Analytically and experimentally based resistance factors for "full-flow" penetrometers

Résistance-facteurs pour "full flow" pénétromètres, basé sur résultats analytiques et expérimentaux

Pinkert S.
Department of Civil Engineering, University of Calgary, Calgary, Canada.

Klar A.
Faculty of Civil and Environmental Engineering, Technion – Israel Institute of Technology, Haifa, Israel.

ABSTRACT: There are several geotechnical problems for which the formulation of large deformations is vital for their solution. Among these problems are in-situ penetration tests. In this paper, a new numerical approach is used to solve such problems efficiently with the aim to calibrate fundamental soil properties to fit the global penetration resistance obtained from experimental studies. The utilized numerical method treats the continuum as rigid plastic with a non-uniform strength field, where the spatial distribution of strength is determined by converting time changes into spatial distributions using the governing equation of steady state flow. For this purpose, the method employs an upstream weighting technique for determination of information flow within the domain. Using the suggested method, the resistance factors for in-situ T-bar and ball penetrometers were obtained under a various soil conditions. These included the rate effect on the soil, strain softening and anisotropy, all of which affect the shear strength of the soil. General expressions for the resistance factors of the T-bar and ball penetrometers are finally suggested for engineering use.

RÉSUMÉ : Il ya plusieurs problèmes géotechniques pour lesquels la formulation des grandes déformations est vitale pour leur solution. Parmi ces problèmes, les tests de pénétration in situ. Dans cet article, une nouvelle approche numérique est utilisée pour résoudre ces problèmes de manière efficace. L'objectif est de calibrer les propriétés fondamentales du sol pour s'adapter à la résistance à la pénétration globale obtenue à partir des résultats expérimentaux. La méthode numérique, qui a été utilisée, représente le continuum comme plastique rigide avec une intensité de champ non uniforme, où la répartition spatiale de la résistance est déterminée par des changements de temps e convertir les distributions spatiales en utilisant des équations de débit en régime permanent. A cet effet, le procédé met en œuvre une technique de pondération pour la détermination de l'amont du flux d'information dans le domaine. L'utilisation de la méthode proposée, les facteurs de résistance pour l'in situ T-bar pénétromètre et le pénétromètre à billes ont été obtenus dans un sol différent. Les analyses incluent les effets du sol ; taux effet, adoucissement et l'anisotropie, qui tous affectent la résistance au cisaillement du sol. Expressions générales pour les facteurs de résistance du pénétromètre barre en T et le pénétromètre à billes sont finalement suggérés d'utiliser l'ingénierie.

KEYWORDS: full-flow, penetration test, in-situ, undrained shear strength.

1 INTRODUCTION

In situ continuous penetration tests have the ability to characterize the soil profile with minimal disturbance. Commonly, the test is performed by inserting a penetrometer at a constant rate while measuring the resistance force, with which the soil strength may be correlated.

This paper focuses on T-bar and ball penetrometers, presented in Fig. 1, which have been used increasingly over the last decade especially in offshore engineering (Randolph, 2012). These devices are also called "full-flow" penetrometers, since the soil can flow fully around them (ignoring the presence of the leading shaft). The penetration resistance of the "full-flow" penetrometers is less affected by the additional volume that is being pushed into the ground (comparing to the CPT), as it is mainly governed by the flow-around failure mechanism. In other words, the behavior is practically independent of the elastic stiffness.

During the penetration process, soil elements which were located below the penetrometer are later found above it. Consequently, the undrained shear strength might be disturbed along this path due to the cumulative shear strains and rotations the soil elements had experienced. Therefore, in order to evaluate the relation between the global penetration resistance and the soil undisturbed undrained shear strength, a thorough investigation of both the failure mechanism of the soil and the different soil strength effects should be performed.

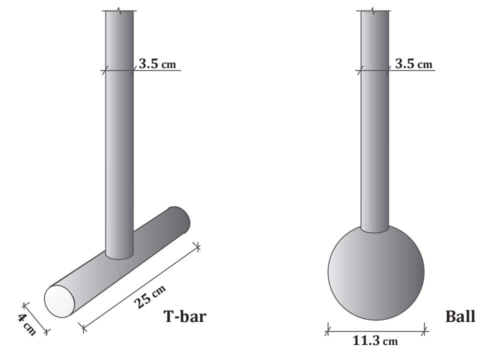

Figure 1. The T-bar and ball penetration devices.

