Application of The Tangent Modulus Method in Nonlinear Settlement Analysis of Sand Foundation

Application de la méthode du module tangent dans le calcul du tassement non-linéaire de fondations sur sol sableux

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ABSTRACT: Foundation settlement computation method is always a hot and difficult issue in geotechnical engineering for the difficulty in which soil parameters obtained from laboratory test are quite different from undisturbed soil in the field. Especially for sand foundation and stiff clay foundation with strong structure, settlement calculating with laboratory test parameters makes distinct error from actual situation. The tangent modulus method, based on calculation parameters determined from in-situ plate loading test, can overcome this shortcoming, and can be used in analyzing nonlinear foundation settlement. This method makes a new progress in foundation settlement computation. In this paper, systematic geotechnical test data from Texas A&M University Riverside Campus are utilized to test the hyperbola model of soil and the tangent modulus method. Then, methods for soil parameter determination in different depth are studied through such simple in-situ tests such as pressuremeter test and cone penetration test, and these methods are verified through plate loading test with different size. The analysis results prove that the tangent modulus method has better accuracy of nonlinear settlement computation. Also, it is feasible to obtain the computation parameters for the tangent modulus method from some simple in-situ tests, which provides an easier way in determining parameters of the tangent modulus method.

RÉSUMÉ : Le calcul de tassement des fondations est toujours un problème difficile dans les études géotechniques, et la difficulté réside dans la différence très grande entre les paramètres géotechniques obtenus à partir d'essais de laboratoire et ceux obtenus à partir d'essais in-situ, en particulier pour les fondations sur sol sableux et les fondations sur argile raide surconsolidée. L'erreur entre les résultats du calcul de tassement basés sur les paramètres issus d'essais de laboratoire et la valeur réelle du tassement peut être très grande. La méthode du module tangent, basée sur le calcul de paramètres déterminés à partir d'essais de plaque, permet de s'affranchir de ce défaut, et peut être utilisée dans une analyse non-linéaire du tassement des fondations. Cette méthode représente un nouveau progrès dans le calcul du tassement des fondations. Dans cet article, on a utilisé les données d'essais géotechniques systématiques réalisés au Campus Riverside de l'Université A & M au Texas pour valider un modèle hyperbolique de comportement du sol et la méthode du module tangent. Puis on a déterminé des méthodes de calcul des paramètres géotechniques à différentes profondeurs à partir d'essais in-situ simples comme l'essai pressiométrique ou le CPT, et on a validé ces méthodes au moyen de résultats d'essais de chargement de fondations superficielle (plaques de différentes tailles). Les résultats montrent que la méthode de module tangent utilisé pour le calcul de tassement non linéaire de la fondation a une meilleure précision. Egalement, il est possible d'obtenir les paramètres de calcul de la méthode au module tangent à partir d'essais in-situ comme l'essai pressiométrique ou le CPT.

KEYWORDS: foundation settlement; tangent modulus method; in-situ test; nonlinear; sandy soil subgrade

1 INTRODUCTION

Due to the complexity of the geomaterial, the calculation of foundation deformation is not accurate, which can be specifically attributed to the unreasonable calculation method and less accurate value of geotechnical parameters. Due to the disturbance of undisturbed soil in the sampling and sample making preparation process, the foundation deformation parameters accessed by the laboratory test will be seriously distorted. Therefore, the development of settlement deformation calculation method based on the in-situ tests has practical significance on the improvement of accuracy of the ground deformation calculation. As to sand foundation, due to the sand-sampling difficulties, currently the international recognized way - Schmertmann semi-empirical method is based on the experience of cone penetration test to determine the deformation modulus of the sand, using the layer-wise summation method to calculate foundation settlement[1]. The existing methods are difficult to fully calculate the nonlinear settlement of the foundation. Based on plate loading test, Yang Guanghua[2~6] proposed that the tangent modulus method can better solve the problem of the accuracy of the foundation settlement calculation. However, as parameters are derived from the plate loading test which has high cost and can not apply to deep soil. Therefore, to explore other simple tests instead of in-situ plate loading test to determine the required parameters is very important. This paper[7]discusses how to use the pressuremeter test to determine the required parameters.

