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Simulation of Pile-Soil interaction using finite element theory in the case of laterally loaded pile

Mô phỏng tương tác cọc - đất theo lý thuyết phần tử hữu hạn trong bài toán cọc chịu tải trọng ngang

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ABSTRACT:
When a pile foundation is subjected to lateral loading, the interaction between the pile and the soil significantly affects the lateral displacement and bending moment of the pile. Interaction models are established based on the subsoil parameters, cross-sectional shape, size, and material of the pile. In this paper, the author presents an analysis of laterally loaded pile problem using the "p-y curve" soil model to simulate the nonlinear pile-soil interaction using the finite element theory. In this model, the pile element is modeled as a continuous beam on a linear elastic foundation, while the soil is modeled as a nonlinear elastic material. The results show that the lateral displacement and bending moment of the pile from the proposed model are in good agreement with the calculations from the TCVN 10304:2014 standard, and depend on the subsoil parameters, pile properties, and the applied loads.

Keywords: Modeling; Lateral load; Pile-soil interaction; p-y curves

TÓM TẮT:
Trong móng cọc đài cao khi cọc chịu tải trọng ngang, tương tác giữa cọc và đất ảnh hưởng khá rõ tới momen uốn và chuyển vị ngang của cọc. Các mô hình tương tác được thiết lập dựa vào các thông số địa chất nền và hình dáng tiết diện, kích thước, vật liệu cọc. Trong bài báo này, tác giả trình bày phân tích bài toán cọc chịu tải trọng ngang dựa trên cơ sở lý thuyết của mô hình nền "đường cong p-y" để mô phỏng tương tác cọc- đất phi tuyến bằng lý thuyết phần tử hữu hạn; trong đó phần tử cọc được mô hình như một dầm liên tục đặt trên nền đàn hồi, đất nền là vật liệu đàn hồi phi tuyến tính. Kết quả thu được cho thấy momen và chuyển vị ngang của cọc từ mô hình tính biến thiên đồng nhất với kết quả tính toán theo các công thức trong tiêu chuẩn TCVN 10304: 2014, phụ thuộc vào các thông số của đất nền, cọc và tải trọng tác dụng lên cọc.

Từ khóa: Mô hình; tải trọng ngang; tương tác cọc- đất; đường cong p-y

1. INTRODUCTION

Calculation of single piles subjected to lateral loads has been studied by many authors [1, 2, 3, 4, 5], and has been divided into two popular methods, which are: 1) Calculating the ultimate lateral capacity based on soil pressure and 2) Calculating the allowable lateral displacement based on analyzing the foundation model, which considers the interaction between the pile and the soil. With the second method, based on the interaction model, the pile is analyzed as a beam structure on an elastic foundation, specifically the Winkler foundation model; in which the interaction between the pile and the soil (referred to as pile-soil interaction) is simulated by two-way spring support brackets that can bear both tension and compression. This is a classic structural mechanics method, with explicit theoretical calculations. However, the complexity of the problem as well as the accuracy of the results depends on the corresponding spring model. The spring material model is essentially the relationship between lateral load (p) and lateral displacement (y), which is called the p-y curve model in theoretical calculations. Currently, many p-y curve models have been proposed to correspond to different soil conditions and loads, such as McCelland and Focht model (1958), MatLock (1970), Lymon C. Resse (1974), and some other authors [6, 7, 8, 9]. Most of these models have been tested through field experiments and incorporated into many design standards and guidelines. Establishing a detailed pile-soil interaction model with high accuracy is possible thanks to the assistance of some powerful computational software such as PLAXIS, ABAQUS, FLAC, etc., based on the finite element method.

However, simulating a nonlinear soil environment with infinite boundary conditions is quite complex and partially limits the widespread application of these soil models. In this article, the authors introduce two simple models by Matlock [10] and Reese [11], which are pre-established to simulate the p-y curve for the corresponding sandy clay soil under static, short-term loading. The application of these models is demonstrated by a lateral pile load problem using Sap2000 software to analyze the non-linear relationship between the pile and soil for a specific geological condition. Based on the calculated results, the authors make some observations and recommendations regarding the conditions for applying the computational model in practical deep foundation design.

2. PILE - SOIL INTERACTION AND P-Y CURVES

The interaction between the pile and the soil is simulated by using bearing pads, where the soil's behavior around the pile is replaced by spring pads at the midpoint of each pile segment in the soil, and the spring stiffness coefficient, k, changes nonlinearly according to the p-y curve at the corresponding depth. The p-y curve is considered as the behavior law of the soil at the depth being examined. This law at each position is independent and not dependent on the behavior at other positions. Below are two p-y curve models for the corresponding clayey soil proposed by Matlock (1970) and Reese (1974).

