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Parameters controlling the capacity of axially loaded drilled shaft foundations in sand, gravel, and cobbles

Paramètres contrôlant la capacité des fondations par pieux forés à chargement axial dans le sable, les graviers, ou les galets

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ABSTRACT

Drilled shafts have become the preferred deep foundation element in many arid environments where coarse material is prevalent, including the southwest USA, because soil conditions are usually unfavorable to driven piles, scour depths on the ephemeral river channels are quite large, and there is increased confidence in the bearing layer afforded by the drilled shaft construction process. Finite element analyses were performed on two case history studies of axially loaded concrete drilled shafts founded in sand, gravel, and cobbles soils (SGC). A parametric study was conducted to determine the most important soil parameters controlling the axial capacity of drilled shafts. The soil parameters used in this study are: soil angle of internal friction, soil dilation, soil modulus, initial coefficient of lateral earth pressure at rest, and angle of internal friction between soil and shaft. The axial bearing capacity and skin friction load were determined in each case. It was found that the soil angle of internal friction, soil dilation, coefficient of friction between soil and shaft, and soil modulus, E, are the most important parameters controlling the behavior of axial loaded drilled shaft in SGC soils. The ratio between horizontal stresses and vertical stresses at failure is completely different from the coefficient of lateral earth pressure at rest.

RÉSUMÉ

Les pieux forés sont devenus les éléments de prédilection pour les fondations profondes dans de nombreux environnements arides, où les matériaux grossiers sont majoritaires, comme par exemple dans le Sud-ouest des USA. Les raisons de cette préférence sont les suivantes : ces types de sols sont d'ordinaire défavorable à l'utilisation de pieux foncés, la profondeur meuble dans le lit d'une rivière temporaire est assez importante, et la confiance en la tablette portante augmente, renforcée par le procédé de fabrication des pieux forés. Des analyses par éléments finis ont été menées sur deux études de cas réelles, de pieux forés chargés axialement en béton et établis dans des sols sableux, gravillonneux et caillouteux (SGC). Une étude paramétrique a été menée, afin de déterminer les paramètres des sols les plus importants, pour le contrôle de la capacité axiale des pieux forés. Les paramètres du sols utilisés dans cette étude sont : l'angle des frictions internes du sol, la dilatation du sol, le module du sol, le coefficient initial de pression latérale de la Terre au repos, et l'angle des frictions internes entre le sol et le pieu. La capacité de portance axiale et les frictions superficielles ont été déterminées pour chacun des cas. Il est apparu que, l'angle des frictions internes du sol, la dilatation du sol, le coefficient de friction entre le sol et le pieu, et le module du sol, E, sont les paramètres les plus importants pour le contrôle du comportement des pieux forés à chargement axial dans les sols SGC. Le rapport entre la contrainte horizontale et la contrainte verticale à la rupture est totalement différent du coefficient de pression latérale de la Terre au repos.

1 INTRODUCTION

A high percentage of the Western region of the United State of America, USA, is underlain by very coarse granular deposits consisting of mixtures of sand, gravel, and cobbles (SGC soil). This study presents finite element results for two axially loaded concrete drilled shafts founded in SGC soils. The main objective of this study is to determine a set of soil properties that represents the SGC soils in field. To achieve this goal, a parametric study was conducted on different soil parameters; soil angle of internal friction, ϕ, soil dilation angle, ψ, coefficient of friction between soil and shaft, f, initial coefficient of at-rest lateral earth pressure, k, and soil modulus of elasticity, E. Finite element analyses using ABAQUS (1998) have been performed on two case history studies with the goal of matching the load-deflection curves of these two tests using different sets of soil parameters and at the same time studying the effect of these parameters on the axial bearing capacity and skin friction loads of drilled shaft foundations.

