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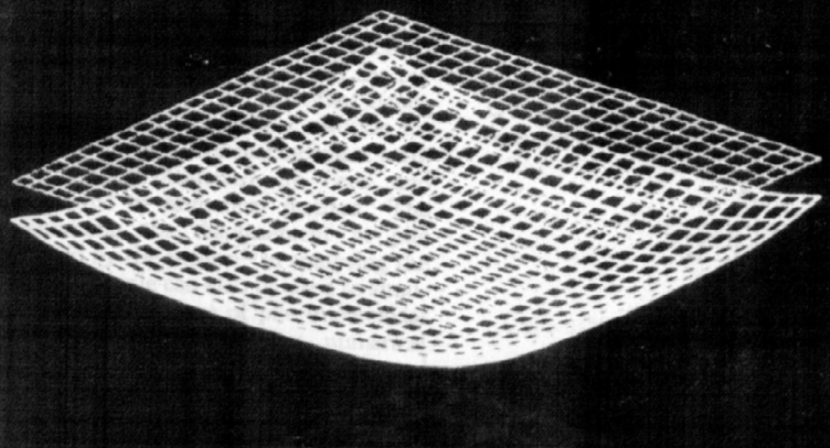

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A new numerical method for the load-settlement prediction of pile

Guolin Zhou & Tingjie Li
Institute of Rock and Soil Mechanics, The Chinese Academy of Sciences, Wuhan, China
Maiu-Bin Su
Civil Engineering Department, National Chung-Hsing University, Taichung, Taiwan, China

ABSTRACT: In this paper, a new numerical method to predict the load-settlement behavior of pile is presented and is used to simulate and analyse the test data of a practical engineering. It is shown that the method can be used to fit the whole load-settlement curve of the pile and can widely be used in engineering.

1 INSTRUCTION

The load transfer method presented by Seed and Reese[1] is an important analysis method in pile foundation. In this method, the pile is divided into a number of elements, and every element and soil are connected by a spring to simulate the load transfer between the pile and soil. The relation between the stress (force) and displacement of the elements is called the load transfer function. A differential equation can be set up using the method. When the transfer-function is simple, such as elastic-perfect plasticity, an analytical solution can be obtained. In practice, the transfer-functions are complex, and the numerical solution is needed. On the other hand, it is convenient to use a numerical solution for the pile in stratified soil. The displacement complementary method presented by Seed and Reese[1] is a kind of numerical method. The method, assuming the displacement at pile head, presented by the author[2] in analysing the negative friction of pile can also be used to simulate the settlement response of pile under axial loading. In this paper, a new numerical method, the load iterating method, is presented and an engineering case is calculated.

2 COMPUTATION MODEL

As is shown in Figure 1, the pile is divided into N elements. The relation of the shaft resistance τ and displacements is $\tau = f(s)$, and the relation of the load P_b and displacement S_b at the pile tip is $P_b = f(S_b)$.

The transfer-function curves measured in site show that the transfer-function curves are influenced by many factors, such as the soil properties, pile lenth, pile diameter, construction and so on. In order to use the transfer-function method in engineering, it is necessary to simplify the transfer functions. usually, we can simplify the transfer-functions of the shaft resistance as follows:

(1) Model of elastic-whole plasticity (Figure 2. a)

$$\begin{cases} S < S_u, \tau = C_s \cdot S \\ S \geqslant S_u, \tau = \tau_u = \text{constant} \end{cases} \tag{1}$$

where S_u is the displacement of elasticity limit, τ_u is the limit resistance of the shaft and C_s is a constant;