American scholar Briaud JL, Gibbens R M., et, al [8]have carried out the plate loading test with five different sizes' plates, static cone penetration test, pressuremeter test and other systematic soil tests on the sand foundation in Riverside Campus, Texas A & M University. The shape of plates are square and the sizes are 1m, 1.5m, 2.5m, 3m, 3m. The purpose is to test the effectiveness of a variety of foundation settlement calculation methods. By making use of these valuable test data, this paper further testifies the applicability of the tangent modulus method[4] for nonlinear settlement computaion and studies how to use the static cone penetration test and pressuremeter test and other simple in-situ tests to determine the parameters of the foundation parameters required in the tangent modulus method, and it can further develop and improve the tangent modulus method.

1.1 *Calculation Principle of Tangent Modulus Method*[4]

The tangent modulus method is a new method based on the in-situ plate loading test to create the P-S curve of soil, in order to calculate the settlement of foundation. Assuming that the basis load - settlement curves can be fitted by using the hyperbolic curve, we create the hyperbolic curve method, as formula (1):

As a and b are the parameters of test, the nonlinear tangent modulus of soil can be calculated as hyperbolic curve formula (1), as formula (2):

$$p = \frac{s}{a+bs} \quad (1) \quad E_t = (1 - R_f \frac{p}{p_u})^2 \cdot E_{t0} \quad (2)$$

E_{t0} is the initial tangent modulus, p is the additional stress of soil, p_u is the ultimate capacity of foundation soil, R_f is the damage ratio coefficient which is similar to that of the Duancan-Chang model.

While the tangent modulus E_t along the depth is solved by formula(2), we could use layer-wise summation method to calculate the settlement. It is a good method to determine the parameters of soil because the soil is undisturbed and the nonlinear properties of soil are well considered, this method can calculated the nonlinear settlement of soil accurately.

Assuming soil layer is Δh_j load increment Δp_i , the amount of compression of this soil layer is as formula (3):

$$\Delta s_{ij} = \frac{\Delta p_i \cdot \alpha \cdot \Delta h_j}{E_{ij}} \quad (3)$$

α is the additional stress of distribution coefficient, and E_{ij} is the tangent modulus on the soil layer corresponding to the load p. After the amount of compression of each layer is calculated, according to layer-wise summation method, the total settlement under added load is , as formula (4):

$$\Delta s_i = \sum_{j=1}^{n} \Delta s_{ij} \quad (4)$$

When using this method to calculate the nonlinear settlement of foundation, the key is to determine three parameters, including the tangent modulus value E_t of the each foundation layer of soil, and the strength parameters - c and φ required in Formula (2) calculation as well as the initial tangent modulus E_{t0} , which are simple.

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1.2 *Foundation settlement calculation parameters determined by plate loading test*

As to the p-s curve measured by the plate loading test, it can inversely calculate the internal friction angle φ of foundation settlement parameters, cohesion c and the initial tangent modulus E_{t0} , resulting in a more reasonable calculation parameters.

Loading test site is located in the Riverside Campus, Texas A & M University, with 0 to 10.5m depth of sand and black stiff clay as the sublayer. The main physical and mechanical parameters of the indoor tested silty sand are shown in Table 1.

Tab.1 physical mechanic index of ground soil

γ (kN/m^3)	w (%)	Gs	e	c (kPa)	φ (°)	depth(m)
15.6	5.0	2.66	0.75	0	34.2	0.6
				0	36.4	3.0

A total of five plate loading tests are conducted in the site, and the plates are square with width of 1~3m. The test is carried out at depth of 0.76 m.

We use two methods to forecast the p-s curve, e.g. the first method uses the aforementioned fitted hyperbolic parameters a and b to directly draw p-s curve based on the assumption[2] that p-s curve complies with the hyperbolic model; the second method is the aforementioned tangent modulus method: first calculate the tangent modulus E_t under different loads as formula(2), then calculate the amount of compression of each layer as(3), and lastly make summary of the foundation settlement under different load by layer-wise summation as (4), and draw p-s curve [4]

When calculating the amount of compression of each layer by tangent modulus method, the ultimate bearing capacity of each layer is determined by the Terzaghi formula (5). The cohesion $c = 0$, and the internal friction angle φ is inversely calculated by loading test data in Formula (5).

$$P_u = \frac{1}{2}\gamma B N_\gamma + q N_q + c N_c \quad (5)$$

By using the above two methods, the p-s curves of the five plates are drawn respectively, and compared with the actually measured data shown in Figures 2 to 6.

