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A new technique to predict the allowable bearing capacity for shallow foundations based on small-strain stiffness

A. Hadad
Assistant Professor, Department of Civil Engineering, Semnan University, Semnan, Iran

R. Amini Ahidashti
M.Sc. Student, Department of Civil Engineering, Semnan University, Semnan, Iran

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ABSTRACT: In-situ direct estimation of small-strain stiffness, of soil is more effective and reliable than those derived from resistance-based correlation or laboratory testing. In this paper, based on theory of elasticity, a new technique is suggested in term of small-strain stiffness in order to estimate the allowable bearing capacity of shallow foundation. In order to evaluate the proposed method, a series case history is studied, that included the loading tests and seismic geophysical tests. These field measurements are compared to the predicted values. The result indicated that the proposed method in this study can be effectively used to predict the allowable bearing capacity of footing on granular soils and that were much more accurate than the SPT or CPT based predictions.

1 INTRODUCTION

Shallow foundations are generally designed to satisfy the bearing capacity and the settlement criteria. It is commonly believed that the settlement criterion is more critical than the bearing capacity one in the designs of shallow foundations, especially for foundation width greater than 1.5 m, which is often the case. By limiting the total settlements, differential settlements and any subsequent distresses to the structure are limited. Generally the settlements of shallow foundations such as pad or strip footings are limited to 25 mm (Terzaghi et al. 1996). The ultimate bearing capacity of a particular soil, under a shallow footing, was investigated theoretically by several researchers using the concept of plastic equilibrium (Das et al, 2009). The formulation however is slightly modified, generalized, and updated later by Terzaghi (1925). There are various uncertainties in representing the real in situ soil conditions by means of a few laboratory tested shear strength parameters. The basic soil parameters are c_u = cohesion, undrained shear strength and φ = angle of internal friction, which can only be determined by laboratory testing of undisturbed soil samples. It is sometimes impossible to take undisturbed soil samples especially in sandy and gravelly soils.

Seismic wave velocity measurements have been used to characterize in-situ soil and rock stiffnesses for use in the evaluation of the response of geotechnical sites to earthquake loading and machine vibrations (Tezcan et al, 2006). The velocity of propagation of a shear wave (V_S), which can then be converted to the shear modulus at small strains (G_{max}), and finally to Young's modulus at small strains (E_{max}).

$$G_{max}= \rho . V_s^2 \quad (1)$$

Where ρ = mass density of the soil.

$$E_{max}=2(1+\upsilon)G_{max} \tag{2}$$

Where ν = Poisson's ratio, 0.15-0.35 for unsaturated cohesionless soils (Matthews et al, 1996). In-situ direct estimation of maximum stiffness or small-strain stiffness (G_{max} or E_{max}) of soil is more effectively and reliably than those derived from resistance-based correlation or laboratory testing.

In this paper, a new method is provided in order to determine the allowable bearing capacity for a 25 mm settlement based on small-strain stiffness. The suggested relationship in this study will be modified small-strain stiffness of the soil layer in according to the level of foundation pressure. In order to validate the proposed method, the results of the survey of loading tests in several sites were evaluated and compared. Appropriate coincidence between the result of loading test and predicted loads, shows the accuracy of proposed method in comparison to other the methods. In general, the predictions based on in situ parameters from seismic measurements are closer to the measured values.

2 MODIFICATION SMALL-STRAIN BASED ON SHEAR STRAIN

The non-linearity of stiffness with strain and stress level, coupled with different directions of loading and drainage conditions, makes it very difficult for a meaningful cross comparison of the various modules derived from the different tests, unless a consistent framework and reference stiffness are established.

It is therefore a difficult issue to recommend a single test, or even a suite of tests, that directly obtains the relevant E_s for all possible types of analyses in every soil type. This is because the modulus varies considerably with strain level or stress level. In this study, the small-strain stiffness G_{max} is a fundamental stiffness applicable to all types of geomaterials including clays, silts, sands, gravels, and rocks for static and dynamic loading (Elhakim, 2005).

Therefore stiffness parameters for practical purposes, may be considered constant at very small strains, but can be expected to reduce as strains increase above this level. Because the strain levels around well-designed geotechnical structures such as retaining walls, foundations and tunnels are generally small, measurements are required in order to determine two sets of parameters (clayton, 2011):

(a) Parameters at very small (ideally reference) strain levels (e.g. E_{max}, υ and G_{max}).