2 CHARACTERISTICS OF THE SGC SOILS

SGC soils were usually deposited by high-energy discharges of rivers and other drainages. SGC soils consist mainly of sand, gravel, and cobbles with a small amount of silt and are generally classified as GP in the Unified Soil Classification System (AASHTO 1998). These soils generally contain particles up to about 12 inches and occasionally contain scattered boulders exceeding 24 inches. SGC soil also contains a very high percentage of quartz, chert, and other very hard particles. This is typically reflected by very high wear on drilling tools used in both foundation drilling and exploratory drilling into the deposit. These types of soils are too coarse to enable the evaluation of relative density or compressibility by conventional standard penetration tests or laboratory methods. Their coarse nature also makes it extremely difficult and costly to obtain in-situ densities. The range of gradation of typical SGC samples are shown in Figure 1 (Beckwith and Bedenkop 1973).

3 SOIL DILATION

When shear stress is applied to an element its volume can either decrease or increase. When it is lightly confined and initially dense, it tends to expand and is said to be dilatant. If it is heavily confined and initially loose, then it tends to densify and is said to be contractive. Therefore, whether or not it tends to dilate during shear and by how much depends on how dense the material is initially and how confined it is. In general, the higher the dilation angle ψ the more the soil dilates, and the stiffer it typically is (Manzari and Nour 2000). When a drilled shaft is loaded axially and starts to move downward relative to the soil, a shear surface is established along the surface of the shaft or in the vicinity of the outer surface of the shaft. It is in this region that dilation primarily occurs. The amount of movement required for particles moving in and near the shaft surface to fully develop dilation depends of the effective particle size and roughness of the shaft.

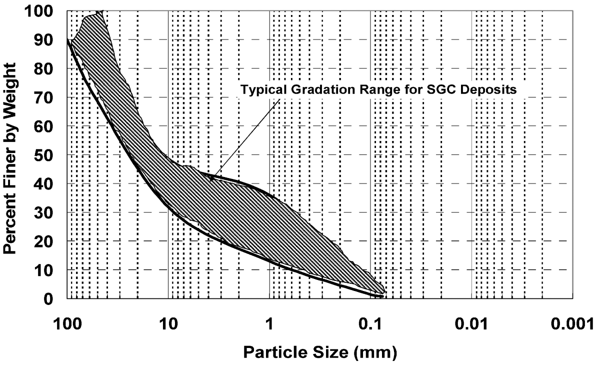

FIGURE 1: Typical grain size distribution of SGC soil, (after Beckwith and Bedenkop 1973)

If a shaft were axially loaded and forced downward 2 inches, then particles around the shaft would be forced to move radially outward a distance up to about 2 inches, due to the dilatory effect, depending on the particle size (Walsh et al. 2002). This outward movement tendency could be accommodated in one of two ways (or a combination of both). First, and perhaps most importantly, outward movement of particle due to dilation is more or less equivalent to cavity expansion and would be accomplished by an increase in radial normal stress as the particles are forced outward. If the material were of very low compressibility and densification could not be accommodated, then the ground surface would heave slightly to accommodate the dilation. In most cases it is expected that dilation is accommodated by both densification and heaving of the ground surface (Walsh et al. 2002).

The amount of dilation and corresponding increase in radial stress is expected to increase with the amount of gravel present in the soil, and the size of the gravel particles. With an increase in radial stress the skin friction capacity of the drilled shaft is expected to increase. As the depth increases, the initial confining pressure due to overburden increases and the outward particle movement is accommodated mostly by local densification around the shaft.

4 FINITE ELEMENT MODEL

Finite element analyses using the program ABAQUS (1998) were performed on a 3-D finite element model with 8-node elements. The boundary conditions include infinite (continuous) elements to reduce the effect of stress concentrations. The mesh shown in Figure 2 represents the results of several mesh refinement runs. In this mesh, the soil and wall were discretized. The model consists of one single shaft. The mesh has 4700 eight-noded hexahedral elements, with 5800 nodes. The load is applied at the top of the shaft. The behavior of the reinforced concrete shaft was modeled as linear elastic. The soil was modeled as an elastic-perfectly-plastic, Drucker-Prager-Type material (Chen and Baladi, 1985), with volumetric dilation. Friction elements with a coefficient of friction, f, were used to represent the interaction between the soil and the shaft.

