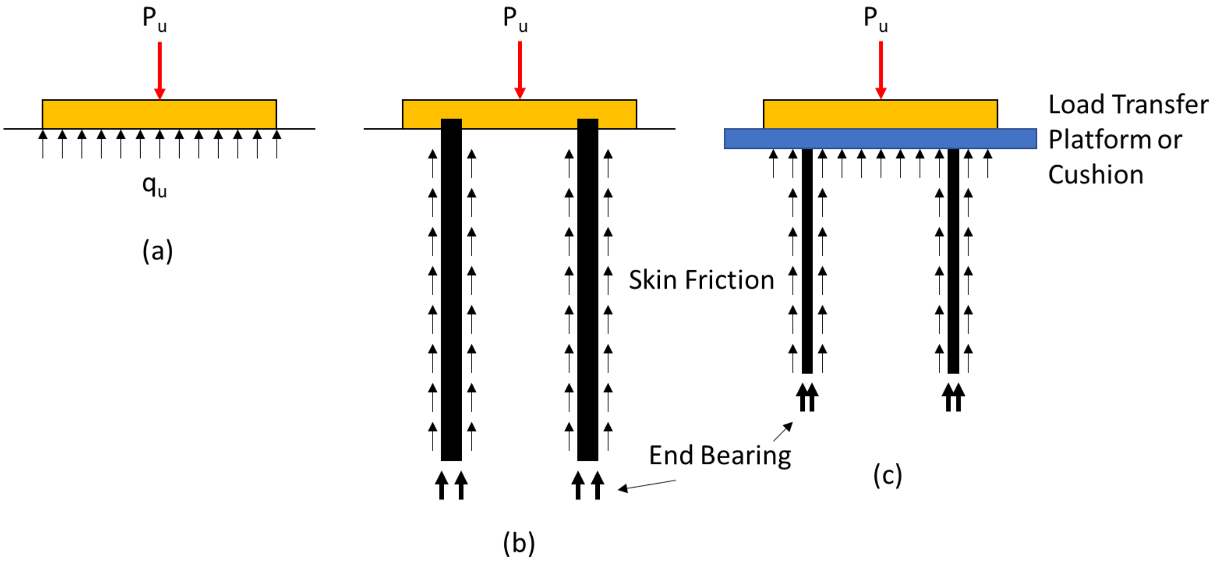

Figure 1. Typical foundation options: (a) shallow foundations (footings), (b) deep foundations (piles), (c) rigid inclusions.

Providing a transfer platform that fully bridges the rigid inclusion elements and develops true uniform bearing pressure at the bottom of footing is expensive and not needed in most applications; full bridging also forces the rigid inclusions to carry more relative load, increasing cost. Alternatively, for column-supported-embankment applications, for example, where the load application is not a rigid footing or slab, full bridging of the load transfer platform is needed to avoid differential deformations (GEC 13 2017, Siegel 2006). This study evaluates the condition of a shallow foundation bearing on a rigid-inclusion-improved soil matrix.

PROCEDURE

To ensure that Fuller Pile rigid inclusion designs allow for a uniform pressure assumption under the supported footing, the authors have performed a parametric study of all currently-used Fuller Pile design configurations. Variables considered in the study include the following:

- Rigid inclusion spacings: 4 ft to 7 ft
- Footing thickness: 12 in. to 36 in.
- Footing material property f'_c: 3,000 psi to 5,000 psi
- Soil reaction stiffness: 125 psi/in. to 250 psi/in.
- Rigid inclusion stiffness: 700 psi/in. to 1,400 psi/in.
- Load transfer platform or cushion: excluded in this evaluation (footing bearing directly on rigid inclusion head)

Results from both field load tests and detailed geotechnical modeling using the finite element software program PLAXIS for all the projects designed to date was reviewed to determine the lower and upper bound soil rigid inclusion stiffnesses presented above, which represents effective element head stiffness inclusive of both structural elastic compression and geotechnical strain. Similarly, the soil reaction stiffness is based on field subgrade modulus load tests. The linear stiffness moduli target the deformation range of interest for rigid inclusion performance, generally 1/4-in. to 3/4-in. vertical deformation. The other variables were selected based on practical applications and author experience.

