# Interpretation of in-situ horizontal stress from self-boring pressuremeter tests in sands: A numerical study

## Interprétation du stress horizontal in-situ à partir d'éprouvettes auto-sondes dans les sables: une étude numérique

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ABSTRACT: In this study, a numerical finite difference model of self-boring pressuremeter test (SBPM) is performed. Limit pressure is believed to be a key parameter for estimation of soil parameters from pressuremeter tests, however; self-boring pressuremeter tests are practically conducted up to 10-15% strains, so determination of limit pressure usually needs extrapolation. For an alternative solution, it is recommended to consider cavity pressure corresponding to 10% strain ($P_{10}$) for interpretation of soil parameters instead of limit pressure; therefore, more than 5000 numerical analyses of SBPM are carried out to correlate cavity pressure corresponding to 10% strain ($P_{10}$) to sand parameters with the aid of genetic algorithm. Based on these extensive numbers of numerical analyses, a new relation is proposed which correlates $P_{10}$ to soil parameters. The new relation is suggested to be used for estimation of soil in-situ horizontal stress. The estimated in-situ horizontal stresses are compared to measured ones obtained from laboratory and field results of SBPM to evaluate the proposed method. Close agreement is found between values of in-situ horizontal stress obtained by the proposed relation with the measured values reported in the literature.

RÉSUMÉ: Dans cette étude, un modèle numérique de différence finie pour l'interprétation des résultats Des essais sur pressiomètre autoforeur est présenté. Cependant, la pression limite est considérée comme un paramètre clé pour l'estimation des paramètres du sol à partir des tests pressiométriques; Les essais de pressiomètre autoforeur sont pratiquement réalisés jusqu'à 10-15% de déformation, de sorte que la détermination de la pression limite nécessite habituellement une extrapolation. Pour une solution alternative, il est recommandé de considérer la pression de cavité correspondant à 10% de déformation ($P_{10}$) pour l'interprétation des paramètres du sol au lieu de la pression limite; Par conséquent, plus de 5000 analyses numériques de SBPM sont effectuées pour corréler la pression de cavité correspondant à 10% de déformation ($P_{10}$) à des paramètres de sable à l'aide d'un algorithme génétique. Sur la base de ces nombreuses analyses numériques, une nouvelle relation est proposée qui corrèle $P_{10}$ aux paramètres du sol. La nouvelle relation est suggérée pour être utilisée pour l'estimation du stress horizontal in situ du sol. Les contraintes horizontales in situ estimées sont comparées à celles mesurées obtenues à partir des résultats de laboratoire et de terrain de la SBPM pour évaluer la méthode proposée. Un accord étroit est trouvé entre les valeurs de contrainte horizontale in situ obtenues par la relation proposée avec les valeurs mesurées rapportées dans la littérature.

KEYWORDS: Pressuremeter, numerical modelling, in-situ horizontal stress, sand parameters, genetic algorithm

## 1 INTRODUCTION

Pressuremeter is a unique and innovative technology, introduced by the French engineer Louis Menard in 1955. Typically, the pressuremeter is composed of a probe and a control unit (Schnaid, 2009). Probe is generally made of a flexible membrane protected by steel strips known as the 'Chinese Lantern'. The length of the flexible part has to be more than 6 diameters to conform to the requirements of interpretation methods which dictate that the expanding probe must be sufficiently long to be modelled as a cylindrical cavity (Schnaid, 2009). Lame (1852) proposed a closed form solution for the problem of cavity expansion in linear elastic medium. Shear modulus of the soil can be obtained from the initial or unload-reload cycle of the cavity stress-strain curve. Gibson and Anderson (1961) assumed that the sand behaves perfectly elastically until failure is reached and after the failure the soil does not experience any volume change which is not realistic in sandy soils. Hughes et al. (1977) developed an analytical method, applicable to determine friction and dilation angle of soil using pressuremeter test results. Carter et al. (1986) proposed a large-strain closed form solution in purely frictional soils in addition to the small-strain solution for cohesive-frictional soils. Houlsby et al. (1986) developed an analysis based on the unloading portion of pressuremeter test which is not sensitive to the initial soil disturbance. Each of the mentioned methods of cavity expansion interpretation has different assumptions which may not be applicable in all situations. In this paper, more than 5000 numerical analyses of SBPM are conducted and values of cavity pressure corresponding to 10% strain, $P_{10}$, are deduced. Genetic algorithm is applied to propose a relationship between $P_{10}$ and sand parameters. The new approach is used to estimate soil in-situ horizontal stress. The estimated in-situ horizontal stresses are compared to measured ones obtained from laboratory and field results of SBPM to evaluate the proposed method. Results show good agreement between measured and estimated values of in-situ horizontal stresses.