5 CASE HISTORY STUDIES

Two case history studies were chosen from the literature, one from the phoenix area, Arizona (Beckwith and Bedenkop 1973), and the other one from Utah (Rollins et al. 1997).

5.1 *Case -1*

This test was done in May, 1973 as a part of research project no. HPR-1-10(122), "An Investigation of the Load Carrying Capacity of Drilled Cast-in-Place Concrete Piles Bearing on coarse Granular Soils and Cemented Alluvial Fan Deposits", prepared by George H. Beckwith and Dale V. Bedenkop (1973) for the Arizona Department of Transportation (ADOT). The load tests were devised such that only the bearing capacity of the soil would be analyzed for shafts.

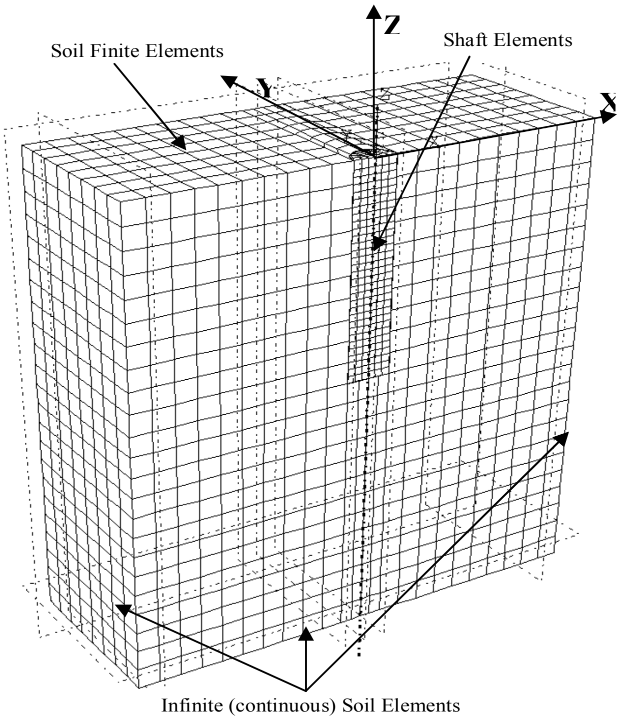

FIGURE 2: Half symmetry of shaft and soil discretization mesh

5.1.1 *Soil Profile*

The soil profile consists of roughly 2.1 meters of uncemented or weakly cemented silty clays and sandy clays underlain by moderate to strong lime cemented clayey sands and sandy clays to a depth of 3.3 to 4.1 m. Beneath this is a layer of moderately cemented clayey gravels and SGC was encountered between 4.4 to 4.9 m, and extended downward a few tens of meter or more. The SGC layer is uncemented and relatively uniform except for a clean, fine to medium sand encountered at between 5.3 to 5.8 m. In general, soil moisture contents were very low throughout the extent of the borings, (Beckwith and Bedenkop 1973).

5.1.2 *Pile Configuration*

The reinforced concrete shaft had an average diameter of 76 cm and was 5.4 m long. The side of the shaft was separated from the soil by a sonotube such that the test was strictly a measure of end-bearing capacity (frictionless shaft).