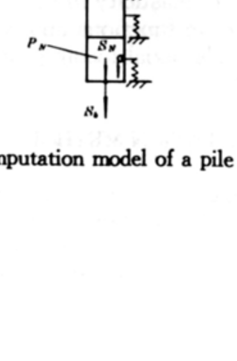

Figure 1. The computation model of a pile under axial loading

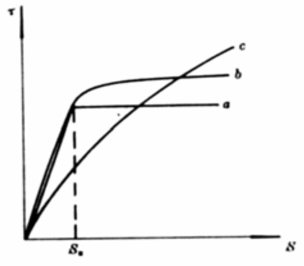

Figure 2. $\tau - S$ curves

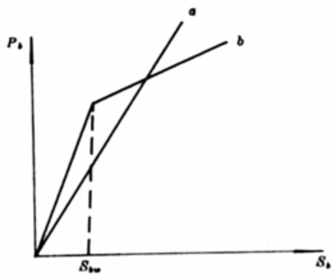

Figure 3. $P_b - S_b$ curves

(2) Model of exponent curve (Figure 2. b)

$$\tau = \tau_u(1 - e^{as}) \qquad (2)$$

where α is a constant;

(3) Model of hyperbolic curve (Figure 2. c)

$$\tau = \frac{S}{a + bS} \qquad (3)$$

where a and b are constants.

The transfer function at pile tip is simplified as follows

(1) Elasticity model (Figure 3. a)

$$P_b = K_b \cdot S_b \qquad (4)$$

where K_b is a constant

(2) Model of elastic-hardening plasticity

$$\begin{cases} S_b < S_{bu}, \ P_b = K_1 \cdot S_b \\ S_b \geqslant S_{bu}, P_b = K_1 \cdot S_{bu} + K_2(S - S_{bu}) \end{cases} \qquad (5)$$

where K_1 and K_2 ae constants and S_{bu} is the displacement of elasticity limit.

With above functions and constants, the settlement under axial loading can be calculated.

3 COMPUTATION METHOD

The computation is carried out according to eight precedures. We assure that the transfer-functions and the settlements at pile head have been known, whereas the loads at pile head are considered as unknown values which are to be determined.

(1) The pile is divided into n elements according to the demand of computation precision (Figure 1). Usually, the pile is divided into ten elements can satisfy the demand in engineering.

(2) Prescribe the displacement S_1 at the central point of the element at the pile head, and assume that the corresponding load applied on the top surface of the element is P_0. Then, the shaft resistance τ_1 can be determined from the $\tau - S$ relation of the element. Assuming that the axial force in the lenth range of an element changes linearly, we can compute the load P_1 applied on the bottom surface of the element and the settlement S_0 on the top surface of the pile by equilibrium equations:

$$P_1^{(1)} = P_0^{(1)} - 2\pi r_0 \frac{L}{N} \tau_1^{(1)} \qquad (6)$$

$$S_0^{(1)} = S_1^{(1)} + \frac{3P_0^{(1)} + P_1^{(1)}}{8AE} \cdot \frac{L}{N} \qquad (7)$$

where L is the length of the pile, r_0 is the half diameter of the pile, A is the area of the cross-section and E is the elasticity modulus.

(3) Assuming that the settlement at the central point of the i-th element is S_i and the axial force at the bottom surface of the element is P_i (Figure 1), we derive the formulas as follows

$$S_i^{(1)} = S_{i-1}^{(1)} - \frac{P_{i-1}^{(1)} \cdot \frac{L}{N}}{AE} \qquad (i = 2, 3, \cdots, N) \qquad (8)$$

$$P_i^{(1)} = P_{i-1}^{(1)} - 2\pi r_0 \frac{L}{N} \tau_i^{(1)} \qquad (i = 2, 3, \cdots, N) \qquad (9)$$

where τ_i is computed by the $\tau - S$ relations, and

$$P_N^{(1)} = P_b^{(1)} \qquad (10)$$

(1) From Equation (8) and (9), we may obtain the settlement $S_b^{(1)}$ of the bottom surface of the element at the pile tip.

$$S_b^{(1)} = S_N^{(1)} - \frac{P_{N-1}^{(1)} + 3P_N^{(i)}}{8EA} \qquad (11)$$

(5) Determine the corresponding axial force $P_b'^{(1)}$ by the $P_b - S_b$ relation.