2 UPSTREAM WEIGHTING METHOD

For this aim, this paper utilizes the topological ordering based upstream weighting method developed by Klar and Pinkert (2010). The method's formulation is relevant to undrained conditions and for problems in which the overall behavior is governed by plastic flow (and not by elastic deformation). The method considered the penetration process as steady state problem, from the penetrometer point of view, in which time changes are interchangeable with spatial distribution. The strength field obtained efficiently by integrating state variables along streamlines. Rather than backtracking and integrating each element behavior along its individual streamline, the method utilizes topological ordering based on upstream weighting, and calculates the cumulative information within the flow direction. The use of this method allows consideration of various aspects of soil behavior, including rate effect, strain softening and anisotropy. General agreement between the results of this method and the numerical "re-meshing" method of Zhou and Randolph (2007, 2009) exists. It should be noted that the upstream weighting method has the engineering advantage of being an upper-bound solution, and thus necessarily conservative for evaluating strength values from penetration resistance.

3 SOIL STRENGTH

The soil strength might be modified due to different soil effects. The formulation of the undrained shear strength in this work describes shear rate strengthening, f_r , strength degradation due to accumulation of shear strains, f_{ss}, and due to the influence of large rotations in anisotropic soils, f_{an}. The effect of these three factors on the undrained shear strength is given by:

$$s_u = f_r f_{ss} f_{an} s_{u0} \tag{1}$$

where s_u is the undrained shear strength and s_{u0} is the reference (undisturbed) undrained shear strength. The above soil strength effects were rigorously studied and presented below:

3.1. Strain rate effect:

The strain rate factor used in this work is based on Dayal and Allen (1975), and is the basis of many other works (e.g., Randolph, 2004, Einav and Randolph, 2005, Yafrate and DeJong, 2007, Klar and Osman, 2008, Klar and Pinkert, 2010, Zhou and Randolph, 2007&2009), given by:

$$\frac{s_u}{s_{u0}} = 1 + \mu \log\left[\max\left(\frac{\dot{\gamma}}{\dot{\gamma}_{ref}}, 1\right)\right] \tag{2}$$

where $\dot{\gamma}$ is the maximum engineering shear strain rate $\left(= \dot{\varepsilon}_1 - \dot{\varepsilon}_3\right)$, $\dot{\gamma}_{ref}$ is the reference shear rate associated with s_{u0} (1%/hour for standard CU triaxial test) and μ is the soil viscosity parameter. Yafrate et al. (2009) suggested extracting μ directly from the global resistance of two penetration tests at different penetration rates using the same logarithmic relation as Eq. 2, applied directly on the velocity. Pinkert (2012) utilized the "upstream weighting" analyses to show that μ used in Eq. 2 is not the same parameter which describes the increasing in the global penetration resistance due to the increase in the penetration rate, μ^*, as can be shown in Fig. 2.

In addition to the numerical analyses, Pinkert (2012) developed an algebraic relation between these two parameters, given by:

$$\mu = \frac{\mu^*}{1 - 5\mu^*} \qquad \mu^* = \frac{q_1/q_2 - 1}{\log\left[(v/d)_1/(v/d)_2\right]} \tag{3}$$

where q is the penetration resistance (in stress units), v is the penetration velocity, d is the penetrometer diameter, and the subscripts 1 and 3 denotes two different penetration tests.

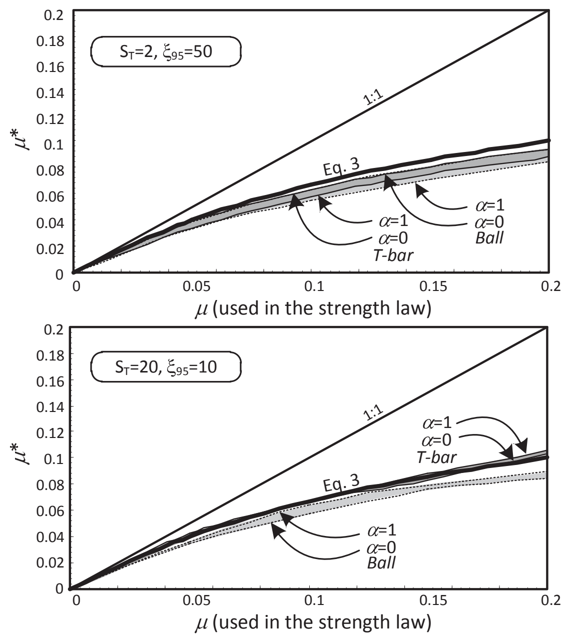

Figure 2. μ versus μ^* for the all range of friction ratio ($0 \le \alpha \le 1$), and for different softening properties, after Pinkert (2012).