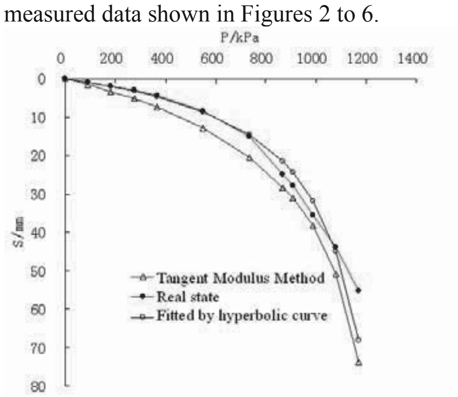


Fig.2 The P-S curve of 5#footing(1.0m×1.0m)

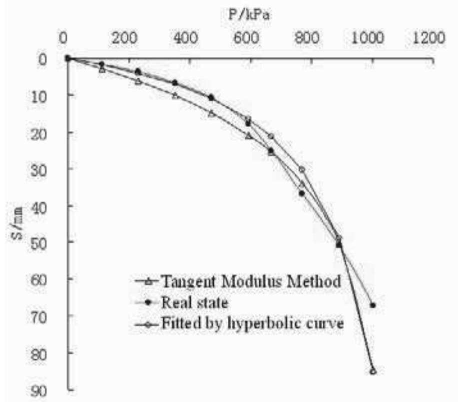


Fig.3 The P-S curve of 2# footing(1.5m×1.5m)

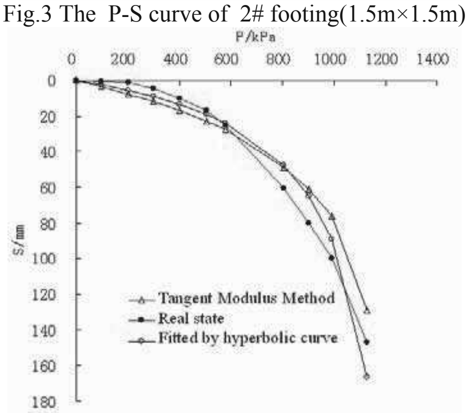


Fig.4 The P-S curve of 4# footing(2.5m×2.5m)

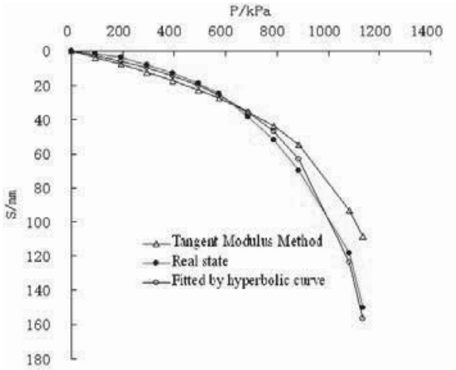


Fig.5 The P-S curve of 1# footing(3.0m×3.0m)

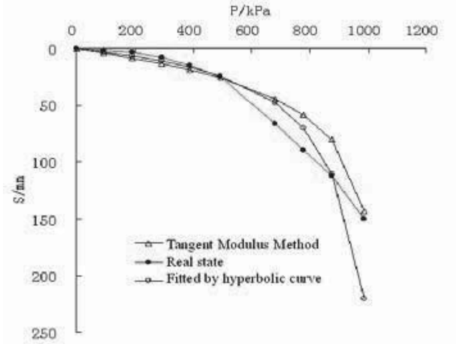


Fig.6 The P-S curve of 3# footing(3.0m×3.0m)

From the predictions of the above two methods, they all get good results. For homogeneous foundation formed by only one category of soil, the two methods result in the same effect, but as to the non-homogeneous layered soil expressed directly by hyperbolic curve, when the small-size plate loading test results are used for the large-size foundation, its reflection of the deep soil is not enough.

When using the second method to calculate the layered foundation settlement by the tangent modulus method, it can adopt different c and φ for different soil layers, as well as the initial tangent modulus E_{t0} of soil to reflect the effect on the deep soil and the soil of different layers, which has better adaptability for the foundation generally composed by the multi-layer soil.