(b) Stiffness parameters are altered by increasing strain and changing stress levels during loading or unloading.

However, G_{max} is too high for direct use in computing settlement of shallow foundation. Therefore, the small-strain stiffness must be modified based on the stress levels or strain levels. The shear modulus degradation with shear strain is commonly shown in normalized form, with current G divided by the maximum G_{max} (or G_0). The relationship between G/G_0 and logarithm of shear strain is well recognized for dynamic loading conditions (e.g., Vucetic and Dobry, 1991).

In order to predict the degradation of small-strain stiffness, the laboratory data for variations soil stiffness with various shear strains were collected from the recent scientific papers and reports (Rollins et al, 1998, Elhakim, 2005). The power law relationship was presented for the modification of the small-strain stiffness by the shear strain:

$$G/G_{MAX} = \frac{0.0725}{\sqrt{\gamma_{\%}}} \tag{3}$$

Where $\gamma_{\%}$= shear strain in percent. Bands defining G/G_{max} versus shear strain for sands (Seed et al 1984) are shown in Figure 1. In this figure, the proposed equation (3) by the authors is drawn. In this study, the proposed curve for defining G/G_{max} versus shear strain generally falls near the center of the range of data for sands, which is defined by Seed et al (1984).

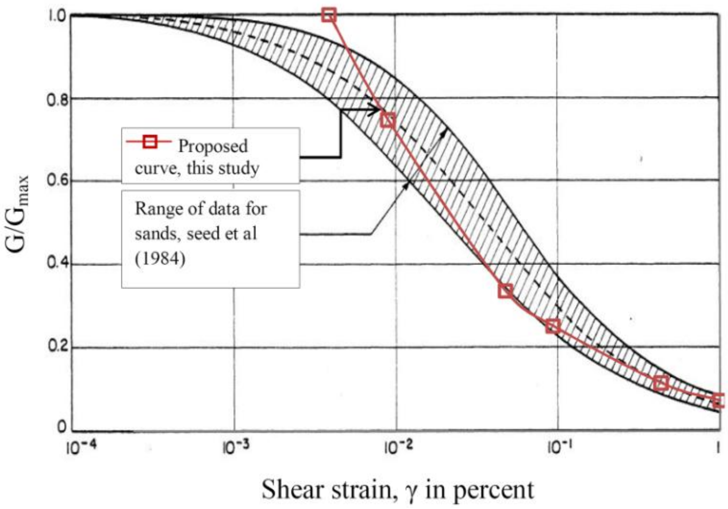

Figure 1. Comparison of the proposed equation (3) in this study and range of data for sands defined by Seed et al. (1984).

3 A NEW TECHNIQUE FOR THE PREDICTION OF THE ALLOWABLE BEARING CAPACITY

Based on the measured small-strain stiffness and elasticity theory, a new technique has been developed which uses these values to calculate Young's Modulus, *E*, at the practical strain levels experienced in actual foundation conditions and so enables ground settlements to be predicted. Suggested Steps to predict the allowable bearing capacity in terms of small-strain stiffness, are as follow:

Step1: Average values of G_{max} in layers from the base of the foundation to twice the foundation width. The seismic methods of SASW and CSW are then conducted to measure the shear wave velocity and shear modulus (G_{max}) of the soil profile with depth.

Step2: Determine the maximum Stiffness (E_{max}) from small-strain stiffness, $E_{max}=2(1+\upsilon)G_{max}$.

Step3: The vertical strain at the centre of the layers, ε, are then calculated from the elasticity theory.

$$\varepsilon = \frac{\sigma_z}{E} - \upsilon\left(\frac{\sigma_x}{E} + \frac{\sigma_y}{E}\right) \quad (4)$$

