Predicting Settlements of Shallow Footings on Granular Soil Using Nonlinear Dynamic Soil Properties

Prédiction des tassements de fondations superficielles sur des sols granulaires en utilisant des propriétés dynamiques non linéaires du sol.

Stokoe K.H., Kacar O.
University of Texas at Austin, Texas, USA

Van Pelt J.
CDM Smith, Inc. Dallas, Texas, USA

ABSTRACT: The governing design criterion for shallow foundations in freely draining granular soils is usually permissible settlement. Due to difficulties in obtaining undisturbed samples of granular soils composed of mainly sands and gravels, settlement predictions are generally based on correlations with in-situ penetration tests. In this study, field seismic measurements are used to evaluate small-strain ("elastic") shear moduli of granular soils (G_{max}). These small-strain moduli, combined with nonlinear normalized shear modulus-shear strain (G/G_{max}-log γ) relationships, are used to predict settlements of shallow foundations under working loads. The G/G_{max}-log γ relationships are based on models developed from dynamic resonant column (RC) tests of reconstituted sands and gravels. The combination of field G_{max} results and laboratory G/G_{max}-log γ relationships have been implemented in a finite element program (PLAXIS) via a subroutine. Settlement predictions with this approach are illustrated by comparison with a load settlement test using a 0.91-m diameter footing. At working stresses, nonlinear footing settlements were predicted quite well, similar to predictions with traditional CPT and SPT procedures.

RÉSUMÉ: Le critère de dimensionnement pour des fondations superficielles sur sols granulaires est, souvent, le tassement admissible. A cause de la difficulté à obtenir des échantillons intacts de sols sableux et graveleux, les prévisions de tassement sont basées sur des corrélations déduites des essais in-situ. Dans la présente étude, des mesures sismiques in situ sont utilisées pour évaluer les modules de cisaillement elastique en petites déformations des sols granulaires (Gmax). Ces modules, combinés avec des relations de variation non-lineaire module-distorsion, G/Gmax-log γ, sont utilisés pour prévoir les tassements des fondations. Les relations G/Gmax-log γ sont basées sur des modèles développés à partir d'essais à la colonne résonante (RC) sur des éprouvettes reconstituées de sables et graviers. La combinaison des mesures de Gmax in-situ et des relations G/Gmax-log γ obtenues en laboratoire sont introduites via une sous-routine dans un programme d'éléments finis (PLAXIS). Les prédictions des tassements obtenues avec l'approche proposée sont présentés en les comparant aux résultats d'un essai de chargement utilisant une fondation de 0.91m de diamètre. Sous contraintes de service, les previsions de tassements non-lineaires sont bonnes. Elles sont similaires à celles déduites des procédures SPT et CPT traditionnelles.

KEYWORDS: in-situ seismic testing, nonlinear dynamic properties, granular soil, footing settlement

1 INTRODUCTION

In shallow foundation design, bearing capacity and settlement are the two main criteria considered. For freely draining granular soils, permissible settlement becomes the governing factor in most cases. Laboratory tests to predict the stress-strain behavior of soils generally require an undisturbed sample which is nearly impossible and/or very expensive to recover from the field for granular soils. Therefore, settlements of shallow foundations on such soils have traditionally been predicted using empirical correlations that relate in-situ penetration test results with load-settlement tests or case histories. In this article, an approach based on field seismic evaluation of small-strain ("elastic") shear modulus (G_{max}) combined with nonlinear normalized shear modulus-shear strain (G/G_{max}-log γ) relationships is presented. The effects of increasing confining pressure and strain amplitude on soil stiffness during loading of the footing are incorporated in this formulation. The approach has several important benefits including: (1) in-situ seismic testing which can readily be performed in all types of granular soils, including gravels and cobbles (2) continuous load-settlement curves that are evaluated to stress states considerably above those expected under working loads, and (3) a methodology that is appropriate for all types of geotechnical materials, even those where the effective stresses change with time.