The finite element program SAP 2000 was then used to model footings of various sizes subject to axial loads applied at the centroid of the footing. Given that the results are linear with respect to axial load, an arbitrary 90 k axial load was used for all models. For comparison purposes, the footings were first modeled only with soil springs under the footing (i.e., no rigid inclusions) so that an original maximum moment at the centroid of the pile cap could be recorded as a baseline value. Next, the footings were modeled with both soil springs and rigid inclusion springs under the footings. The maximum moment at the centroid of the footing was recorded for this case as well. Square footings 6 ft x 6 ft to 12 ft x 12 ft were considered in this study. Rigid inclusion configurations for the different footing sizes were limited by the spacings permitted in the parameter presentation above.

RESULTS

In all cases analyzed as part of this parametric study, it was determined that the presence of Fuller Pile rigid inclusions under footings resulted in a maximum increased design moment in the footing of 8% as compared to the no rigid inclusion case. In most cases, the increase was significantly smaller and the design moment actually decreased where the configuration included a rigid inclusion directly under the supported column. The 8% increase, as expected, was associated with maximum rigid inclusion spacing and no rigid inclusion directly under the supported column. Overall, the results suggest to the authors that a uniform pressure under the footing is an appropriate assumption for typical Fuller Pile rigid inclusion foundations. It should also be noted that even under the conservative assumption of no load transfer platform of cushioning as used in this parametric study, maximum compressive stresses on the bottom face of the footing directly above the rigid inclusion did not exceed 500 psi for any of the cases considered or for any Fuller Pile rigid inclusion applications currently used in practice. As such, no special details are needed beyond typical grout installation inside and around the Fuller Pile rigid inclusion element and two-way (i.e., punching) shear from the rigid inclusion element need not be a design consideration. Where the project structural engineer would like to check two-way shear of the footing around the rigid inclusion, typical installations suggest a maximum factored demand of 25 k acting on an 10 in. diameter surface can be considered, or the project geotechnical engineer can provide a project specific number if desired.

To clearly explain the results of this study, one example configuration is presented here in detail. As shown in Figure 2, a 9 ft x 9 ft footing is to be designed with four rigid inclusions under the footing.

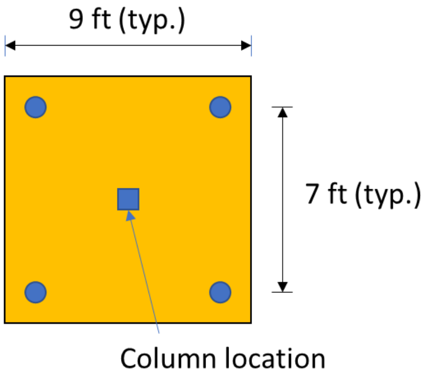

Figure 2. Example footing supported by four Fuller Pile rigid inclusions.

Neglecting the presence of the rigid inclusions, the factored pressure q_u under the 9 ft x 9 ft footing can be calculated for $P_u = 90$ k as follows:

$$q_u = \frac{P_u}{A} = \frac{90}{9(9)} = 1.11 \ \ ksf$$

The maximum one-way moment caused by this pressure can be found as:

$$M_u = 1.11(9)(4.5)(4.5/2) = 101 \ \ k - ft$$

This moment can be expressed on a per ft basis as:

$$M_u = 101/9 = 11.22 \ \ k - ft/ft$$

Figure 3 shows the results of a finite element model for this case. In this model, the soil springs are assumed to have a stiffness of 125 psi/in. The $f'_c = 5{,}000$ psi footing is assumed to be 24 in. thick. Note that although the common assumption of uniform bending moment across the footing width is used extensively for footing design and is allowed by ACI 318, the actual distribution of the bending moment results in a maximum moment of 18.0 k-ft/ft at the centroid of the footing that decreases to around 5.0 k-ft/ft at the edge of the footing. Note that the average value of the moment across the width of the footing would be close to the 11.22 k-ft/ft calculated above as expected and the overall 101 k-ft moment is required by statics which could be shown with a simple section cut in SAP 2000.