2.1. The p-y curve of cohesive soft clay under static, short-term loading

From the lateral static load test on the pile in soft clay, Matlock [10] proposed to develop the p-y curve of normally consolidated soft clay according to equation (1):

$$\frac{P}{P_u} = 0{,}5\left(\frac{y}{y_{50}}\right)^{\frac{1}{3}} \quad (1)$$

In which: P, Pu are the ultimate soil reaction and resistance per unit length of the analyzed pile. The value of Pu is taken according to (2):

$$P_u = N_p P_b \quad (2)$$

Where P_b is the soil pressure coefficient, which depends on the inclination angle β between the horizontal plane and the ground surface, and its value is determined by (3); (4) or (5):

$$P_b = \left(\frac{1}{(1+\tan(\beta))}\right) \text{ với } \beta > 0 \quad (3)$$

$$P_b = \left(\frac{\cos(\beta)}{\left(\sqrt{2}\cos\left(\frac{\pi}{4}+\beta\right)\right)}\right) \text{ với } \beta < 0 \quad (4)$$

$$P_b = 1 \text{ với } \beta = 0 \quad (5)$$

N_p is the maximum value between two values in the formula (6) and (7):

$$N_p = 9C_u B \quad (6)$$

$$N_p = 3C_u B + \gamma' Z B + J Z C_u \quad (7)$$

With: C_u: Shear strength under undrained conditions.

B: Diameter (for circular cross-section) or side length (for square cross-section) of the pile.

γ': Average effective unit weight of soil layers from the surface to the current depth being considered.

Z: depth of the analyzed section of the pile.

J: The non-integer parameter depends on the soil type: J=0.5 for soft clay, J=0.25 for stiff and medium clay.

In formula (1), y represents horizontal displacement, y_c represents the horizontal displacement of the pile when P is equal to half of the ultimate soil resistance, and y_c is calculated as y_{50} according to the formula (8):

$$y_{50} = 2{,}5B\varepsilon_{50} \quad (8)$$

Where ε_{50} is the strain of the soil in the triaxial compression test at which the stress reaches 50% of the failure stress.

2.2. The p-y curve of clayey sand soil under short-term static loading under groundwater

To develop the characteristic p-y curve for silty sand, Reese and Grubbs [12, 13] conducted experiments on a type of silty soil with internal friction angle, φ, cohesion, C_u, and unit weight γ.

At different depths of the soil, calculate the following quantities in:

$$a = \frac{\phi}{2},\ b = 45 + \frac{\phi}{2},\ K_0 = 0{,}4,\ K_\alpha = \tan^2\left(45 - \frac{\phi}{2}\right) \quad (9)$$

$$S_0 = \gamma Z,\ S_1 = \frac{K_0 Z \tan(\phi)\sin(b)}{\tan(b-\phi)\cos(a)} \quad (10)$$

$$S_2 = \frac{\tan(b)}{\tan(b-\phi)}\left(B + Z\tan(b)\tan(a)\right) \quad (11)$$

$$S_3 = K_0 Z \tan(b)[\tan(\phi)\sin(b) - \tan(a)] \quad (12)$$

$$S_4 = K_\alpha B \quad (13)$$

$$S_5 = K_\alpha B\gamma Z\left(\tan^8(b) - 1\right) \quad (14)$$

$$S_6 = K_0 B\gamma Z \tan^4(b) \quad (15)$$

In which B is the diameter of the pile (for circular cross-section piles) or the side length of the pile (for square cross-section piles).

Ultimate unit end-bearing capacity P_{ult} determined according to (16):

$$P_{ult} = A_S P_{ult\phi} + P_{ultc} \quad (16)$$

In which: the frictional resistance component $P_{ult\phi}$ is taken as the smaller value between the two quantities (17) and (18):

$$P_{st} = S_0(S_1 + S_2 + S_3 - S_4) \quad (17)$$

$$P_{sd} = S_5 + S_6 \quad (18)$$

The adhesive force component P_{ultc} is taken according to (2), the AS coefficient is taken based on experimental results, and compiled into a lookup table.

3. ESTABLISHING THE P-Y CURVE FOR DIFFERENT SOIL CONDITIONS

Analysis of the problem of a single pile subjected to lateral load in cohesive soil with the following main parameters: 1) A round steel pipe pile with an outer diameter of B is 500mm, thickness t is 12mm, embedded length in soil L is 40m, moment of inertia I is 3.15x10-4m4, and elastic modulus E is 2x105MPa; 2) The cohesive soil consists of three layers, in which layer 1st is a clayey sand in a plastic state with a thickness of 15m, friction angle is15o, cohesion Cu is 15kPa, layer 2nd is a partially hardened clayey soil with a thickness of 5m, friction angle is21o, cohesion Cu is 15kPa, and layer 3rd is a fully hardened clayey soil with an undrained shear strength Cu is 40kPa. 3) The load applied to the pile head: a vertical force N is 100 kN, a horizontal force H is 100 kN, and a moment M is 50 kNm. The pile and the load applied to the pile are shown in Figure 3a.

