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A state parameter-based cavity expansion analysis for interpretation of CPT data in sands

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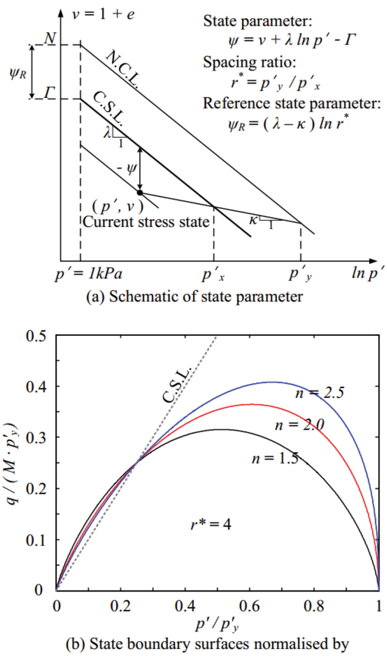
ABSTRACT: Cone Penetration Testing (CPT) serves as a useful in-situ tool for site investigation and soil characterization, while the end-bearing and shaft capacities of driven piles could be directly related to the CPT measurements. In terms of interpretation of CPT data, state parameter concept has been employed largely owing to its good indication of soil behaviour at different stress levels and densities. Drained cavity expansion solution in a unified state parameter model for clay and sand (CASM) is adopted in this paper for the applications to CPT in sands regarding to in-situ soil state. The effects of initial stress condition, friction angle and soil compressibility on the correlations between cone tip resistance, sleeve friction and state parameter are presented and discussed. The proposed method indicates the influence of initial state parameter on the evaluation of normalised penetration resistance, and the state parameter is directly related to the soil behaviour type index. The analysis contributes to the theoretical background of the framework for interpretation of CPT data.

1 INTRODUCTION

The cone penetration test (CPT) has become a widely used in situ soil testing method, owing to its repeatability and accuracy at relatively low cost (IRTP, 1999; Robertson, 2009; Shuttle & Jefferies, 1998). Interpretation of CPT data aims to obtain soil parameters from the CPT continuous soundings by solving the inverse boundary value problem, which is usually replaced by empirical correlations determined from calibration chamber tests. Based on geometric similarity, CPT-based design methods for driven piles have been developed with examination of relationships between cone tip resistance and pile capacity in siliceous sands (e.g. Fugro-05, ICP-05, NGI-05, UWA-05). However, penetration mechanism is not well understood yet because penetration in soils is a complicated process in which soil flows around the penetrometer, large strains and stress distributions are generated, together with the hardening/softening of soils. In consideration of a soil model with strain hardening, numerical simulations have been conducted to analyze various boundary value problems, including cone penetration test and pile installation (e.g. Dijkstra et al., 2007; Kouretzis et al., 2014; Ahmadi & Golestani Dariani, 2017), while analytical solution is rather difficult and limited. In terms of available analytical solutions, cavity expansion methods have been proved to be suitable for analysis of penetration problems (Mo et al., 2017; Mo & Yu, 2017), whereas numerical techniques are usually employed for more realistic situations (Shuttle & Jefferies, 1998; Suzuki & Lehane, 2015).

Compared to the conventional interpretation methods using the relative density or void ratio, the state parameter (ψ, difference between the void ratio in the current state and that at the critical state for the same stress condition, after Been & Jefferies, 1985, see Figure 1a) is of a more fundamental importance to practicing engineers due to its correlations with friction/dilation angles derived from the critical state soil mechanics, as well as some indication of potential soil liquefaction. The use of state parameter has also been reported by many researchers for interpreting CPT data (Been et al., 1986; Ghafghazi & Shuttle, 2008; Reid, 2015). The correlations between normalised cone tip resistance and initial state parameter were found to be arguably unique for sand with various conditions. The interpretation of CPT data with the state parameter concept is therefore preferred for characterizing sand behaviour, and the state parameter-based prediction of pile bearing capacity in sands using CPT measurements is potentially an effective approach. However, the current correlations for CPT data interpretation are still heavily



(a) Schematic of state parameter

(b) State boundary surfaces normalised by preconsolidation pressure

Figure 1. Illustration of CASM after Yu (1998): (a) schematic of state parameter, (b) state boundary surfaces.

relying on empirical methods, which remain the lack of theoretical explanations and hold the limitations for implication on variety of soil types.