Where σ_z, σ_y and σ_x are vertical and horizontal stresses, υ= passion ratio this means Poisson's Ratio which is assumed to be 0.3 and *E*= young modulus. With the axial symmetric loading condition, $\sigma_x = \sigma_y$ (horizontal stresses) and equal to $k_0.\sigma_z$ that k_0 is coefficient of lateral earth pressure at rest (dimensionless). For soil deposits that have not been significantly preloaded, a value of k_0 = 0.5 is often assumed in practice (day, 2006). Hence, from eq. (4):

$$\varepsilon = 0.7\frac{\sigma_Z}{E} \quad (5)$$

Step4: Modify the small-strain stiffness. The relationship between the shear strain and the axial strain is as follow:

$$\gamma_{\%} = (1+\upsilon)\varepsilon_{\%} \quad (6)$$

Where $\varepsilon_{\%}$= axial strain in percent = 100. ε. Substituting eq. (6) into eq. (3) and υ=0.3 yields**:**

$$G/G_{MAX} = \frac{0.0725}{\sqrt{\varepsilon_{\%}(1+\upsilon)}} = \frac{0.0636}{\sqrt{\varepsilon_{\%}}} \quad (7)$$

Step5: Calculate the axial strain. Regarding to eq. (5) and eq. (7), enables us to write:

$$\varepsilon_{\%} = \left(\frac{1101.\sigma_z}{E_{MAX}} \right)^2 \tag{8}$$

Step6: The settlement of foundation is obtained by multiplying the calculated strain in the soil layer thickness. The soil layer thickness considers from the bottom of the footing to a depth of *2B′* below the footing that $B' = \left(\frac{4BL}{\pi} \right)^{0.5}$ is equivalent to the diameter of a rectangular footing. Hence, the vertical stress at the centre of the layer at depth equal to *B′* below the footing, σ_z, is then calculated from the Boussinesq formula.

$$\sigma_z = q \left[1 - \frac{1}{(1 + \left(\frac{B'/2}{B'} \right)^2)^{\frac{3}{2}}} \right] = 0.285q \tag{9}$$

Where *q*= applied pressure at foundation level. Therefore, substituting eq. (9) into eq. (8), we obtain:

$$\varepsilon_{\%} = \left(\frac{313.75.q}{E_{MAX}} \right)^2 \tag{10}$$

The settlement *S* of the soil layer, may be expressed from eq.(10) , as:

$$S = \frac{\varepsilon_{\%}}{100}.2B' = \left(\frac{313.75.q}{E_{\max}} \right)^2 . \frac{B'}{50} \tag{11}$$

Where *S* = elastic settlement and *B′* = equivalent diameter of a rectangular footing. Substituting *S*=25 mm into eq. (11), we obtain the bearing capacity for a 25 mm settlement, as follows:

$$q_{allowable} = \frac{E_{\max}}{280.63\sqrt{B'}} \tag{12}$$

This is the desired expression to determine the allowable bearing capacity of circular footing over granular soils in term of small-strain stiffness.

4 CASE HISTORIES

As summarized in Table 1, in order to evaluate the accuracy of the proposed method in this paper, eq. (11), for estimating the settlement of shallow foundation, a database of nine load tests on footings and large plates from three sites was compiled. The case histories are: 1- Texas A&M University, USA and 2-Vattahammar, Sweden. For each case, the in-depth geotechnical, loading test and geophysical site investigations have been conducted and soil parameters have been determined.
Comparison of the predicted versus measured load for 25 mm settlement from the proposed method in this paper is presented in Tables 2. Figure 2 shows the curve of normal variations of the proposed method. Paying attention to the curves, we can see that the normal curve of the proposed method is close to one.
This can be confirmed the more accuracy of the proposed method than the other methods. Specification of the normal curves is shown in Table 3. Based on the normal curves of the proposed method, the ratio of the predicted loads to the measured loads is 0.98 at the nine case histories.

Table 1. Case histories general specification

SITE	REFERENCE	LOCATION	SOIL TYPE	FOOTING	FOOTING

NO.				SHAPE	SIZE B (M)
①	BRIAUD & GIBBENS (1994)	USA	SAND, SILTY SAND	SQUARE	1
①	BRIAUD & GIBBENS (1994)	USA	SAND, SILTY SAND	SQUARE	1.5
①	BRIAUD & GIBBENS (1994)	USA	SAND, SILTY SAND	SQUARE	2.5
①	BRIAUD & GIBBENS (1994)	USA	SAND, SILTY SAND	SQUARE	3
①	BRIAUD & GIBBENS (1994)	USA	SAND, SILTY SAND	SQUARE	3
①	PARK ET AL (2010)	USA	SAND, SILTY SAND	CIRCULAR	0.25
①	PARK ET AL (2010)	USA	SAND, SILTY SAND	CIRCULAR	0.46
②	LARSSON (1997)	SWEDEN	SILT	SQUARE	0.5
②	LARSSON (1997)	SWEDEN	SILT	SQUARE	1