5.1.3 *Finite Element Analysis*

A finite element model was created using ABAQUS (1998). The shaft was treated as a linear elastic material with modulus of elasticity, E, equal to 3.3×10^7 kPa, and Poisson's Ratio, υ, 0.30. The unit weight of the concrete is assumed to be 23.5 kN/m^3. The unit weight of the soil is assumed to be 19.6 kN/m^3 with a Poisson's Ratio of 0.40. Sliding elements have been installed between the shaft and the soil and have a coefficient of friction equal to zero to represent a frictionless shaft. A parametric study was done to study the effect of the soil internal angle of friction, ϕ, soil dilation angle, ψ, soil modulus of elasticity, E, and initial coefficient of lateral earth pressure at-rest on the bearing capacity of the shaft. Figure 3 shows the effect of soil angle of internal friction, ϕ, on the bearing capacity of the shaft. It is shown that the higher the ϕ value, the higher the capacity. of the shaft. The effect of soil modulus of elasticity, E, on the load deflection curve is shown in Figure 4. The load deflection curves for different dilation angles, ψ, are shown in Figure 5. From Figure 5, it is clear that the higher the dilation angle, the more strength the soil exhibits. The effect of initial coefficient of lateral earth pressure at-rest, k, is shown in Figure 6. As it is shown in Figure 6, the initial coefficient of lateral earth pressure at-rest has little or no effect on the bearing capacity of the shaft. From the previous study, we can conclude that soil modulus, E, soil angle of internal friction, ϕ, and soil dilation, ψ, are very important parameters controlling the bearing capacity of drilled shafts.

5.2 *Case -2*

This test was done in January 1997 at Mapleton, Utah, as a part of research project no. UT-97.02, "Drilled Shaft Side Friction in Gravelly Soils", prepared by Kyle M. Rollins, Robert J. Clayton, Rodney C. Mikesell, and Bradford C. Blaise for the Utah Department of Transportation (UDOT). The main objective of this test was to evaluate the side friction between the shaft and the soil generated by applying an uplift load on the shaft.