2 TRADITIONAL AND RECENT SETTLEMENT-PREDICTION METHODS

One of the first methods of predicting footing settlements on granular soils was proposed by Terzaghi and Peck (1948). They conducted plate-load tests on 300-mm square plates on sand and then predicted the settlements of full-size footings using an empirical relationship. Meyerhof (1965) proposed a method where the settlements were predicted based on standard penetration test (SPT) blow count, N_{60}. One of the most widely used methods today was originally proposed by Schmertmann (1970). He used elastic theory, model load tests, field cone penetration tests (CPT) and finite element analysis to develop the approach. In Schmertmann's method, the soil stiffness is expressed as an equivalent elastic modulus which is based on CPT results. Burland and Burbidge (1985) reviewed a data set of case histories and developed a method using corrected SPT results. In all methods, a key parameter, the strain dependency of the soil stiffness, is not directly considered.

One of the earliest methods to take the strain dependency of the soil stiffness into account was proposed by Berardi and Lancellotta (1991). They proposed an iterative scheme where the soil stiffness was evaluated based on the corrected

SPT blow count and varied according to the calculated relative strain levels. Lee and Salgado (2001) proposed a model where soil stiffness is reduced based on the tolerable settlements and relative density of the soil. A simplified method was proposed by Lehane and Fahey (2002) which takes the soil nonlinearity into account by reducing the small-strain Young's modulus with increasing axial strain.

None of these methods incorporate field seismic testing to estimate soil stiffness near the base of footing where much of the settlement occurs. In addition, none of the methods considers the combined effects of shear strain level, stress state and gradation on nonlinear stress-strain behavior of granular soils. In this study, an approach implementing dynamic nonlinear soil behavior and field seismic testing is proposed to estimate the settlement of footings as discussed below.

3 NONLINEAR BEHAVIOR OF GRANULAR SOIL

The stress-strain behavior of granular soil ranges from linear ("elastic") at small strains to highly nonlinear at large strains. The shear strain below which the shear modulus is constant is defined as the elastic threshold strain, γ_t^e. For granular soils with no plasticity, γ_t^e varies with effective confining pressure, σ_0', and gradation, usually expressed by the uniformity coefficient, C_u (Menq, 2003). For working stresses associated with shallow foundations, γ_t^e likely ranges from 0.0001 to 0.003%. Advances in in-situ seismic measurements, especially development of surface wave tests like the Spectral-Analysis-of-Surface-Waves (SASW) test (Stokoe et al.,1994), permit small-strain shear wave velocity (V_s) and shear modulus (G_{max}) to be evaluated very near the surface and in granular soils, even soils with gravel and cobbles. Other dynamic laboratory testing methods, such as the torsional resonant column, have made it possible to investigate the nonlinear shear modulus of granular soils over a wide strain range. For instance, Hardin and Drnevich (1972) conducted the first comprehensive study of nonlinear soil behavior and the parameters affecting nonlinearity. They proposed a hyperbolic model to define nonlinear soil behavior. This hyperbolic model was modified by Darendeli (2001) based on a large dataset of combined resonant column and torsional shear tests (RCTS) as follows:

$$G/G_{max} = \frac{1}{1+\left(\frac{\gamma}{\gamma_r}\right)^a} \qquad (1)$$

where a = curvature coefficient; γ_r = reference shear strain at $G/G_{max} = 0.5$; and G is the shear modulus at shear strain = γ. The value of the reference shear strain depends on plasticity, confining pressure and overconsolidation ratio. The modified hyperbolic model was further refined by Menq (2003) for sands and gravels with no plasticity by defining reference strain, γ_r, and curvature coefficient, a, as follows:

$$\gamma_r = 0.12{C_u}^{-0.6}\left(\frac{\sigma_0'}{P_a}\right)^{0.5{C_u}^{-0.15}} \qquad (2a)$$

$$a = 0.86 + 0.1\log\left(\frac{\sigma_0'}{P_a}\right) \qquad (2b)$$

where γ_r is in %; C_u = uniformity coefficient; σ_0' =mean effective confining pressure in the same units as P_a; and P_a = reference mean effective confining pressure (1 atm).

A subroutine using the modified hyperbolic model described by Equations 1 and 2 was written and implemented in a commercially available finite element program (PLAXIS). The subroutine uses a small-strain reference shear modulus (discussed below and represented by Equation 3) adjusted to the increasing stress state and the G values in the G/G_{max}-log γ relationship are adjusted to the increasing shear strain level. The subroutine is used to perform equivalent linear calculations (Kacar, 2013).