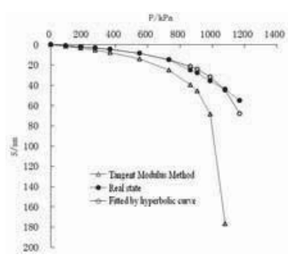
The parameters of different test points inversely calculated by the tangent modulus method are shown in Table 2.

Table 2. Foundation soil parameters of 5 plates inversely calculated by loading test data

Plate loading test Number	E_{t0} /MPa	p_u /kPa	c / kPa	φ /°
5#(1.0m×1.0m)	83.4	1399	0	37.2
2#(1.5m×1.5m)	84.4	1202	0	35.5
4#(2.5m×2.5m)	84.7	1340	0	34.8
1#(3.0m×3.0m)	90.9	1405	0	37.0
3#(3.0m×3.0m)	86.4	1128	0	35.6

The average of soil parameters in Table 2 are as follows: E_{to}=86Mpa, φ=36°. The settlement load curve of each plate calculated by taking these soil parameters and using tangent modulus method is shown in Figures 7 to 11.

The figures show that the calculation and test results are in consistent to a large extent. But the accuracy is less than that of Figures 2 to 6. This is mainly because the soil parameters in Figures 2 to 6 are inversely calculated by each pilot point, while Figures 7 to 11 are calculated by using the average value of inversely calculated parameters at each test point. In actual engineering, this heterogeneity makes it unlikely to conduct plate loading test for each foundation location. Therefore, this paper further explores the use of easier pressuremeter test to determine the initial tangent modulus E_{to} of tangent modulus method in the soil at different depth by using static cone penetration test (CPT) to determine the angle of internal friction φ in the tangent modulus method in sand of different layers. And c = 0.



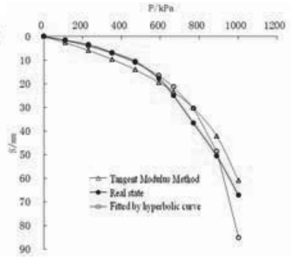
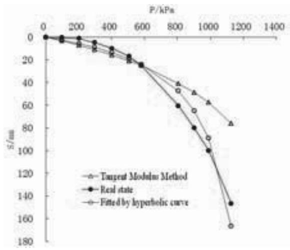


Fig.7 5#footing(1.0m×1.0m)Fig.8 2#footing(1.5m×1.5m)



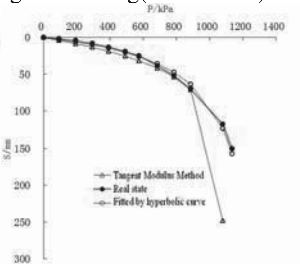


Fig.9 4#footing(2.5m×2.5m)Fig.10 1#footing(3.0m×3.0m)

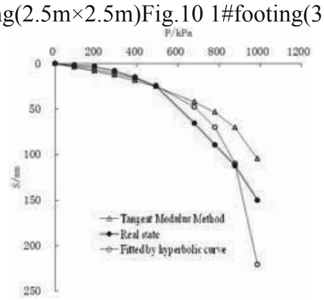


Fig.11 3#footing(3.0m×3.0m)

1.3 *The initial tangent modulus of soil layer determined by pressuremeter test*

The formulation of the initial tangent modulus can be determined by the curve of pressuremeter test:

$$E_{t0} = \frac{(p_l - p_0)}{(p_l - p_0) - (p_f - p_0)} \cdot E_m = \frac{(p_l - p_0)}{(p_l - p_f)} \cdot E_m \qquad (6)$$

The initial tangent modulus of foundation E_{to} can be determined by using the corresponding loading interval (p_0, p_1), critical edge pressure p_f, limit pressure p_l and the pressuremeter modulus E_m.

It should be pointed out that the above calculated tangent modulus is the level indicator. If the sand foundation is recognized as isotropic media, then the above calculation results can be used as the vertical indicators in settlement calculation.