## 2 NUMERICAL MODELLING

In this study, self-boring pressuremeter (SBPM) test has been modelled using the FLAC software. The soil is assumed to behave elastic-perfectly plastic and the Mohr-Coulomb constitutive model is chosen. Model parameters used for all of the analyses will be discussed in later sections.

### 2 .1 *Geometry, mesh grid and boundary conditions of the model*

The cavity expansion is assumed to occur under axially symmetric condition. The length and diameter of the SBPM are 500 and 80 mm, respectively, the same as the Cambridge SBPM instrument. Bahar (1992) showed that a typical ratio of $r_m/r_0$ (ratio of model radius to cavity radius) equal to 30 is sufficient to model the condition of infinite soft clay medium around the expanding cavity. This ratio should be especially higher for dense sands and stiff clays. To study the effect of $r_m/r_0$ on pressuremeter test results, three series of numerical analyses have been performed. These series of analyses correspond to dense sand with friction angle of 36°, medium dense sand with friction angle of 33°, and loose sand with friction angle of 30°. Other soil properties are given in Table 1. Values of peak dilation angles shown in Table 1 are estimated from the correlation published by Bolton (1986).

$$\phi - \phi_{cv} = 0.8\Psi_{max} \quad (1)$$

Where $\phi$ is the soil friction angle, $\phi_{cv}$ is the soil critical friction angle, and $\Psi_{max}$ is the soil peak dilation angle. A mean value of 33° is chosen for the critical friction angle for determination of peak dilation angle.

The mesh grid and boundary conditions of the axisymmetric model are shown schematically in Figure 1.

Table 1. Three different soil properties for determination of appropriate $r_m/r_0$ ratio

| | $\phi_{cv}$ | $\phi$ | $\Psi$ | $\mu$ | G MPa | $\sigma_{h0}$ kPa | $\sigma_{v0}$ kPa |
|---|---|---|---|---|---|---|---|
| Loose sand | 33 | 30 | -4 | 0.3 | 5 | 50 | 50 |
| Medium dense sand | 33 | 33 | 0 | 0.3 | 15 | 50 | 50 |
| Dense sand | 33 | 36 | 4 | 0.3 | 25 | 50 | 50 |

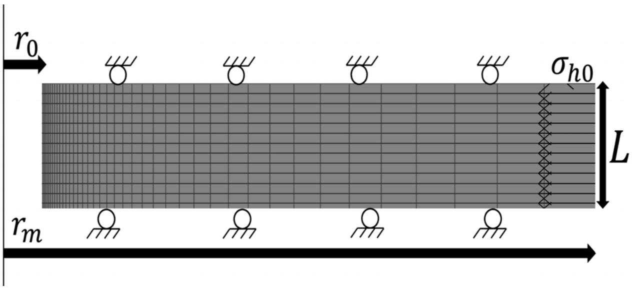

Figure 1. Mesh grid and boundary conditions of the axisymmetric model

Vertical strains can be restrained, since the ratio of length to diameter of the Cambridge SBPM is higher than 6. The left limit, where horizontal pressure due to probe expansion is applied, is the borehole wall placed at 40 mm from the axis to simulate an 80 mm diameter borehole. Hence, in this region, the mesh is designed with more congested elements. At the right boundary, a constant in-situ total horizontal stress is applied. Although SBPM tests frequently expand to 10-15% cavity strains, cavity pressure at 20% strain ($P_{20}$) was chosen as the representative of cavity stress to take into account the tests with cavity strains greater than 10-15%. Numerical analyses with different $r_m/r_0$ values were carried out for each soil property, and values of $P_{20}$ were plotted against $r_m/r_0$ ratios (see Keshmiri 2015). It was observed that as the soil stiffness becomes higher and its strength increases, $P_{20}$ is more affected by $r_m/r_0$ ratio. For all of the models with $r_m/r_0$ greater than 60, effect of $r_m/r_0$ on $P_{20}$ was properly negligible. Conservatively, ratio of $r_m/r_0$ is set to be 100 so that the outside boundaries would have little influence on the numerical results.

### 2.2 *Validation of numerical model used in this study*

Schnaid (2000) performed a curve-fitting analysis for the experimental results of SBPM in the site located in Kowloon Peninsula in Hong Kong, adjacent to Kowloon Bay. Soil parameters deduced from curve-fitting are shown in Table 2. These same parameters were used in the numerical model performed in this study. Comparison of numerical and experimental results is presented graphically in Figure 2. This figure shows good agreement between simulation using numerical model and the SBPM test.