4 FIELD LOAD-SETTLEMENT TEST

To begin to develop a database of measured footing settlements at granular sites with in-situ seismic and nonlinear dynamic laboratory measurements, a small-scale footing was constructed at a site in Austin, Texas. A detailed geotechnical investigation was carried out at the site, including soil sampling, cone penetration testing (CPT), Spectral-Analysis-of-Surface-Waves (SASW) seismic tests, and crosshole seismic tests.

4.1. *Soil Properties at Test Site*

Based on standard laboratory tests, the soil at the field site is a lightly overconsolidated, non-plastic silty sand with a friction angle of 39 degrees and a cohesion of 6.1 kPa (likely resulting from capillary stresses). Results from SASW and crosshole seismic tests and CPT tests are presented in Figure 1. The friction ratio averages about 1.1% between depths of 0-2.1m and about 0.7% between depths of 2.1m-4.9 m.These friction ratios are indicative of nonplastic granular soils (Lunne et al., 2002). As seen in Figure 1, good agreement exists between the crosshole and SASW results. Therefore, the average V_s profile from four SASW tests was used to model the soil. With this profile and the average mass density of the soil determined from intact samples (1.70 g/cm^3), the small-strain shear modulus (G_{max}) versus depth profile before loading the footing was modeled as:

$$G_{max} = G_{\max\_1atm}\left(\frac{\sigma_0'}{P_a}\right)^{n_G} \qquad (3)$$

where $G_{\max\_1atm}$ = small-strain shear modulus at an effective confining pressure of 1atm; σ_0' = mean effective

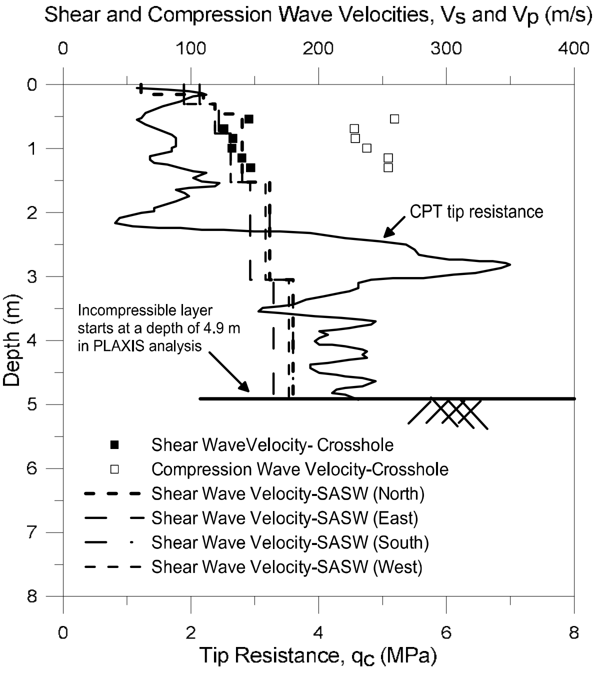


Figure 1. In-situ seismic and CPT test results at the field site of the load-settlement tests with a 0.91-m diameter footing

confining pressure (calculated using $K_0 = 0.70$ and a capillary stress of 3 kPa); $P_a =$ reference mean effective confining pressure, 1 atm; and $n_G =$ slope of the $\log G_{max}$–$\log \sigma_0'$ relationship. The modeling represented by Equation 3 resulted in the two-layer profile presented in Figure 2. The G_{max_1atm} and n_G parameters for each layer are: layer 1 - G_{max_1atm} = 86.2 MPa and 0.48; layer 2 - G_{max_1atm} = 74.2 MPa and 0.51, respectively. The values of n_G close to 0.5 indicate that the soil in each layer is uncemented.

4.2. *Load-Settlement Test*

A reinforced concrete footing with a diameter of 0.91 m and a thickness of 0.30 m was constructed at the site after removing the upper 0.25 m of soil. Linear potentiometers, attached to a reference frame were used to measure footing settlements. The load was applied by a hydraulic jack reacting against the weight of a tri-axial vibroseis truck, named T-Rex, as shown in Figure 3a. The load was measured with a 50-kip load cell and was applied to the top of the footing through a loading frame (see Figure 3b). The load–settlement test was performed in March, 2010. The measured load-settlement curve is presented in Figure 4 by the solid line.