(6) Compute $|P_b^{(1)} - P_b'^{(1)}| = D$. If the different value D equals zero or is less than a small value, then the equilibrium condition and boundary condition of the pile are satisfied and P_b is the solution, else P_b is changed to satisfy the conditions. We consider that there is a relation between the different value of P_0 and real solution and D. Therefore, we take

$$P_0^{(2)} = P_0^{(1)} - \lambda(P_b^{(1)} - P'^{(1)}_b)$$

Table 1. The soil characteristics of each layer soil

No.	soil name	layer thickness (meter)	compressive modulus E_s (MPa)	standard bearing capacity f_k (kPa)
1	mucky clay (2—1)	1.5	3.6	90
2	mucky clay (2—2)	2.1	2.8—4.0	70—100
3	clay (3—1)	1.4	4.3	110
4	clay (3—2)	1.0	5.4	140
5	clay (3—3)	3.5	2.8	70
6	clay (4—1)	1.5	9.5	250

Table 2. The parameters of back analysis

No.	soil name	τ_u (kPa)	α (1/mm)	soil parameters at pile tip
1	mucky clay (2—1)	24.3	0.35	
2	mucky clay (2—2)	40.0	0.40	
3	clay (3—1)	47.1	0.35	$K_1=7\times10^7$N/m $K_2=5\times10^6$N/m $S_{bu}=0.02$m
4	clay (3—2)	50.0	0.35	
5	clay (3—3)	25.0	0.20	
6	clay (4—1)	75.0	0.40	

where λ is a constant. It is relative to $P_0^{(1)}$. Usually, it is taken 1, but when the different value of $P_0^{(1)}$ and real solution is very large, it is necessary to take $0<\lambda<1$ because this can ensure the iteration to contract.

(7) Iterate the procedures from (2) to (6) until the computation of the N-th iteration satisfies $|P_b^{(n)} - P_b'^{(n)}| \leqslant \varepsilon$, where ε is a small prescribed value.

(8) Iterating the procedures from (2) to (7), we can compute the corresponding loads to different settlement S_0. Thus, the $P-S$ curve can be obtained.

4 EXAMPLE

In order to examine the method, we simulate and analyse the data[3] of load testing in a site. The soil stratums are divided into six layers. The soil characteristics of each layer soil is shown in table 1. The pile length is 11.0 meter and the pile diameter is 0.6 meter. In computing, the model of the transfer-function used is the exponent curve (Eq. (2)) model for the shaft resistance and the elastic-hardening plasticity (Eq. (5)) model for the soil resistance at the pile tip. The parameters of the transfer-functions are obtained by back analysis[4]. Table 2 is the result of the back analysis. In Fig. 4, the simulated result is compared with the testing result.

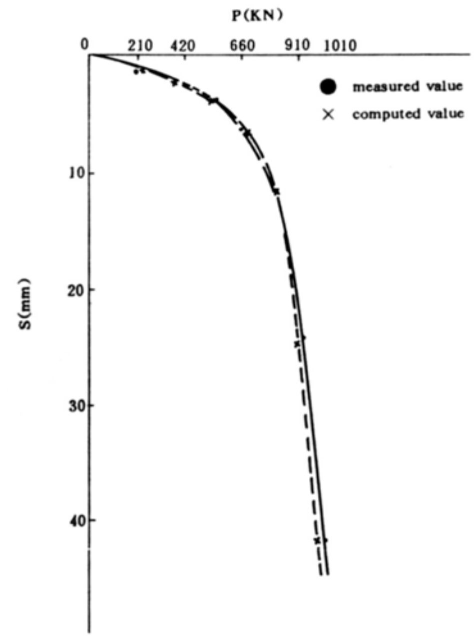

Figure 4. $P-S$ curve

5 CONCLUSION

The example shows that the load iterating method can simulate the load transfering procedure, and can be used in the pile in stratified soil. Especially, the method can fit the $P-S$ curve of pile. Therefore, it may widely be applied in engineering.

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