Coupled Site Characterization and Foundation Analysis Research Project:

Further Research into the Rational Selection of ƒ for Bearing Capacity Analysis under Drained-Strength Conditions

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by

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References

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INTRODUCTION

This report is a direct follow up to one published earlier this year by the author (Horvath 2000). To avoid unnecessary duplication of content, the present report is structured as an addendum to that earlier one. Consequently, it is essential that Horvath (2000) be read prior to reading this report to understand the conceptual and theoretical bases for the results presented herein.

SCOPE AND PURPOSE OF REPORT

The primary purpose of the study reported in Horvath (2000) was to present a new, rational analytical algorithm developed by the author for the end result of calculating the gross ultimate geotechnical bearing capacity (ultimate limit state) of shallow foundations bearing on soil under drained shear strength conditions. This algorithm linked a sophisticated yet relatively simple site characterization process based on commonly available and routinely used exploration and testing technology with the traditional three-component[1] (N_c, N_q, N_γ) solution for bearing capacity. Thus the primary focus of Horvath (2000) was to illustrate the theoretical bases and development of this unique, holistic algorithm. Consequently, illustration of the application of the proposed algorithm was intentionally of secondary importance so only a single example problem using one particular bearing capacity solution (Hansen's) was included.

Subsequent to the publication of Horvath (2000), personal communication between the author and other geotechnical professionals raised the issue of the sensitivity of the author's analytical algorithm to the particular bearing capacity solution used as well as reproducibility of the excellent results achieved in the example problem to other problems. Each of these is a valid issue. The former is easily addressed by analyzing a given problem using any number of published bearing capacity solutions. The latter is much more difficult to address. This is because there is a dearth of published, properly documented, good-quality, physical (either full-scale 1-g or small-scale centrifuge) load tests of embedded shallow foundations to the geotechnical ultimate limit state. Nevertheless, the purpose of the present report is to address these two issues as best as possible and document additional work by the author to apply the analytical algorithm in Horvath (2000) to two spread footings using four different bearing capacity solutions for each footing to explore in at least a preliminary way the sensitivity of calculated results.

DESCRIPTION OF PROBLEMS ANALYZED

Introduction

The two footings chosen for assessment in the current study were both from one of the very few well-documented case histories in the published literature of full-size spread footings loaded to bearing capacity failure. The footings were two of the five constructed and load tested for the *Spread Footing Prediction Symposium* that was a part of the American Society of Civil Engineers (ASCE) *Settlement '94* geotechnical engineering specialty conference. The author had access to and used only the relevant soil and footing data that were made available publicly beforehand to all those participating in the symposium (Gibbens and Briaud 1994a, 1994b).

As information, the reason that only two of the five footings from this symposium were analyzed for the present study is that only two had a maximum-settlement-to-footing-width ratio, ρ/B, that

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[1] In this report, "component" refers not just to a bearing capacity factor (e.g. N_q) itself but collectively to the product of all shape, embedment, etc. factors and other variables that multiply a bearing capacity factor.

was judged by the author to be within the range of values considered necessary to define a geotechnical bearing capacity failure based on criteria presented by Vesic (1975). In retrospect, given the level of effort and expense expended for this symposium it is most unfortunate that the symposium organizers did not load the other three footings to settlement magnitudes that would generally be considered to constitute bearing failure. This would have greatly increased the utility of the load-settlement data obtained for these footings and allowed their inclusion in the present study.

It should be noted that one of the two footings chosen for assessment in the present study was used in the author's original study (Horvath 2000). This footing was reused in the present study primarily to explore the sensitivity of results obtained from three bearing capacity solutions in addition to the originally used Hansen solution.

Footing Details

Table 1 contains the relevant physical dimensions of the two footings considered in the present study. Note that the 1-m footing was the one used for the example problem in Horvath (2000).