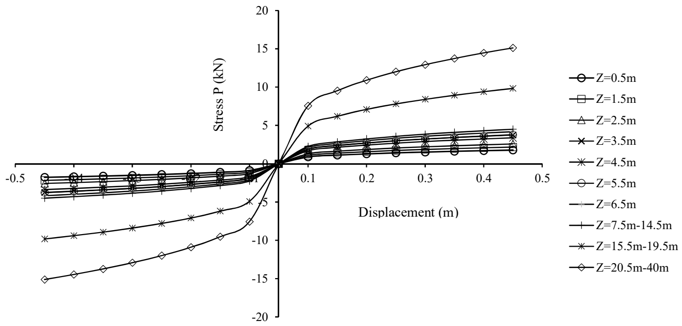


Figure 1: The p-y curve for soft clay according to Matlock model

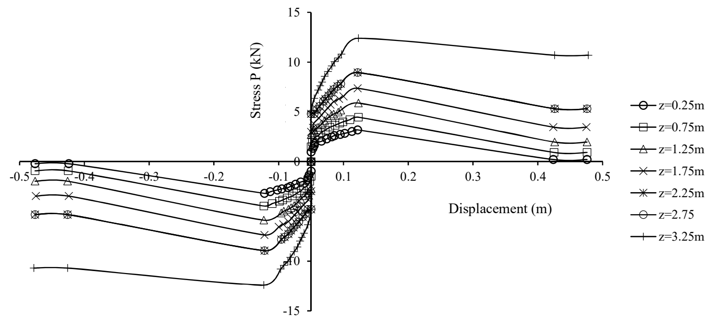
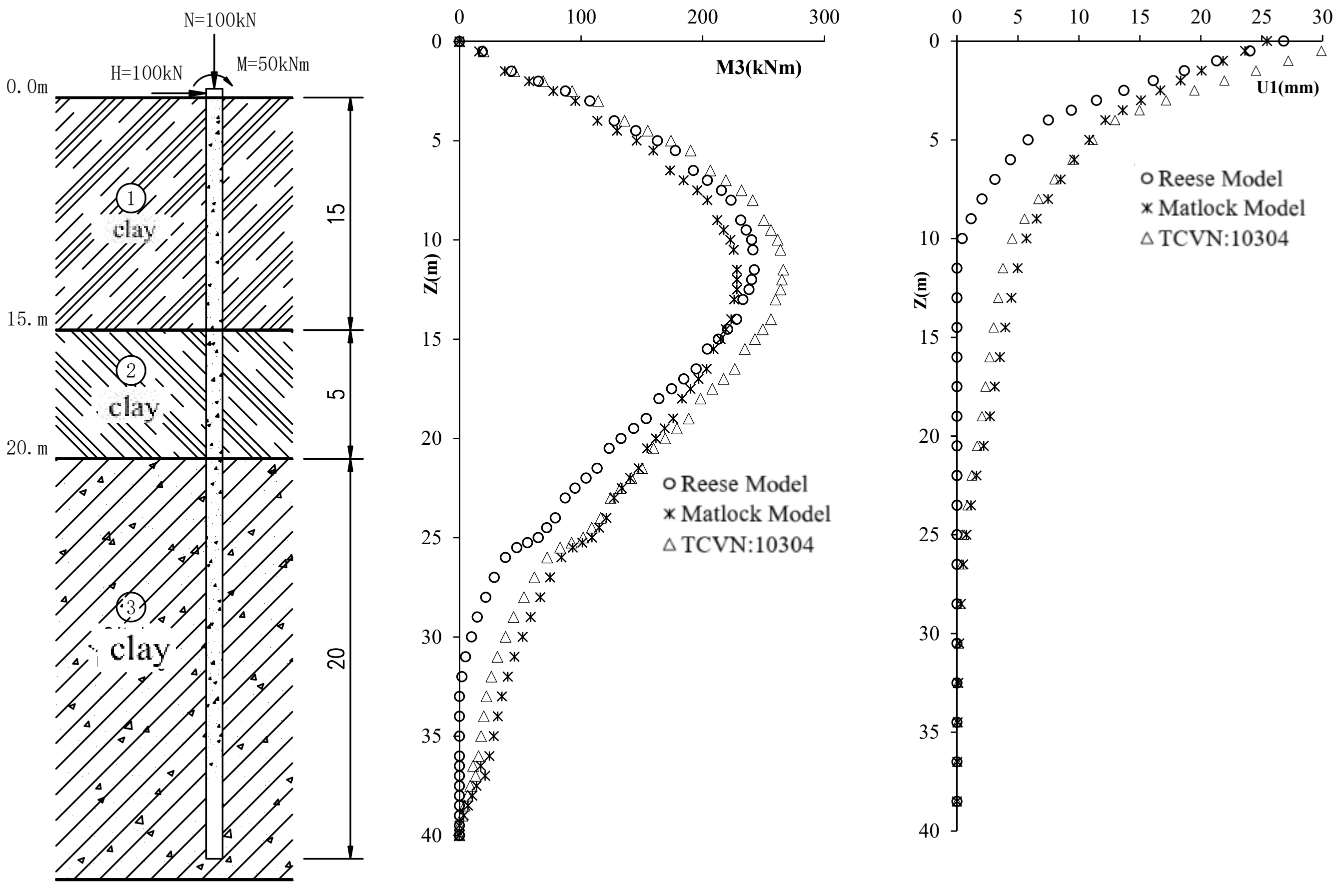