This paper aims to develop the interpretation with a more sophisticated soil model and the cavity expansion theory, which could contribute to the establishment of framework for interpretation with following investigations. In this study, a newly developed drained cavity expansion solution is adopted for the investigation of CPT data in sands using state parameter concept. After applying the large strain analysis with critical state soil model CASM, the cone tip resistance is predicted from the spherical cavity expansion solution. The effects of initial stress condition, friction angle, and soil compressibility are investigated in associated with the influence of initial state parameter.

2 CAVITY EXPANSION SOLUTION AND INTERPRETATION APPROACH

In this study, the drained cavity expansion solution in sands is provided by Mo & Yu (2018), in which the unified state parameter soil model CASM (Yu, 1998) is applied. The model, adopting the critical state concept, was developed based on the original Cam-clay model and formulated in terms of the state parameter, which is illustrated in Figure 1(a). Comparing to the original Cam-clay model, two additional parameters (spacing ratio r^* and stress-state coefficient n) were introduced to propose a general stress-state relation for both clay and sand by modifying the state boundary surfaces (see Figure 1b), which was then validated to capture overall behaviour of various soils under both drained and undrained loading conditions. The details on parameter determination and the comparisons with experimental data could also be found in Yu (1998).

Based on the developed cavity expansion solution in sandy soils, an initial cavity with a radius of a_0, embedded in an infinite geomaterial with isotropic stress condition, is uniformly expanded to an arbitrary size of a. The increased cavity pressure corresponding to the process of expansion is thus utilized for the analyses of cone tip resistance and sleeve friction, where spherical cavity expansion is assumed around the cone tip based on the analogous observation of soil deformation (Mo et al., 2015). The penetration of a probe is modeled as an expansion of cavity with radius from 0.1mm (equivalent to grain size level) to 17.8mm (radius of a standard CPT probe), and the relation between cavity pressure and cone tip resistance can be given by Eq. (1), following Ladanyi & Johnson (1974) and Suzuki & Lehane (2015).

$$q_c = \sigma_{r,wall,sph}^{a_0 \to a} \times \left(1+\sqrt{3}\tan\phi_{sph}\right) \tag{1}$$

The sleeve friction (τ_s) of penetrometer could be predicated by Eq. (2), following the UWA-05 CPT based design method for driven piles in siliceous sand (Xu, 2007).

$$f_s = \left\{0.03\, q_c\, (h/D)^{-0.5} + 4G_0 \Delta y/D\right\} \times \tan\delta_y \tag{2}$$

where h is penetration depth of the probe, G_0 is shear modulus from the cavity expansion solution ($G_0 = [3(1-2\mu)\nu_0\ p_0]/[2(1+\mu)\,\kappa]$, following Mo & Yu, 2018), Δy is the radial displacement during penetrometer loading $\Delta y \sim 0.02$ mm), and δ_y is the interface friction angle ($\delta_y \sim 15°$).