Table 1. Footing Dimensions

footing name	footing width, B, in mm (ft)	footing length, L, in mm (ft)	footing thickness, t_f, in mm (ft)	foundation depth, D_f, in mm (ft)
"1-metre footing"	991(3.25)	991 (3.25)	1168 (3.83)	711 (2.33)
"1.5-metre footing"	1492 (4.89)	1505 (4.94)	1219 (4.00)	762 (2.50)

Each of these footings was loaded until a settlement of approximately 150 mm (6 in) was achieved. Thus the maximum-settlement-to-footing-width ratio, ρ/B, was approximately 15% and 10% for the 1-m and 1.5-m footings respectively. These were judged by the author to be within the range of values considered necessary to define a bearing capacity failure (Vesic 1975).

Subsurface Data

The following parameters based on data given by Gibbens and Briaud (1994a, 1994b) were used as input for the site characterization process described in detail in Horvath (2000):

- average minimum soil dry unit weight, $\gamma_{d(min)}$ = 13.5 kN/m^3 (86.0 lb/ft^3)
- average maximum soil dry unit weight, $\gamma_{d(max)}$ = 15.9 kN/m^3 (101.3 lb/ft^3)
- average soil-particle D_{50} = 0.20 mm
- average depth below ground surface to ground water table, z_w = 4.9 metres (16.1 ft)
- average soil natural water content, w_n, within vadose zone above foundation level = 14%
- average soil natural water content, w_n, within vadose zone below foundation level = 17%

Conditions at the site were judged to be reasonably consistent with respect to the above parameters so that the same data were used for both footings. However, to take advantage of the fact that essentially a separate piezocone (CPTu) probe was performed for each footing, the CPT/CPTu q_c data required for the analytical algorithm described in Horvath (2000) were different for each footing analyzed for the present study. Specifically, the data from probes CPT-1 and CPT-6 were used for the 1-m and 1.5-m footings respectively.

Bearing Capacity Solutions

Many solutions have been developed for the shallow foundation bearing capacity problem since Terzaghi's original, seminal work on the subject (Terzaghi 1943). With few exceptions, each solution has as a common element in its derivation the assumption that the bearing ("foundation") soil exhibits idealized rigid-plastic material behavior. In the context of modern interpretations of bearing capacity, this means that the *compressibility* of the bearing soil and concomitant settlement of the foundation element prior to failure are neglected and what is called a *general-shear* type of failure is presumed to occur (Vesic 1975). Although solutions that consider compressibility (sometimes expressed in terms of its reciprocal phenomenon, *rigidity*) have been developed, most notably by Vesic (De Beer 1987, Kulhawy 1984, Vesic 1975), theory and other experience indicate that compressibility/rigidity does not affect the bearing capacity of most shallow foundations under drained-strength conditions (De Beer 1987, Vesic 1975). Therefore, the present study was limited to traditional "rigid" solutions based on general-shear failure.

The four solutions considered were (listed in alphabetical order):

- Hansen,
- Meyerhof,
- Terzaghi and
- Vesic (basic "rigid" solution with compressibility/rigidity effects neglected).

It is relevant to note that these solutions, taken either severally or together, are found in most modern textbooks on geotechnical engineering, at least those published in the U.S.A. The author used Bowles (1996) as the basic reference for evaluating the various specific factors applicable to each solution with the exception that Coduto (2001) provided a better (and more accurate due to a typographical error in Bowles (1996)) reference for Terzaghi's solution, especially with regard to evaluation of the N_γ factor.

RESULTS OF ANALYSES

Site Characterization

Table 2 contains the results of the site characterization assessment that was performed for the present study using the procedure outlined in Horvath (2000). Zero cohesion was assumed for all soils.