According to the typical pressuremeter test curve (PMT-2, the standard method of test execution standard [8]) on loading test sites in Riverside Campus, Texas A & M University, $p_l = 400kP_a$, $p_f = 280kP_a$, $p_0 = 20kP_a$. After substituting in to the above formula, it can get:

$$E_{t0} = \frac{(400-20)}{(400-280)} \cdot E_m = 3.2E_m \qquad (7)$$

1.4 *Foundation strength parameters determined by static cone penetration test*

In the process of static cone penetration test (CPT), the foundation soil strength failure occurs. The test data can vividly reflect the strength indicators of the different stratigraphic depths.

If it can figure out the mechanism of the mechanical destruction of the foundation soil by the CPT test, thereby establishing the relationship of the CPT test foundation and strength indicator, it will help to use the CPT data to a more rational extent.

In accordance with the numerical analysis method, it selects different soil strength indicators φ to calculate the tip resistance and lateral resistance, then the total penetration resistance of CPT test is transfered. As to the comparison between $\varphi \sim p_s$ data determined by the numerical analysis and the empirical relationship proposed by the Chinese railway specifications shown in Figure 19, φ determined by the numerical calculation is slightly larger than the value recommended by railway specifications. After fitting the $\varphi \sim p_s$ data by power function, they have good correlation and the fitted empirical relationship is shown as follows:

$$\varphi = 29.352 \times p_s^{0.0915} \qquad (8)$$

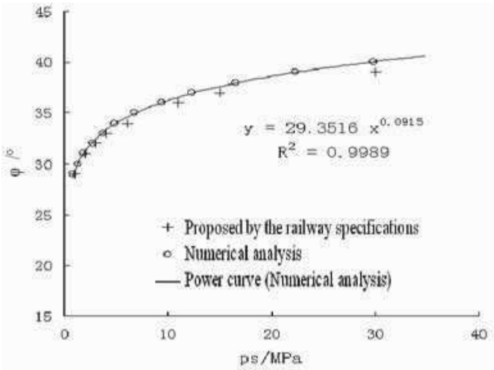


Fig.12 the fitting relationship of $\varphi - p_s$

1.5 *Foundation settlement calculations based on pressuremeter test and the static cone penetration test parameters*

With using the method motioned above, the initial tangent modulus E_{t0} along the depth can be determined by in-situ pressuremeter test, the shear strength indicator along the depth determined by static cone penetration test. With the parameters of tangent modulus method , we calculated the settlement of each footing by layer-wise summation method based on tangent modulus method, and compare with the measured results and the calculated results of each plate by the tangent modulus method when average foundation inversely calculated value E_{t0} =86MPa , φ =36°in the loading test, the result is good. The result of 2# footing is showed as figure 13.

From the settlement of each plate, after using the simple in-situ tests such as pressuremeter test and static cone penetration test to determine the calculated parameters of each foundation layer, the calculated settlement curves match well with the measured curves, which indicates that it is feasible to use pressuremeter test and static cone penetration test to determine the tangent modulus parameters of each foundation layer, thus calculating the nonlinear settlement of the foundation. These ways are easier to be achieved than the plate loading test, as well as easier to obtain the deep soil parameters.

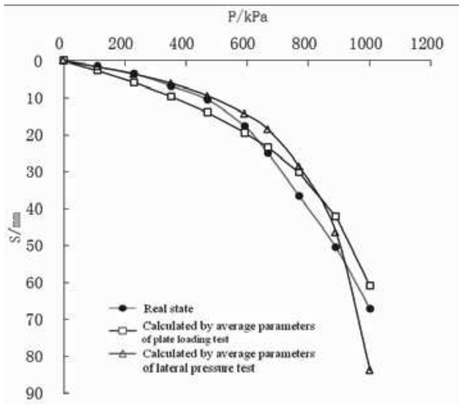


Fig.13 2# footing(1.5m×1.5m)

2 CONCLUSIONS

By analyzing the nonlinear settlement results of five plate loading tests by tangent modulus method on the sand foundation in Riverside Campus, Texas A & M University, this paper shows that the tangent modulus method can calculate the nonlinear settlement of foundation in a better way. At the same time, this paper also seeks more simple in-situ tests such as the static cone penetration test and pressuremeter test to replace the plate loading test to determine the foundation parameters required in nonlinear settlement calculation, which achieves a better effect. Therefore, this paper provides a more convenient way to promote the use of the tangent modulus method to calculate the nonlinear settlement of foundation, which is of great significance to the improvement on the design level of the foundation.

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