3 PARAMETRIC STUDY FOR INTERPRETATION OF CPT DATA

As the solution utilized the state parameter as an important property determining soil behaviour, the interpretation of CPT data gains its benefits. Previous experimental and numerical study have also shown the correlations between state parameter and CPT measurements. Results of parametric study are presented in this section to investigate the effects of initial stress condition, friction angle, critical state parameter λ, as well as the initial state parameter. The sand model parameters in this paper are selected for Ticino sand (after Yu, 1998 and Mo & Yu, 2018): $\mu = 0.3$, $\Gamma = 1.986$, $\lambda = 0.024$, $\kappa = 0.008$, $\phi_{tx} = 32°$, $r* = 108.6$, $n = 2.0$. The effect of initial state parameter on the computed behaviour of drained triaxial compression tests on Ticino sand was provide by Yu (1998) and shown in Figure 2. The selection of Ticino sand is also because of its extensively investigations from laboratory elementary tests and CPT tests. For spherical scenario, the critical-state friction angle is assumed as $\phi_{sph} = \phi_{tx}$, and the friction constant is then determined with $M = 6\sin\phi_{sph}/\left(3-\sin\phi_{sph}\right)$. State parameter ($\psi$) is taken as an important indicator for the interpretation of CPT data, and the variation of ψ_0 ranges from -0.3 to 0.075 ($\psi_R = (\lambda-\kappa)\ln r^* = 0.075$ as the reference state parameter) in this study. Note that sand with negative value of ψ_0 is located at the 'dry' side of the critical state line, indicating a denser initial condition with a high value of overconsolidation ratio. Figure 3 shows the stress paths of cavity expansion with variation of initial state parameter for tests under a constant initial stress condition $p_0 = 200\ kPa$. The ultimate stresses after expansion decrease with the state parameter, and the ultimate specific volume is higher for a larger value of initial state parameter. The difference on stresses is over an order of magnitude from $\psi_0 = -0.3$ to $\psi_0 = 0.075$ thus the influence of initial state parameter is obviously significant.

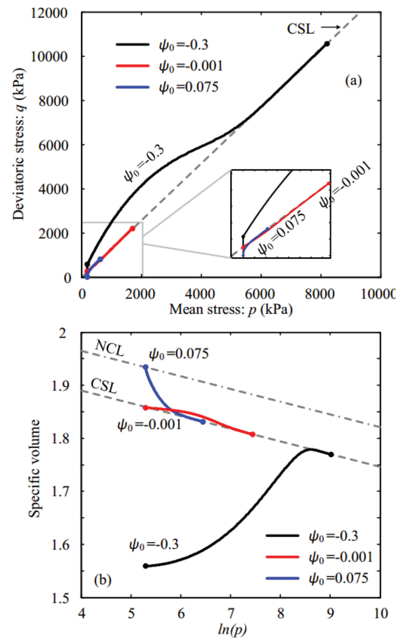


Figure 3. Relationships of (a) spherical cavity pressure and (b) normalised cone tip resistance against initial state parameter with various initial stress condition.

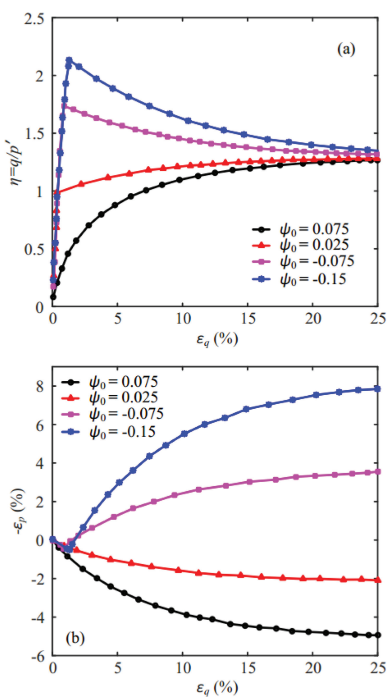


Figure 2. Estimation of responses of drained triaxial compression tests for Ticino sand: (a) stress ratio against deviatoric strain; (a) volumetric strain against deviatoric strain (after Yu, 1998).