Table 2. Curve-fitting parameters used by Schnaid (2000)

| $\phi_{cv}$ | $\phi$ | G (MPa) | $\sigma_{h0}$ (kPa) |
|---|---|---|---|
| 31 | 33 | 40 | 103 |

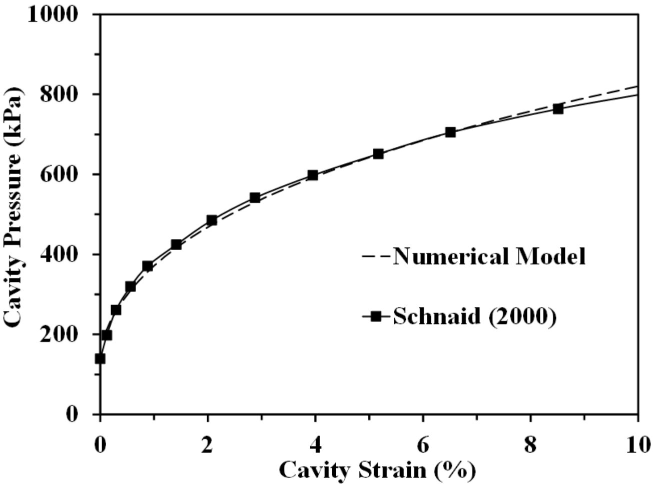

Figure 2. Validation of the numerical model in this study with measured values of SBPM reported by Schnaid (2000)

## 3 PROPOSED METHOD FOR THE INTERPRETATION OF THE SBPM IN SAND

Limit pressure is believed to be a key parameter for estimation of soil parameters from pressuremeter tests. Monnet (2007) and Bouassida (2007) have proposed relationships to determine limit pressures for the interpretation of pressuremeter tests. In SBPM tests, cavity strains do not exceed 10%; therefore, limit pressure is not reached during the test procedure. Thus, an alternative concept more applicable for the interpretation of SBPM test is required. Authors suggest a simple relationship for the cavity pressure at 10% strain ($P_{10}$) instead of limit pressure. At this strain, it is assured that plastic strain occurs, and cavity is typically expanded up to this strain in SBPM tests. Considering cavity expansion theories such as Hughes et al. (1977) and Carter et al. (1986), the most important soil properties affecting the cavity stress are friction angle, shear modulus, in-situ total horizontal stress, and critical friction angle (or dilation angle). A relationship in the following form can be assumed to correlate $P_{10}$ to sand parameters.

$$P_{10} = a(\phi)^b (G)^c (\sigma_{h0})^d + e \quad (2)$$

Where G is the soil shear modulus, $\sigma_{h0}$ is the in-situ total horizontal stress, and $\phi$ is the friction angle. To determine the five parameters of a, b, c, d and e, in Equation 2, more than 5000 numerical analyses have been conducted. In these analyses, friction angle and in-situ total horizontal stress varied between 30° to 45° and 30 to 1000 kPa, respectively. Dilation angles were calculated by Bolton's (1986) relationship assuming critical friction angle to be 33°. Elastic Young's moduli of sands typically range from 10 to 80 MPa. Assuming Poisson's ratio of 0.3, this corresponds to shear moduli of 4 to 30 MPa. A wider range of 4 to 50 MPa is chosen for the shear moduli values to cover the stiffness characteristics of most sandy soils. It should be noted that some combinations of these parameters result in unrealistic and incompatible soil properties, but their analyses are necessary to find a precise relationship for $P_{10}$. It was observed that for a constant value of in-situ total horizontal stress, total vertical stress has negligible effect on $P_{10}$. Hence, in all of the analyses, in-situ total vertical stresses can be assumed to be equal to the corresponding in-situ total horizontal stresses to avoid soil failure prior to the exertion of cavity displacement. In other words, $K_0$ is assumed to be equal to 1. Values of $P_{10}$ are deduced from each of the analyses. Parameters a, b, c, d, and e, are determined from the large data base of $P_{10}$ values using genetic algorithm (GA) as a method of optimization.