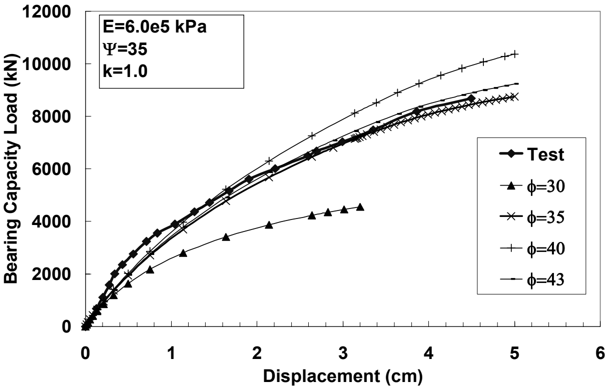

FIGURE 3: Effect of soil angle of internal friction, ϕ, on bearing capacity load

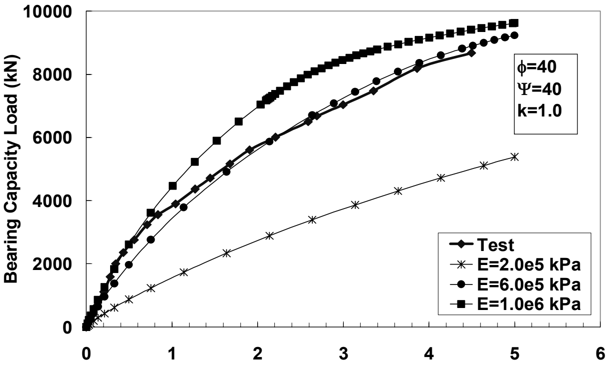

FIGURE 4: Effect of soil modulus, E, on bearing capacity load

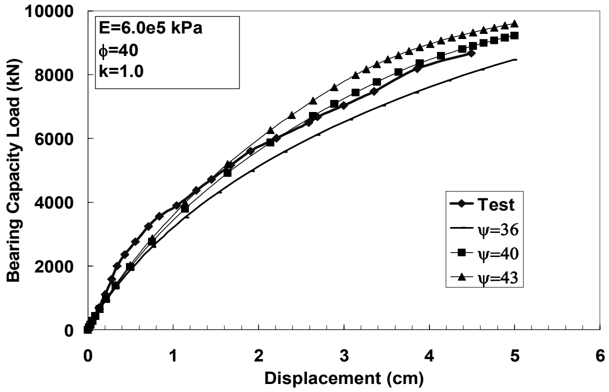

FIGURE 5: Effect of soil dilation angle, ψ, on bearing capacity load

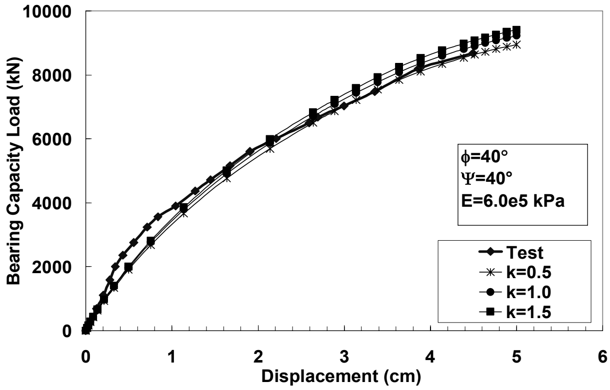

FIGURE 6: Effect of initial coefficient of lateral earth pressure at-rest, k, on bearing capacity load

5.2.1 *Soil Profile*

A general description of the subsurface materials is as follows: from the ground surface to a depth of 3.7 m, very dense coarse to fine gravel with cobbles, from 3.7 m to the maximum depth of exploration (4.6 m), medium density sand. Percent gravel for the site ranges from 68% in the gravely materials to 2% in the silty sand. Maximum particle size is 10 cm and ground water was encountered at 3.8 m in the 4.6 m shaft boring (Rollins et al. 1997).

5.2.2 *Pile Configuration*

The reinforced concrete pile had an average diameter of 60 cm and is 3.8 m long.

5.2.3 *Finite Element Analysis*

A finite element model has been created using ABAQUS Finite Element Program (1998). The pile was treated similarly to the first case study as a linear elastic material with modulus of elasticity, E, equal to 3.3×10^7 kPa, and a Poissoin's Ratio, υ, of 0.30. The unit weight of the concrete is assumed to be 23.5 kN/m^3. The soil is also treated as an elastic fully plastic material represented by the Drucker-Prager Model. The unit weight of the soil is assumed to be 19.6 kN/m^3 with a Poissoin's Ratio of 0.40. Friction elements were installed between the shaft and the soil.

Figure 7 shows the effect of soil modulus of elasticity, E, on the skin friction (uplift) load. The effect of the coefficient of friction between soil and shaft, f, on the skin friction load is shown in Figure 8. Figure 9 shows the effect of the initial coefficient of at-rest lateral earth pressure, k, on the skin friction load. From Figure 9, it is shown that the k value has a slight effect on the skin friction values.

The ratio between the horizontal to vertical stresses at failure, K, was determined, and Figure 10 shows the relation between this ratio and the shaft depth. The continuous line in figure 10 represents the results from the finite element runs, while the dashed lines represent the extrapolation for longer shafts. From Figure 10, it is clear that the K value at failure is much higher than the initial coefficient of lateral earth pressure at-rest, k and this value is higher near the ground surface and decays with depth. This result shows why most empirical models used to predict the axial capacity of drilled shaft foundations in SGC under estimate these values (Harraz et al. 2005). Essentially all of these models ignored the effect of soil dilation and used the initial coefficient of lateral earth pressure, k, to estimate the axial capacity, while the actual K (at failure) value is higher than the initial values due to the effect of dilation of the SGC soils.