3.2. Strain softening effect

The strain softening factor used in this work was developed by Pinkert (2012), and may be considered a modification of the "common" strain softening model used in all previous works (e.g., Randolph, 2004, Einav and Randolph, 2005, Yafrate and DeJong, 2007, Klar and Osman, 2008, Klar and Pinkert, 2010, Zhou and Randolph, 2007&2009), given by:

$$\frac{s_u}{s_{u0}} = \frac{1}{S_T} + \left(1 - \frac{1}{S_T}\right)e^{-3\left(\xi/\xi_{95}\right)^{\beta}} \tag{4}$$

where S_T is the soil sensitivity (=$s_{u0}/s_{u,residual}$), ξ is the cumulative engineering strain rate, ξ_{95} is the amount of ξ required for 95% remolding and β is a constant. The β parameter does not exist in all previous (aforementioned) works. Pinkert (2012) showed that a value of 2/3 for β gives a good fit to the decay function observed in cyclic penetration tests, under a wide range of soil sensitivities. Note that the relation between ξ_{95} and N_{95} (the number of cycles required to achieve 95% degradation in the measured resistance, in a cyclic penetration test) as presented in Einav and Randolph (2005) is somewhat inconsistent, since N_{95} is associated with degradation from the first insertion which cannot truly represent an undisturbed state (since ξ does not remain zero at the first insertion). For that reason, Pinkert (2012) suggested a theoretical parameter, N^*_{95}, which is related to N_{95}, and thus can be extracted from field test results. The expression for evaluating ξ_{95} from cyclic field test results is given by:

$$\xi_{95} = 2\xi_p N^*_{95} = 2\xi_p\left(N_{95}^{2/3} - 0.5^{2/3}\right)^{3/2} \tag{5}$$

where N_{95} can be correlated with S_T following Yafrate et al. (2009):

$$N_{95} = 9.6 S_T^{-0.27} \tag{6}$$

and ξ_p is the average magnitude of shear strain undergone by soil elements passing through the failure mechanism in individual penetration, which can be estimated based on values presented in Zhou and Randolph (2009) for both T-bar and ball:

$$\xi_{p,Tbar} = 0.83\log\left(S_T\right) + 3.09 \qquad \xi_{p,ball} = 1.1\log\left(S_T\right) + 2.62 \tag{7}$$

Fig. 3 shows the agreement between the results obtained using the new softening model (Pinkert, 2012) and the commonly used softening model, for one of the examined test sites reported by Yafrate et al. (2009). Similar agreement was obtained for the other sites. This degradation model is later used in the creation of a general expression for engineering use.

3.3. Anisotropy effect:

Klar and Pinkert (2010) examined the effect of soil anisotropy. In this specific problem the resistance is also affected by the rigid body rotation which soil elements experience through the penetration process. Two models of anisotropy were considered: [a] in which the anisotropy ratio remain constant with degradation, and [b] in which the anisotropy ratio diminishes with increasing cumulative shear strains. It was found that if an "average" undrained shear strength value (i.e. average of the undrained shear strengths measured in the horizontal and the vertical directions) is used in the normalization of the resistance factor, the effect of anisotropy is minimal. Consequently, the measured penetration resistance may only indicate on the average strength.

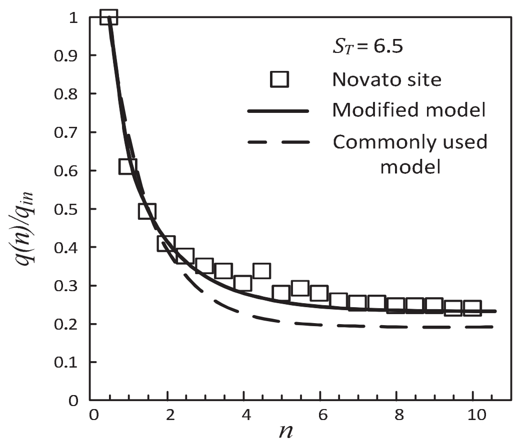

Figure 3. Normalized cyclic penetration resistance results for each cycle, *n*, of the (1) experimental results, (2) the numerical results using the commonly used stain softening model and (3) the numerical results using the new strain softening model.