## 4 APPLICATION OF GENETIC ALGORITHM FOR OPTIMIZATION

Genetic algorithm (GA) is used to obtain the parameters a, b, c, d, and e. In this algorithm, the best-suited parameters are gained by 500 iterations of population generation on the 2000 sets of five parameters [a, b, c, d, and e]. Population generation is conducted by the two processes of crossover and mutation. The fitness of the parameters [a, b, c, d, and e] is evaluated by a fitness function (F.F) defined as the summation of the absolute differences between the values of $P_{10}$ from the numerical analyses and values computed from Equation 2.

$$F.F = \sum | P_{10} - P'_{10} | \tag{3}$$

Where $P_{10}$ is deduced from numerical analyses, and $P'_{10}$ is computed from the substitution of the values of a, b, c, d, and e in Equation 2. The main objective of the GA process is to determine the best values of a, b, c, d, and e that minimize the fitness function. Coincidently, it was realized that normalizing the shear modulus to its logarithm gives better results (less values of fitness function). Moreover, other soil parameters were normalized to constant numbers to find sensible values for parameters a, b, c, d, and e. The optimization process, allows finding values of 1.4, 1, 0.4, 0.6, and -35 for a, b, c, d, and e, respectively. It should be emphasized that the genetic algorithm gives exact and optimized values for each parameter. Equation 4 can be applied for the estimation of $P_{10}$.

$$P_{10} = 1.4(\frac{\phi}{30})(\frac{G}{\log G})^{0.4}(\sigma_{h0})^{0.6} - 35 \tag{4}$$

Where $P_{10}$, G and $\sigma_{h0}$ are in kPa, and $\phi$ is in degrees. In Figure 3, values of $P_{10}$ calculated from Equation 4 are compared to those achieved from numerical analyses. As can be seen, close agreement is found between the results of numerical analyses and the ones calculated by Equation 4. By using Equation 4, a chart is proposed for determination of in-situ horizontal stress (Figure 4). In Figure 4, in-situ horizontal stress normalized to shear modulus coefficient can be determined by deduction of $P_{10}$ and friction angle from SBPM stress-strain curve. Shear modulus coefficient, A is defined as:

$$A = 570(\frac{G}{\log(G)})^{-2/3} \tag{5}$$

Where G is the shear modulus of soil (in kPa) obtained from the initial slope of the pressure-expansion curve. Therefore, in-situ horizontal stress can be predicted from this method.

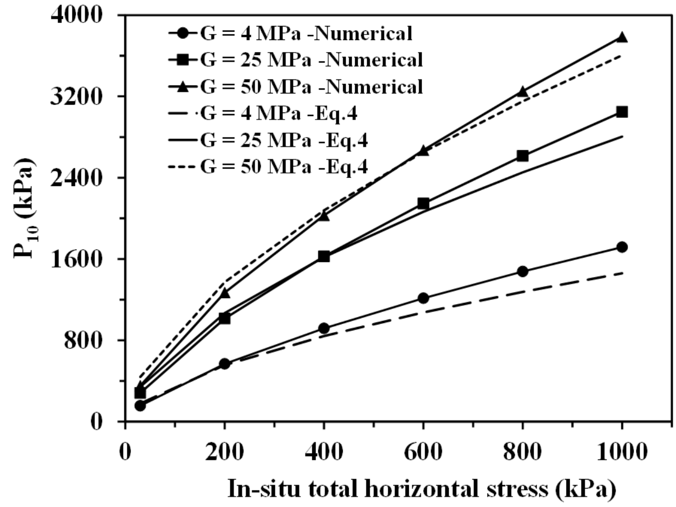

Figure 3. Variation of $P_{10}$ versus in-situ total horizontal stress

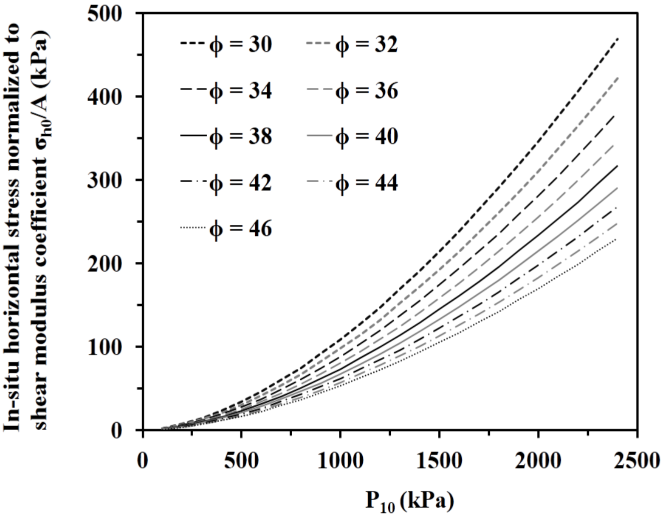

Figure 4. Relationship between $P_{10}$ and $\sigma_{h0}$ normalized to shear modulus coefficient