5 COMPARISON OF PREDICTED AND MEASURED LOAD-SETTLEMENT CURVES

To investigate the settlement prediction methods, predicted and measured load-settlement curves are compared. The prediction methods are: (1) Schmertmann et al. (1978) CPT-based method, (2) Burland and Burbidge (1985) SPT-based method and (3) the method based on dynamic soil properties presented herein. The predicted and measured load-settlement curves are presented in Figure 4 and are discussed below.

For the Schmertmann et al. method, the elastic moduli were calculated based on the CPT results using:

$$E_s = 2.5q_c \tag{5}$$

where $E_s =$ modulus of elasticity of the soil; and $q_c =$ cone penetrometer tip resistance. The upper 2 m of soil under the footing was divided into 5 layers and an average value of 1.53 MPa of q_c was assigned to each layer. Additional details on the procedure can be found in Van Pelt (2010). As seen in Figure 4, the predicted load-settlement curve is not as nonlinear as the measured curve, but predicts quite well in the working-load range.

For the Burland and Burbidge (1985) method, settlements are estimated using the SPT blow count, N_{60} in the correlation:

$$s = \frac{1.71 q B^{0.7}}{{N_{60}}^{1.4}} \tag{6}$$

where $s =$settlement (mm); $q =$applied bearing pressure (kPa); $B =$footing diameter (m); and $N_{60} =$ average SPT blow count over the depth of influence which is about 1 m for a footing with B = 1m, uncorrected for overburden pressure. As no SPT tests were performed at the field site, the CPT tip resistance values were correlated to SPT blow count using the correlations proposed by Robertson et al. (1983). For an average q_c value of 1.53 MPa, this correlation gives an average value of 5 for the SPT blow count. As seen in Figure 4, the predicted load- settlement

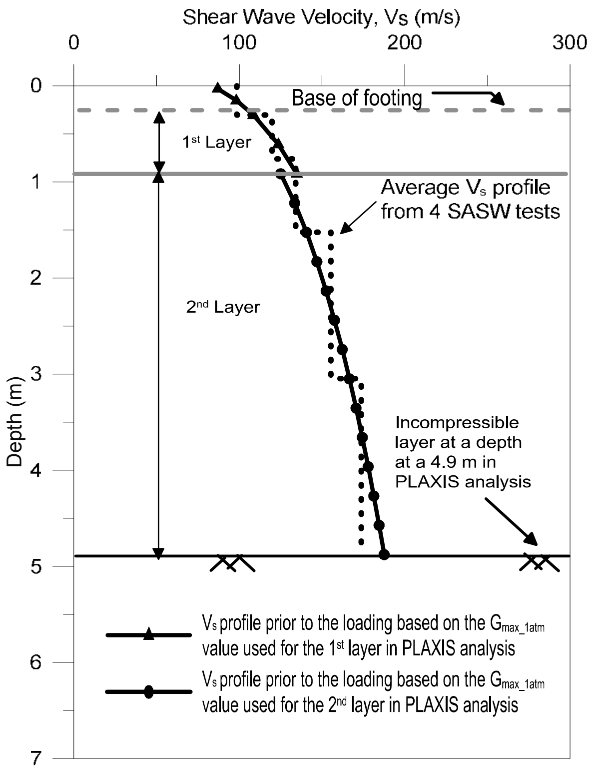
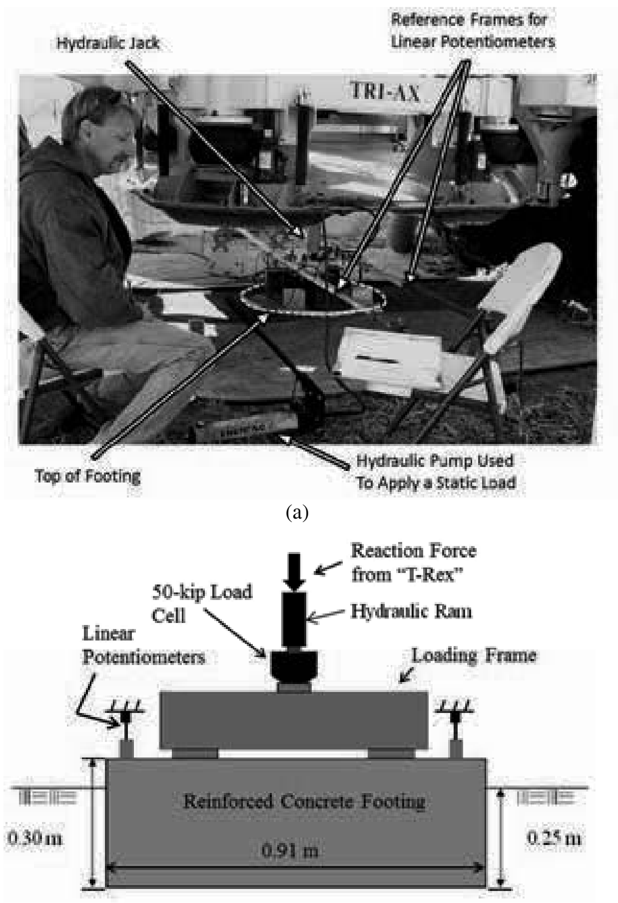