4 ALGEBRAIC EXPRESION FOR ENGINEERING USE

The above trends and solutions were unified to result in a single algebraic expression, which was calibrated using the topological ordering based upstream weighting method developed by Klar and Pinkert (2010). The range of calibration corresponds to $\mu^*\leq 0.15$, $S_T\leq 50$ and $0.05\leq v/d\leq 12.5$. For engineering use, the undisturbed undrained shear strength, s_{u0}, may be evaluated as follows:

$$s_{u0} = \frac{P}{AN_i} \tag{8}$$

where P is the measured penetration force, A is the projected area of the penetrometer, and N_i is the resistance factor for T-bar and ball as given by:

$$N_{Tbar} = \beta_1 N_{Tbar,ref} \left(1 - 0.22\log(S_T) - \frac{0.114}{1+\left(\frac{S_T}{15}\right)^{-7}} \right)$$
$$\beta_1 = \left(1 + \frac{4.5\mu^*}{1-5\mu^*} \right) \left(1 + \mu^* \log \frac{v/d}{(v/d)_{ref}} \right) \tag{9}$$

$$N_{ball} = \beta_2 N_{ball,ref} \left(1 - 0.55\log(S_T) + \frac{0.438}{1+\left(\frac{S_T}{11}\right)^{-1.8}} \right)$$
$$\beta_2 = \left(1 + \frac{4.2\mu^*}{1-5\mu^*} \right) \left(1 + \mu^* \log \frac{v/d}{(v/d)_{ref}} \right) \tag{10}$$

where $N_{Tbar,ref}$ =11.98 and $N_{ball,ref}$ =15.23, which relate to the conventional penetration velocity and penetrometer geometry, for a non-viscous soil. $(v/d)_{ref}$ is equal to 0.5 for T-bar and 0.18 for ball. The parameter μ^* may be evaluated from at least two test results, at different v/d ratios, according to Eq. 3 and the value of S_T can be evaluated using the first insertion and first extraction of the penetrometer (Yafrate et al., 2009):

$$S_T = \left(\frac{q_{in}}{q_{out}} \right)^{3.7} \tag{11}$$

where q_{in} and q_{out} are the penetration resistances (=P/A) at the first insertion and extraction, respectively, in a cyclic penetration test.

5 CONCLUSIONS

The paper utilizes an advance numerical approach, which is calibrated using field experimental tests results, to produce a unified expression for the evaluation of the undrained shear strength from "full-flow" penetrometers (T-bar and ball). The resulting expressions may be used for determination of the soil undrained strength value, by a set of minimum two tests, one cyclic and the other under different penetration rate.

6 REFERENCES

Dayal U. and Allen J.H. 1975. Effect of penetration rate on strength of remolded clay and sand samples. *Canadian Geotechnical Journal* 12 (3), 336–348.

Einav I. and Randolph M. 2005. Combining upper bound and strain path methods for evaluating penetration resistance. *International Journal for Numerical Methods in Engineering* 63 (14), 1991-2016.

Klar A. and Osman A. S. 2008. Continuous velocity fields for the T-bar problem. *International Journal for Numerical and Analytical Methods in Geomechanics* 32, 949–963.

Klar A. and Pinkert. S. 2010. Steady state solution for cylindrical penetrometers. *International Journal for Numerical and Analytical Method in Geomechanics* 34, 645-659.

Pinkert S. 2012. Solution of steady state plastic flow problems in saturated clays, *PhD dissertation*, Technion - ITT, Israel.

Randolph M. F. 2004. Characterisation of soft sediments for offshore applications. Proc. 2nd Int. Conf. on Site Characterisation 1, 209–231, Porto.

Randolph, M.F. 2012. Offshore Geotechnics – the Challenges of Deepwater Soft Sediments. ASCE Geotechnical Special Publication No. 226: Geotechnical Engineering State of the Art and Practice: Keynote Lectures from GeoCongress 2012. 241-271.

Yafrate N. J. and DeJong J. T. 2007. Influence of penetration rate on measured resistance with full-flow penetrometers in soft clay. *In New Peaks in Geotechnique*, GeoDenver. Denver. US.

Yafrate N.J., DeJong J.T., Degroot D. and Randolph M.F. 2009. Evaluation of remolded shear strength and sensitivity of soft clay using full flow penetrometers. *Journal of Geotechnical and Geoenvironmental Engineering* 135 (9), 1179-1189.

Zhou H. and Randolph M.F. 2007. Computational techniques and shear band development for cylindrical and spherical penetrometers in strain-softening clay. *International Journal of Geomechanics* 7(4), 287-295.

Zhou H. and Randolph M. F. 2009. Numerical investigations into cycling of full-flow penetrometers in soft clay. *Geotechnique* 59(10), 801–812.