Table 2. Comparison between measured and predicted loads for 25 mm settlement

FOOTING SIZE, B (M)	LOCATION	PREDICTED LOAD FOR 25 mm SETTLEMENT (kPa)	MEASURED	$\frac{q_{predicted}}{q_{measured}}$
		PROPOSED METHOD IN THIS STUDY		
0.25	USA	1355	970	1.40
0.46	USA	997	900	1.11
1X1	USA	790	850	0.93
1.5X1.5	USA	645	667	0.97
2.5X2.5	USA	490	576	0.85
3X3 (NORTH)	USA	456	578	0.79
3X3 (SOUTH)	USA	456	500	0.91
0.5X0.5	SWEDEN	875	820	1.07
1X1	SWEDEN	616	780	0.79

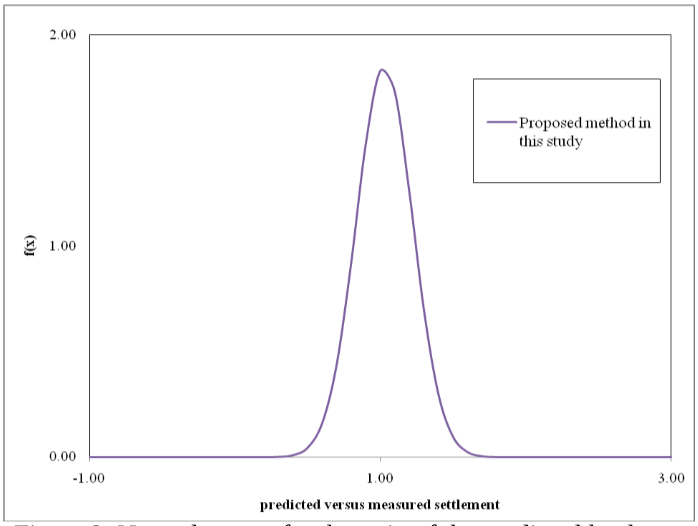

Figure 2. Normal curves for the ratio of the predicted loads to measured loads @ 25 mm settlement, for the proposed method

Table 3. Specification of the normal curves for the proposed methods.

	PROPOSED METHOD IN THIS STUDY
MEAN	0.98
STANDARD DEVIATION	0.19

It means that the new method predicts the allowable bearing capacity with less overestimation or underestimation. The results of the comparison indicate better accuracy and less scatter for the proposed method. A good agreement was obtained between the measured and the predicted soil deformation data.

5 SUMMARY AND CONCLUSIONS

In the present study, estimation of the settlement of circular footings on granular soils was investigated based on the shear wave velocity (V_s) and the shear modulus at small strains (G_{max}), and Young's modulus at small strains (E_{max}).
The results of this study are as follow:

1) The advantage of using a real soil property (such as E_{max}) in settlement predictions/analyses, field seismic measurements make it possible to provide information about a whole site much more accurately than can be obtained with point measurements in soil borings or soundings. The seismic measurements have considerable advantage of being made in situ on undisturbed soil.
2) The soil behaviour is non-linear and the stiffness of the soil reduced with increasing the strain level. For this purpose, we presented a power law formula to predict the variations of stiffness according to strain level. Based on the theory of elasticity and the proposed formula, a new method was developed in term of small-strain stiffness in order to estimate the allowable bearing capacity of shallow foundation over the granular soils.
3) In order to validate the proposed method, the results of the survey of loading tests in two sites were evaluated and compared. Appropriate coincidence between the result of loading test and the predicted load, shows the accuracy of proposed method in comparison to the other methods. Evaluation of the normal curves for the studied method shows that the average of the ratio of the calculated load to the measured load at 25 mm settlement are 0.98 for the proposed method in this study. This comparison shows that the proposed method is better than the other methods with standard deviation equal to 0.19.
4) In general, predictions based on in situ parameters from seismic measurements are closer to the measured settlement under service loads.

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