Figure 2: The p-y curve for soft clay according to Reese model



a) Diagram of pile in soil *b) Bending moment (kNm)* *c) Lateral displacement U_1 (mmm)*

Figure 3: The diagram of piles in soil and the calculation results of piles subjected to lateral loads

The soil is assumed to be divided into multiple layers, with a thickness of 0.5m for layers within the depth of 10m from the ground surface and 1m for layers deeper than 10m. Based on the given parameters, the values for the p-y curve parameters are calculated using basic mathematical tools for both Matlock and Reese theoretical models in Part 2. The resulting p-y curves for the cohesive soil with normal consolidation at different depths corresponding to each model are illustrated in Figures 1 and 2 below. The p-y curve parameters are defined for the Support element in the simulation model in Sap2000 to calculate the lateral displacement and internal forces of the pile under the specific conditions of the problem described above.

4. CALCULATION RESULTS AND OBSERVATIONS

The bending moment diagram (M_3) and lateral displacement diagram (U_1) of the pile calculated using two p-y curve models are shown in Figure 3. The results show that the bending moment reaches a maximum value quite close to the pile head, approximately one quarter of the pile length in this problem. The M_3 diagram in Figure 3b clearly reflects that the soil layer receiving the lateral load is mainly the top soil layer, which is consistent with the experimental results presented in [18].

Figures 3b and 3c also show that using the p-y curve to simulate the interaction between the pile and soil according to the experimental models of Reese and Matlock gives fairly similar results in terms of both pile bending moment and lateral displacement. The pile bending moment is equivalent for both models in the range from 0-12m from the ground level, but beyond 12m, the pile bending moment is greater when calculated using the Matlock model. For lateral displacement of the pile, both models approximate the maximum value at the pile head, but according to the Matlock model, the lateral displacement value is distributed along the length of the pile, with a smaller slope. This can be explained by the fact that in the Matlock model, the parameters of the p-y curve do not take into account the influence of the soil's ϕ and Cu coefficients.

The table below summarizes the values of moment and lateral displacement at the head of the pile according to different p-y curve models in SAP2000 and the calculation results using the formula in Appendix A of Vietnamese standard TCVN 10304: 2014 [17].

Table 1. Calculation results of moment and displacement at the head of the pile

Reference Calculation	Maximum moment (kNm)	Displacement of pile head (mm)
Reese Model	242.3	26.81
Matlock Model	228.1	25.43
TCVN 10304: 2014	285.9	31.09

The result shows that the maximum moment and settlement values calculated according to TCVN 10304:2014 are greater than those calculated using Sap2000 in both models. The calculation according to TCVN 10304:2014 is relatively simple using established formulas, however, it can be seen that the interaction between the pile and the soil is determined through the coefficient K, selected from a pre-established table, depending on the soil type and with a fairly wide range of variation. The method based on accurate and objective p-y relationship curves is better established as it is based on soil parameters such as the soil's , , and C_u coefficients, and also considers pile parameters such as size, shape, and embedment depth in the soil.

5. CONCLUSION

This article discusses the characteristics of the interaction between pile and soil, specifically the subgrade modulus using two load-settlement curves proposed by Matlock (1970) and Reese (1974), which are currently widely used in the analysis of deep foundation subjected to lateral loads. The method of determining the subgrade modulus using the p-y curve is a modern, scientific, and highly reliable method that has been recommended for use by many organizations. Currently, many foundation software have integrated libraries of these curves, making calculations more convenient and simple. However, to obtain accurate calculation results under the geological conditions of Vietnam, more experiments are needed to develop p-y curve libraries that are appropriate for different geological conditions.

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