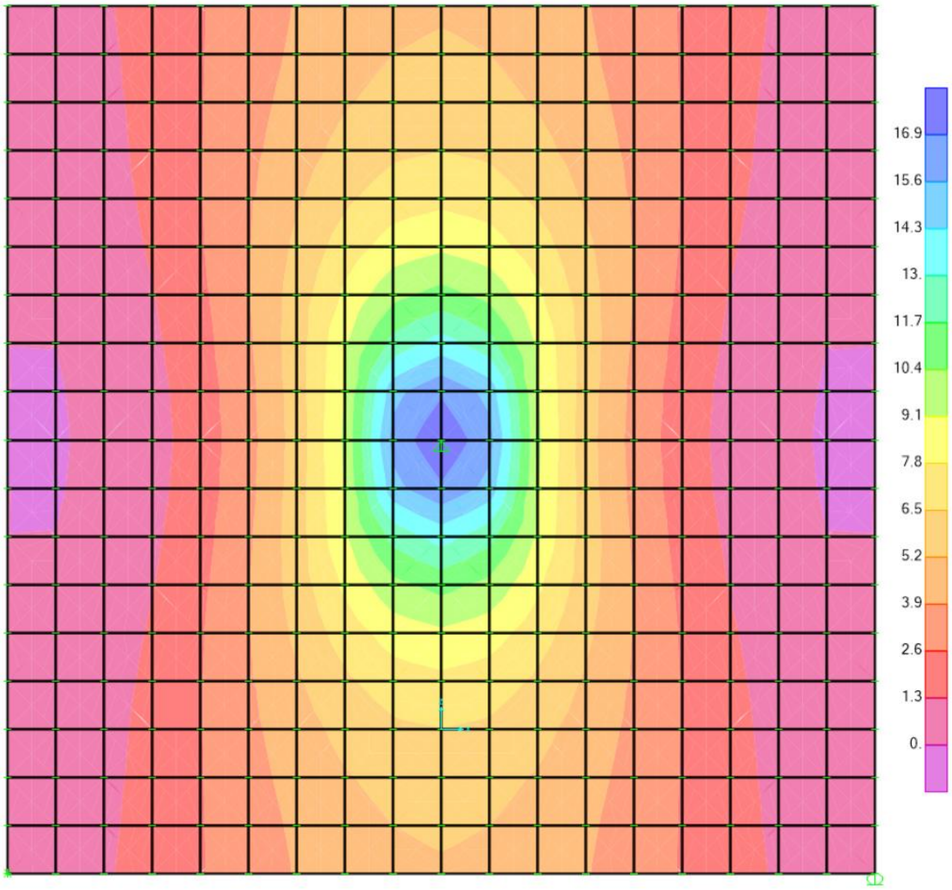

Figure 3. Finite element results for one directional bending moment (k-ft/ft) and no rigid inclusions in the model.

If the rigid inclusions are considered infinitely rigid (i.e., neglecting the stiffness of the soil springs directly under the footing), the factored force in each rigid inclusion R_u under the 9 ft x 9 ft footing can be calculated for P_u = 90 k as follows:

$$R_u = \frac{P_u}{4} = \frac{90}{4} = 22.5 \quad k$$

The maximum moment caused by the point loads from the rigid inclusions acting 3.5 ft perpendicular from the column centroid can be found as:

$$M_u = 2(22.5)(3.5) = 157.5 \quad k - ft$$

This moment can be expressed on a per ft basis as:

$$M_u = 157.5 / 9 = 17.5 \quad k - ft / ft$$

Finally, Figure 4 shows the results of the finite element model for the actual case of the rigid inclusions combined with the soil springs directly under the footing. For this model and for comparison with Figure 3, the soil springs are assumed to have a stiffness of 125 psi/in. (lower bound stiffness) and the rigid inclusions are assumed to have a stiffness of 1,400 psi/in. (upper bound stiffness). The f'_c = 5,000 psi footing is assumed to be 24 in. thick. The distribution of the bending moment results in a maximum moment of 19.2 k-ft/ft at the centroid of the footing that decreases to around 7.0 k-ft/ft at the edge of the footing. The presence of rigid inclusion increases the maximum moment from the soil springs only case (Figure 3) by 6.7%.