3.1 *Effect of initial stress condition*

The effect of initial stress condition is examined by varying p_0 from 200 kPa to 1000 kPa in this section. Increased initial stress condition relates to a high magnitude of shear modulus, resulting to the growth of spherical cavity pressure, as presented in Figure 4(a). The decrease of cavity pressure with state parameter shows non-linear behaviour. Applying the correlation between q_c and $\sigma_{r,wall,sph}$ (Eq. 1), the normalized cone tip resistance is defined as Eq. (3), according to Robertson (1990) and Been et al. (1986).

$$Q_{t1} = \frac{q_c - p_0}{p_0} \tag{3}$$

It can be found from Figure 4(b) that the normalized cone tip resistance is hardly affected by the initial stress condition, in contrast to the trends

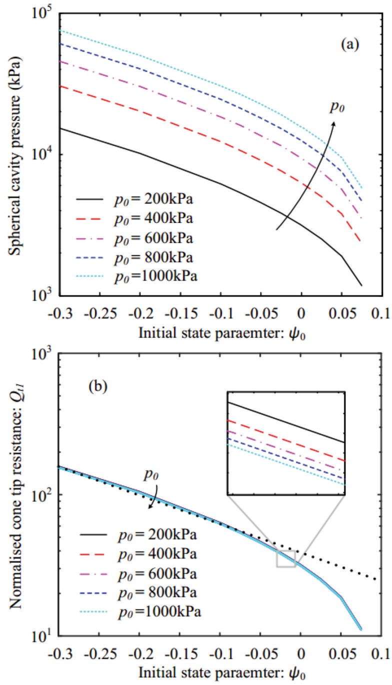


Figure 4. Relationships of (a) spherical cavity pressure and (b) normalised cone tip resistance against initial state parameter with various initial stress condition.

of cavity pressure. This phenomenon indicates the direct relationship between Q_{tl} and ψ_0, irrespective of stress condition and relative density, which is also confirmed by numerical simulation of cone penetration tests (Kouretzis et al., 2014). The linear expression between ψ_0 and $\log Q_{t1}$ was reported by Been et al. (1988), providing an expression of $Q_{t1} = k \cdot \exp(-m \cdot \psi_0)$. The results show that m value increases with ψ_0, and linear curve fitting provides the soil-specific coefficients as: $k = 39$ and $m = 4.67$ for $\psi_0 < -0.05$.

Considering the nonlinear increase of q_c with p_0 for various soils, the normalization of cone resistance is suggested with a variable stress exponent n (approximated by the SBTn index and effective overburden stress, after Robertson, 2009), where

$$Q_{tn} = \frac{(q_c - p_0)/p_a}{(p_0/p_a)^n} \tag{4}$$

and p_a is the atmospheric pressure. The normalised tip resistance Q_{tn} shows a slight decrease with initial stress condition (see Figure 5). Finite element simulation of calibration chamber testing in Ticino 4 sand was reported by Ghafghazi & Shuttle (2008), indicating the relation between Q_{tn} and ψ_0. Additional, experimental data from Maki (2014) was originally derived from calibration chamber tests of Ticino sand by Been et al. (1986), and both calibration chamber corrections by Been et al. (1986) and Salgado et al. (1998) were applied. The predictions on the basis of the proposed cavity expansion solution shows good comparisons with experimental and numerical results, as illustrated in Figure 5. In short, the determination of state parameter based on the normalised cone tip resistance seems to be obtained from the correlations as long as the soil parameters are known. This also confirms the direct interpretation of in situ state of soil based on the CPT data.

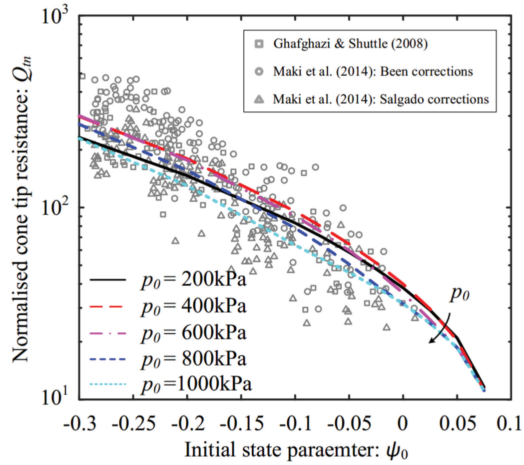


Figure 5. Normalised cone tip resistance Q_{tn} against initial state parameter with comparisons of numerical simulation for Ticino sand.