Table 2. Site Characterization Results

footing	**average total unit weight, g_t, above foundation level in kN/m^3 (lb/ft^3)**	**average effective (total in this case) unit weight, g_{eff}, for one footing width, *B*, below foundation level in kN/m^3 (lb/ft^3)**	**average relative density, D_r, for one footing width, *B*, below foundation level in percent**	**average Mohr-Coulomb friction angle under constant-volume conditions, f_{cv}, in degrees**
1 m	17.0 (108)	17.4 (111)	62	34
1.5 m	16.8 (107)	17.0 (108)	47	34

Footing Capacity

Tables 3a and 3b contain the results of the capacities calculated using the inputs in Table 2 and the analytical procedure described in Horvath (2000). Also shown in Tables 3a and 3b are the actual measured capacities reported by Briaud and Gibbens (1994).

Table 3a. Summary of Capacity Results: 1-Metre Footing

source of result	secant value of peak Mohr-Coulomb friction angle, $f_{peak(secant)}$, in degrees	gross ultimate bearing capacity, q_{ult}, in kPa (k/ft^2)	net ultimate bearing capacity, q_{net}, in kPa (k/ft^2)	net column load at bearing failure, P_{net}, in kN (kips)	$\frac{P_{net(calculated)}}{P_{net(measured)}}$
measured	-	-	-	1740 (391)	-
calculated (Hansen)	40.0	1876 (39.2)	1849 (38.6)	1816 (408)	1.04
calculated (Meyerhof)	39.5	2432 (50.8)	2405 (50.2)	2362 (531)	1.36
calculated (Terzaghi)	40.1	1854 (38.7)	1827 (38.1)	1794 (403)	1.03
calculated (Vesic)	39.8	2137 (44.6)	2110 (44.1)	2072 (466)	1.19

Table 3b. Summary of Capacity Results: 1.5-Metre Footing

source of result	secant value of peak Mohr-Coulomb friction angle, $f_{peak/(secant)}$, in degrees	gross ultimate bearing capacity, q_{ult}, in kPa (k/ft^2)	net ultimate bearing capacity, q_{net}, in kPa (k/ft^2)	net column load at bearing failure, P_{net}, in kN (kips)	$\frac{P_{net(calculated)}}{P_{net(measured)}}$
measured	-	-	-	3400 (764)	-
calculated (Hansen)	38.0	1556 (32.5)	1527 (31.9)	3433 (771)	1.01
calculated (Meyerhof)	37.6	2092 (43.7)	2063 (43.1)	4637 (1042)	1.36
calculated (Terzaghi)	38.0	1619 (33.8)	1590 (33.2)	3575 (803)	1.05
calculated (Vesic)	37.8	1784 (37.2)	1755 (36.6)	3945 (887)	1.16

Note that the measured and calculated (Hansen) results shown in Table 3a are slightly different than those given in Horvath (2000). This is because the value of relative density was rounded off slightly (from 61.5% originally to 62% in the present study) and the measured value of footing load at failure used in the present study (1740 kN (391 kips)) was taken from Table 3 in Briaud and Gibbens (1994) as opposed to being scaled (1690 kN (380 kips)) from their Figure 7 as was done originally.

Other Results of Interest

An unanticipated outcome of this study derived from the author's incidental observation of an interesting variation in the relative contribution of the N_q and N_γ components[2], which reflect the effect of footing embedment and soil weight within the failure zone below foundation level respectively, to the gross ultimate bearing capacity, q_{ult}. This is an issue that appears to be discussed very little if at all in textbooks and the literature. However, the relative contribution of these two components can be important in many practical situations where embedment may change during the life of the foundation. Examples include footings in water where scour may occur or footings on land where there may be future excavation for utility line installation or some other reason.

Table 4 shows the relative contribution of the embedment (N_q) and soil-weight (N_γ) components for the two footings considered in the present study.