Figure 2. Average V_s profile from SASW tests and the two-layer model used in the finite element analysis



(a)

(b)

Figure 3. Field Load-settlement test: (a) T-Rex in position during loading (b) Cross-section of the load-settlement arrangement

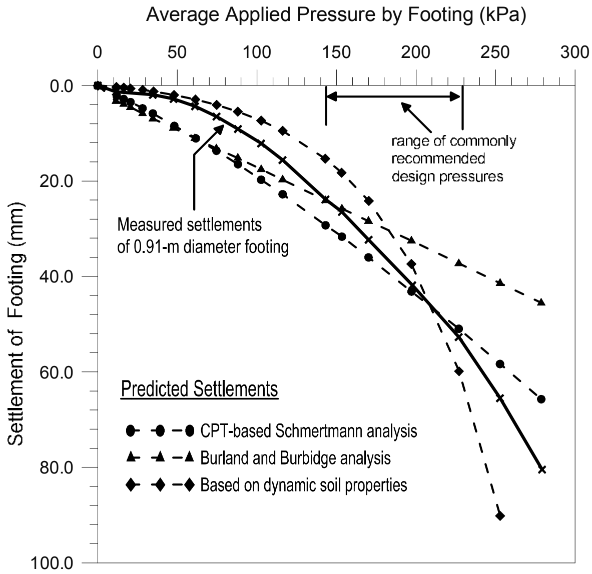


Figure 4. Measured and predicted load-settlement curves for the 0.91-m diameter footing

curve is linear while the measured settlements are nonlinear. Also, the predictions underestimate the measured settlements at higher working loads.

For the method based on dynamic soil properties, a two-layer G_{max} profile was developed from the two-layer V_s profile presented in Figure 2. A thickness of soil beneath the footing of 5B was used in the settlement analysis to eliminate boundary effects (Brinkgreve et al, 2011). With the subroutine that incorporates Equations 1, 2 and 3 in PLAXIS, a finite element analysis was performed. As noted earlier, the G_{max} values were adjusted to the increasing stress state and the G values in the G/G_{max}-log γ relationships were adjusted to the increasing shear strain during loading. As seen in Figure 4, the predicted load-settlement curve captures much of the nonlinearity exhibited in the load-settlement curve. The primary point of concern is that the predicted curve is more nonlinear than the measured curve, particularly above settlements around 70 mm. This difference is being investigated. However, it must be pointed out that the predictive method based on dynamic soil properties worked quite well in this case study with fine-grained granular soils and, in theory, should be just as readily applied to coarse-grained granular soils with gravel and cobbles.

6 CONCLUSIONS

A new method for predicting settlements of shallow footings on granular soils is presented. The method is based on field seismic measurements to evaluate the small-strain shear moduli (G_{max}) combined with nonlinear normalized shear modulus-shear strain (G/G_{max}-log γ) relationships determined in the laboratory from dynamic resonant column testing. Important factors in the model are that: (1) G_{max} values are adjusted to the increasing stress during loading and (2) the G values in the G/G_{max}-log γ relationships are adjusted to increasing strain levels. A subroutine was written to incorporate this formulation in a commercially available finite element program, PLAXIS. The method was investigated by comparing with a load-settlement test using a 0.91-m diameter footing. In the working stress range, predicted nonlinear footing settlements compared quite well with the measured ones. The predicted nonlinear settlements in this range were also in reasonable agreement with predictions from traditional CPT and SPT procedures.