Together with the prediction of sleeve friction (Eq. 2), the SBT chart (Robertson, 2009) is employed to examine the variation of stress condition and initial state parameter, as shown in Figure 6. The normalised sleeve friction is defined as $F_r = [f_s/(q_c - p_0)] \times 100\%$. The effect of p_0 *seems to be negligible in* $Q_{tn} - F_r$ *space, whereas higher state parameter results in a smaller value of Qtn* and a larger F_r *for a given stress condition. When the variation of* ψ_0 from -0.3 to 0.075, the trend is almost linear in the SBT chart, with increase of the soil behaviour type index, I_c, as defined by Robertson (2009).

3.2 *Effects of friction angle and critical state parameter λ*

The measured CPT data is normally interpreted to obtain soil properties, including friction angle, density and elastic parameters. Since the concept of critical state has enabled the significant

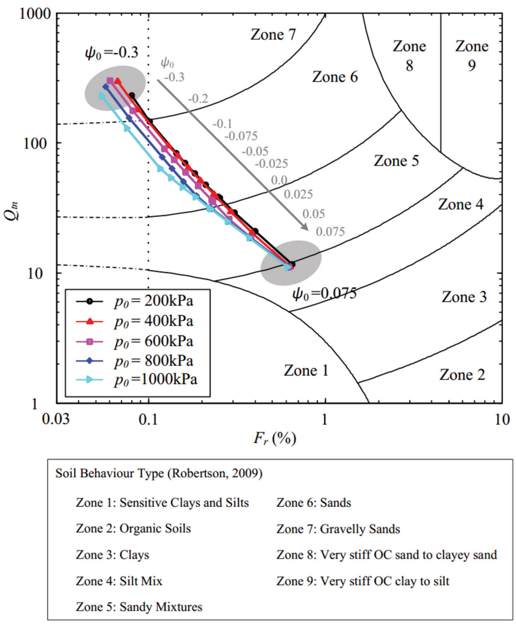


Figure 6. Effects of initial stress condition and state parameter on the SBT chart.

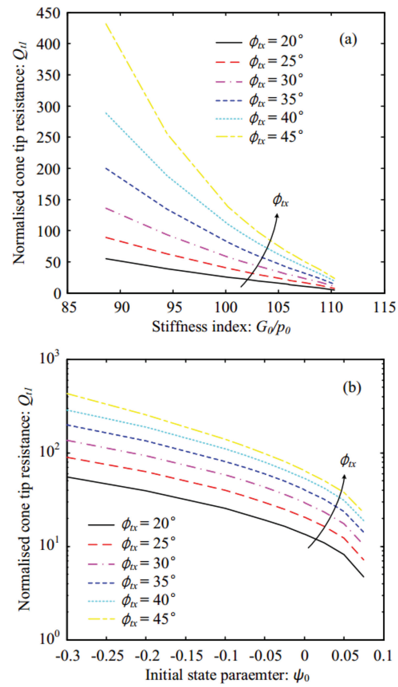


Figure 7. Effect of friction angle: (a) normalised cone tip resistance against stiffness index, (b) normalised cone tip resistance against initial state parameter.