Table 4. Relative Contribution of Embedment and Soil-Weight Components to Gross Ultimate Bearing Capacity

bearing capacity solution	**$N_q : N_g$ components in percent of calculated bearing capacity, q_{ult}**	
	1-metre footing	**1.5-metre footing**
Hansen	78 : 22	73 : 27
Meyerhof	50 : 50	44 : 56
Terzaghi	54 : 46	49 : 51
Vesic	74 : 26	68 : 32

DISCUSSION OF RESULTS

Comparing results within and between Tables 3a and 3b indicates the following with respect to the accuracy and consistency of calculated bearing capacity results:

- For a given footing, the value of $\phi_{peak(secant)}$ at which the calculated gross ultimate bearing capacities, q_{ult}, converged within the author's analytical algorithm is essentially the same regardless of the particular solution used (approximately 40° and 38° for the 1-m and 1.5-m footings respectively).

- For a given footing, both the Hansen and Terzaghi solutions produced similar results that were very close to those measured. The Meyerhof and Vesic solutions both consistently overestimated the gross ultimate bearing capacity with Meyerhof's solution the least accurate (i.e. greatest overestimate).

- For a given bearing capacity solution, the relative results (as expressed by the ratio of P_{net} calculated to measured) were essentially the same for the two different footings considered.

Next considering results in Table 4, for the two footings considered in the present study the relative proportion of gross ultimate bearing capacity attributed to embedment (N_q component) versus soil weight within the failure zone below foundation level (N_γ component) fell into two

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[2] The contribution of the N_c component was zero in this study.

distinct patterns. For the Hansen and Vesic solutions, embedment accounted for approximately 75% of q_{ult} whereas for the Hansen and Meyerhof solutions it accounted for about 50%. Note, however, that these relative proportions should not be interpreted as being universal. The magnitude of the soil-weight component is linearly proportional to the footing width, B, and thus the relative contribution of the soil-weight component would be expected to increase for wider footings (such a trend can even be seen in Table 4 between the 1-m and 1.5-m footings considered in the present study). Nevertheless, this relatively significant disparity between different solutions in the relative contributions of embedment and soil weight to gross ultimate bearing capacity is something that should be considered more in the future for problems where foundation embedment is an important design issue. The results of the present study, albeit limited in scope, suggest that the Hansen and Vesic solutions are more conservative to use in situations where embedment may control design because they assign a relatively greater proportion of gross ultimate bearing capacity to embedment. Thus if some or all of the embedment is removed, the calculated value of gross ultimate bearing capacity will decrease proportionately more than for the Meyerhof and Terzaghi solutions. This would tend to result in a more conservative assessment of the effect of embedment loss on bearing capacity.

CONCLUSIONS

The results of the present study, although limited in scope because of the paucity of appropriate data in the published literature, are nevertheless sufficient to draw the following conclusions:

- The bearing capacity analysis algorithm proposed by the author in Horvath (2000) still appears to be the best approach at the present time to rationally addressing this type of problem.

- Hansen's solution to the shallow foundation bearing capacity problem appears to offer the best combination of accuracy, generality and dealing conservatively with foundation embedment, and thus appears to be the clear method of choice in practice. It is of interest to note that the author already held this opinion of Hansen's solution prior to undertaking the study reported in Horvath (2000). This is the reason that only Hansen's solution was used in the example problem in Horvath (2000).

- Vesic's solution has several of the desirable attributes of Hansen's solution (generality, conservative assessment of foundation embedment) although Vesic's solution appears to be less accurate in that it produces less-conservative estimates of gross ultimate bearing capacity. Thus use of Vesic's solution should be reserved for those applications where compressibility/rigidity affects bearing capacity and must be considered analytically because rigidity factors have been developed to date only for Vesic's solution.

As always, future opportunities should always be sought to evaluate the analytical algorithm proposed in Horvath (2000) with appropriate physical testing (either full-scale 1-g or centrifuge), as well as to update or improve this algorithm as newer site characterization or theoretical correlations are developed. This is in keeping with the broad philosophy of technology development long espoused by the author which recognizes that technical knowledge is never static but undergoes a constant growth spiral involving research, technology transfer and implementation into practice which in turn spurs further research and continues the cycle.

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