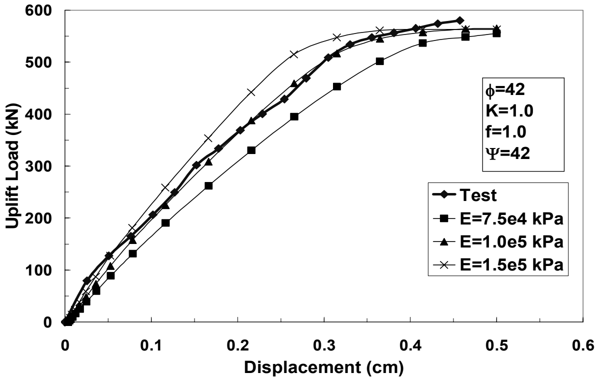

FIGURE 7: Effect of soil modulus, E, on skin friction load

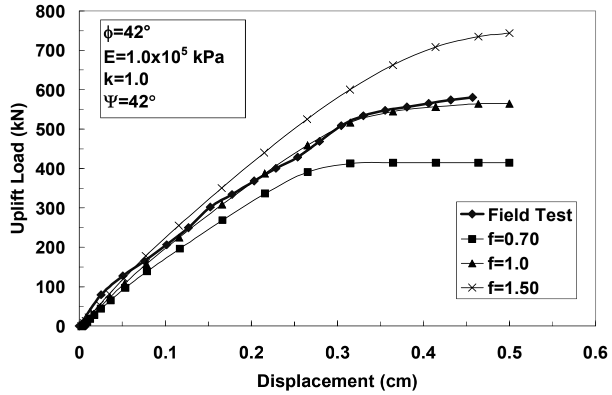

FIGURE 8: Effect of coefficient of friction between soil and shaft, f, on skin friction load

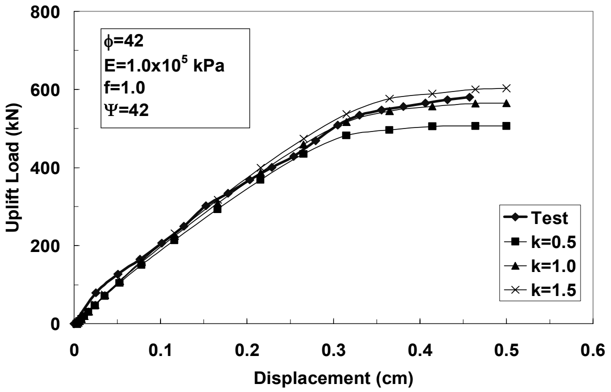

FIGURE 9: Effect of initial coefficient of lateral earth pressure at-rest, k, on skin friction load

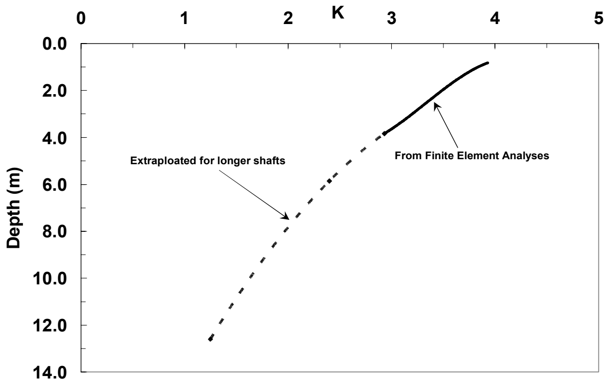

FIGURE 10: Relation between horizontal stress to vertical stress ratio and soil depth

6 SUMMARY AND CONCLUSIONS

Finite element analyses were performed on two chosen case history studies. A parametric study was conducted to determine the most efficient and important soil parameters controlling the bearing and skin friction axial capacity of drilled shaft foundations. It was found that the soil angle of internal friction, soil dilation, coefficient of friction between soil and shaft, and soil modulus of elasticity are the most important parameters controlling the behavior of axial loaded drilled shaft in SGC soils. Two similar sets of parameters were found to match the load deflection curve for each case history study as shown in Table 1.

It is found also that the ratio between the horizontal stresses and vertical stresses at failure is higher than the initial coefficient of lateral earth pressure at-rest due to the high dilation behavior of SGC soils.

Table 1: SGC Soil Parameters for Two Case-History Studies

Parameter	Case 1	Case 2
ϕ°	40	42
ψ°	40	42
E (kPa)	6.0×10^5	1.0×10^5
k	1.0	1.0
f	1.0	1.0

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