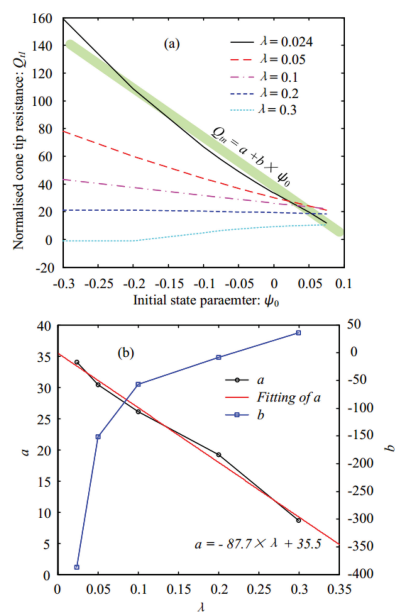


Figure 8. Effect of friction angle: (a) normalised cone tip resistance against stiffness index, (b) normalised cone tip resistance against initial state parameter.

development of soil constitutive models with consideration of volumetric changes, the critical state parameters are becoming important to geotechnical engineers. Friction angle is correlated to the critical state friction ratio M. The influence of friction angle on the normalised cone tip resistance is examined and presented in Figure 7. Note that this test series keeps the constant initial confining stress with $p_0 = 500kPa$. Based on the aforementioned definition of G_0, the stiffness index G_0 / p_0 is directly related to initial specific volume, and thus to initial state parameter with constant p_0. The trends in both $Q_{t1} - G_0 / p_0$ and $Q_{t1} - \psi_0$ spaces show non-linear increases of Q_{t1} with friction angle.

Critical state parameter λ (slope of critical state line in $v - \ln p$ space) indicates the soil compressibility, and the impact of compressibility was reported to be significant to CPT data. Shuttle & Jefferies (1998) noted that the relationship between Q_{t1} and ψ_0 is weakly reliance on λ, whereas Reid (2015) stated that the relationship of Q_{t1} and ψ_0 is dependent of λ and M, with λ the dominant factor. The effect of λ is investigated in this study with interpretation of state parameter, as illustrated in Figure 8(a). The significant influence on the relations between Q_{t1} and ψ_0 is observed, and the decreasing rate of tip resistance with state parameter decays as the value of λ increases. When a linear curve fitting in $Q_{t1} - \psi_0$ space is applied, the parameters varying with λ are shown in Figure 8(b). The results also provide the possible estimation of λ based on CPT data, in addition to sample tests in laboratory.

In general, it can be found the clear indication of initial state parameter for the interpretation of CPT data in sands. While the results of CPT measurements are dependent of soil inherent and state parameters, further study on variety of sands is still needed, together with the analysis of sleeve friction and soil behaviour type index. The cavity expansion solution with an applicable soil model and concept of state parameter could serve as an effective tool and provide a theoretical background for the interpretation of CPT data and CPT-based pile design methods. However, the interpretation of CPT data is actually dealing with the estimation of soil properties, corresponding to an inverse analysis of cavity expansion. By adopting a more sophisticated soil model like CASM, the number of soil parameters is usually larger than that of measurements, and therefore the derivations of direct correlations between CPT data and soil parameters are not available. Further techniques, including stochastic analysis, probabilistic analysis and neural network methods, are required to incorporate with the current analysis for the development of framework for interpretation of CPT data.

4 CONCLUSIONS

A state parameter based method was developed in this paper for the interpretation of CPT data using cavity expansion solution, which could also be extended to the prediction of bearing capacity of closed-ended piles. Drained cavity expansion solution in a unified state parameter model was adopted for the analyses owing to the benefits of state parameter concept. The presented investigation showed that the relationship between normalised cone tip resistance and state parameter is independent of stress condition, whereas the effects of friction angle and soil compressibility constant are relatively significant. The prediction of sleeve friction indicated that the effect of stress condition *is nearly negligible and the state parameter seems to increase with the* soil behaviour type index in the exponent space of normalised penetration resistance against normalised sleeve friction. The derivation of state parameter based on CPT measurements was therefore obtained from the correlations as long as the soil model parameters are known. To obtain correlations between CPT data and soil properties, further study on variety of soils is required with more investigations on penetration resistance and sleeve friction, together with probabilistic methods. It was concluded that the state parameter based cavity expansion analysis with the unified soil model provides further insight into our understanding of the measured results from in-situ soil tests and pile foundations.

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