The new predictive method has several advantages over traditional CPT and SPT methods. First, field seismic measurements are used to characterize the soil in-situ. Field seismic measurements, especially those done with surface-wave tests, are readily applied to all granular soils, including soils containing gravel and cobbles which are difficult to test by CPT and SPT methods. Second, the nonlinear characterization of granular soil modeled with G/G_{max}-log γ relationships captures the nonlinear stress-strain curve of the granular soil during loading. Third, in the case of field seismic measurements with surface-wave tests, all equipment is placed on the ground surface (no boreholes). The V_s profile is nearly continuous with depth. They are quickly performed, cost effective and begin evaluating stiffness within centimeters of the surface. Finally, the new method is applicable to all geotechnical materials, even cemented gravelly soils and fine-grained soils that are consolidating under the footing loads. Work is presently underway with large-grained cemented alluvium.

7 REFERENCES

Berardi R. and Lancellotta R. 1991. Stiffness of granular soil from field performance. *Geotechnique* 41(1) 149-157

Brinkgreve R.B.J., Swolfs W.M and Engin E. 2011. Plaxis 2D 2011. *Tutorial Manual*

Burland J.B. and Burbidge M.C. 1985. Settlement of foundations on sand and gravel. *Proceedings, Institution of Civil Engineers*. 78(1) 1325-1381

Darendeli M.B. 2001. Development of a new family of normalized modulus reduction and material damping curves. *Ph.D. Dissertation, University of Texas at Austin*, 362 p.

Hardin B.O. and Drnevich V.P. 1972. Shear modulus and damping in soils; Design equations and curves. *Journal of the Soil Mechanics and Foundation engineering Division, ASCE* 98(7) 667-692

Kacar O. 2013 (expected) Predicting settlement of shallow footings on granular soil using field seismic and laboratory dynamic nonlinear soil properties. *Ph.D. Dissertation, University of Texas at Austin*

Menq F. 2003. Dynamic properties of sandy and gravelly soils. *Ph.D. Dissertation, University of Texas at Austin,* 364 p.

Meyerhof G.G. 1965. Shallow foundations. *Journal of the Soil Mechanics and Foundations Division, ASCE* 91(SM2), 21-31

Lehane B. and Fahey M. 2002. A simplified nonlinear settlement prediction model for foundations on sand. *Canadian Geotechnical Journal* 39(2) 293-303

Lee J. and Salgado R. 2001. Estimation of footing settlement in sand. *International Journal of Geomechanics* 2(1) 1-28

Lunne T., Robertson P.K. and Powell J.J.M. 2002.*Cone Penetration Testing in Geotechnical Practice,Spon Press, New York*

Robertson P.K., Campanella R.G. and Whightman A. 1983. SPT-CPT correlations. *Journal of Geotechnical Engineering* 109(11) 1449-1459

Schmertmann J.H. 1970. Static cone to compute static settlement over sand. *Journal of the Soil Mechanics and Foundations Division, ASCE* 96(3), 1011-1043

Schmertmann J.H., Hartman J.P. and Brown P.R. 1978. Improved strain influence factor diagrams. *Journal of the Geotechnical Engineering Division, ASCE* 104(8), 1131-1135

Stokoe K. H., II, Wright S.G., Bay J.A., and Roesset J.M. 1994. Characterization of geotechnical sites by SASW method. *Geophysical characteristics of sites,ISSMFE, Techical committee 10 for XIII ICSMFE, International Science Publishers, New York* 15-25

Terzaghi K. and Peck R.B. 1948. *Soil Mechanics in Engineering Practice,* 1st edition, John Wiley & Sons, New York

Van Pelt J. 2010.Predicting of settlements of shallow foundations on cohesionless, granular soil using dynamic soil measurements. *M.S. Thesis. University of Texas at Austin*, 363 p..