Some estimated values of $\sigma_{h0}$ from proposed method and $\sigma_{h0}$ deduced either from lift-off method (for field results) or from SBPM calibration chamber measurements (for laboratory results) are shown in Table 3 (other data can be found in Keshmiri 2015). In most of the cases, friction angles obtained from laboratory tests are not reported, therefore, method of Hughes et al (1977) is applied for inference of this parameter. Shear moduli were deduced from the initial slope of pressure-expansion curve. In some cases such as laboratory results of Fahey (1986), application of Hughes et al (1977) method for determination of friction angle gives unrealistic values, however; this limitation produce marginal inaccuracy in prediction of $\sigma_{h0}$, since friction angle will have negligible effect on $P_{10}$. Figure 5 shows the difference between predicted and measured values of $\sigma_{h0}$ according to the data of Table 3 in addition to other data deduced from (Hughes et al. 1977; Hughes and Robertson 1985; Jewel et al. 1980; Wroth 1984; Cunha 1994; Bellotti et al. 1987; Bruzzi et al. 1986; Wride and Robertson 1998; Robertson and Hughes 1986) presented by Keshmiri (2015). It is observed that the differences are dominantly less than 20%.

Table 3. Comparison of the measured and predicted values of $\sigma_{h0}$

| | $\phi$ | G (MPa) | $\phi_{cv}$ | Measured $P_{10}$ (kPa) | Measured $\sigma_{h0}$ (kPa) | Predicted $\sigma_{h0}$ (kPa) |
|---|---|---|---|---|---|---|
| Schnaid (2000) | 33 | 40 | 31 | 777 | 103 | 81 |
| | 35 | 48 | 31 | 882 | 100 | 81 |
| Fahey (1986) | 46 | 31 | 34 | 1030 | 90 | 86 |
| | 45 | 27 | 35 | 954 | 90 | 85 |
| | 55 | 19 | 33 | 1145 | 90 | 101 |
| | 48 | 28 | 34 | 1025 | 90 | 84 |
| | 48 | 30 | 34 | 1100 | 90 | 91 |

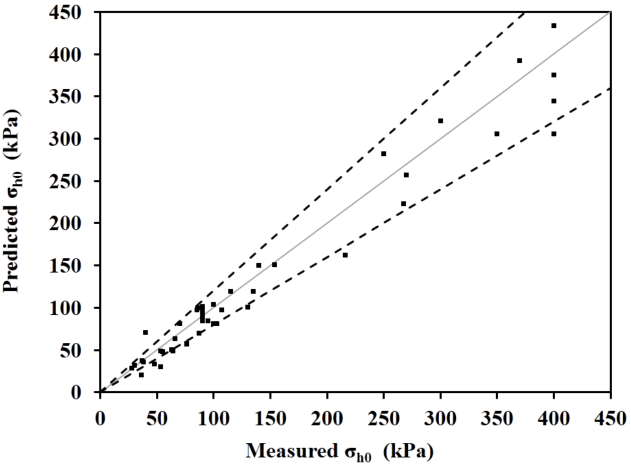

Figure 5. Comparison of measured and predicted values of $\sigma_{h0}$. Dashed lines indicate 20% difference

## 5 CONCLUSION

A new method was established for the interpretation of SBPM test using the results of numerical modelling. It was proposed to use cavity pressure at 10% strain ($P_{10}$) for interpretation of SBPM tests, instead of limit pressure. A series of 5000 numerical analyses were conducted and values of $P_{10}$ were deduced. Based on the genetic algorithm approach, a new relationship was developed for the interpretation of SBPM results from the cavity pressure at 10% cavity wall strain ($P_{10}$). Correction factors were proposed to account for the effect of critical friction angle of soil on the proposed relationship. By the comparison of the predicted values of $P_{10}$ from the proposed relationship and the measured ones, it was concluded that the proposed method produces reliable results. The main advantage of the new method is its simplicity compared to other analytical expressions suggested in the literature allowing prediction of in-situ horizontal stress from pressuremeter curve. A chart was provided from the proposed relationship for $P_{10}$, which is useful for the deduction of the in-situ horizontal stress. The method introduced in the paper can be applied to predict the in-situ horizontal; however, this method uses other prior methods for determination of shear modulus and friction angle. It is believed that with the aid of the new method, values of in-situ horizontal stress deduced from lift-off method can be evaluated and corrected. Also in the case of knowing two of the soil parameters, it is possible to estimate the values of the third parameter using the proposed relationship.

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