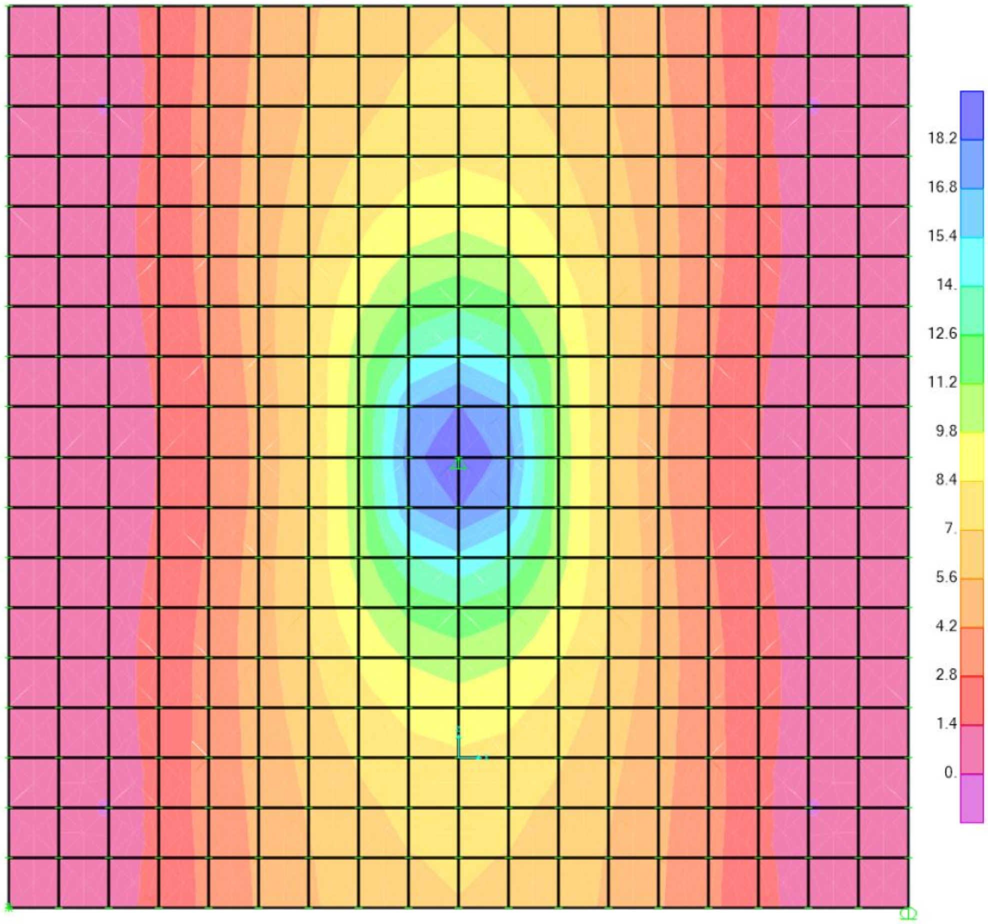

Figure 4. Finite element results for one directional bending moment (k-ft/ft) and rigid inclusions as shown in Figure 2.

CONCLUSIONS

This paper presents the results of a parametric study of Fuller Pile rigid inclusions. The goal of the research was to determine if standard practice assumptions of uniform pressure under footings is appropriate for cases where Fuller Pile rigid inclusions are used as a soil improvement method. Based on parameters that include soil stiffness, rigid inclusion stiffness, pile spacings, footing thickness, and overall material properties, this paper concludes that a uniform soil pressure assumption is appropriate for Fuller Pile rigid inclusion design applications. For all cases considered, the presence of Fuller Pile rigid inclusions under footing resulted in less than an 8% increase in design moment as compared to the traditionally assumed uniform pressure model used in practice. Where Fuller Pile rigid inclusions are being used for site improvement, permissible bearing pressures under shallow foundation elements, that account for the effects of the site improvement, are determined by the project geotechnical engineer in accordance with ACI 318 Section 13.3.1.1 and Chapter 18 of the 2021 International Building Code.

ACKNOWLEDGEMENT AND LIMITATIONS

This research was funded by Fuller Pile, LLC. Although the theory and design practice discussion associated with the material presented in this paper may be appropriate for application and design of other rigid inclusion products, the conclusions and recommendations are intended for use specifically with Fuller Pile rigid inclusion designs.

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