doi.org/10.62683/SINARG2025.120

Research paper

ANALYSIS OF THE BEHAVIOR OF LATERALLY LOADED PILE–SOIL SYSTEM

Zoran Bonić[1], Andrija Vlašković[2], Nikola Romić[3]

Abstract

Piles, as a type of deep foundations, are primarily intended to accept the vertical load from the superstructure; however, under certain circumstances, they are also exposed to significant lateral loads. This is the case with retaining structures, bridge piers, transmission line poles, chimneys, tall buildings, dock facilities, oil platforms, etc. In the focus of this paper is the analysis of the behavior of laterally loaded piles. First, the most common analytical models for the calculation of this problem were presented, and then the described models were evaluated with the results of experimental investigations on laterally loaded piles tested in situ. Based on the conducted comparative analysis, it was concluded that the integrated approach – the enhancement of existing analytical models with the results of experimental investigations – results in models that more realistically take into account the interaction of the pile and the surrounding soil, which is of crucial importance in the case of laterally loaded piles.

Key words: *Geotechnical engineering, laterally loaded piles, soil–structure interaction, load–displacement response.*

[1] Prof., University of Niš, Faculty of Civil Engineering and Architecture of Niš, Serbia, zoran.bonic@gaf.ni.ac.rs , ORCID 0000-0002-7452-6756

[2] Teach. Assist., University of Priština, Faculty of Technical Sciences of Kosovska Mitrovica, Kneza Miloša 7, 40000 Kosovska Mitrovica, Serbia, andrija.vlaskovic@pr.ac.rs, ORCID 0000-0003-3648-9058

[3] Teach. Assist., University of Niš, Faculty of Civil Engineering and Architecture of Niš, Serbia, nikola.romic@gaf.ni.ac.rs , ORCID 0000-0002-1075-2738

1. INTRODUCTION

Like other deep foundations, piles are primarily designed to support significant vertical loads. However, under certain conditions, they are also exposed to significant transverse (horizontal) loads. This is the case with retaining structures, transmission line poles, dock facilities, oil platforms, bridge piers, chimneys, etc. For some structures, the criterion for the design of piles is the ultimate force that causes the pile to fail or the soil around the pile to fail, whereas for other structures the criterion is the maximum displacement of the pile. In both cases, when designing piles, it is necessary to determine the values of bending moments, shearing forces and displacements along the depth of the pile.

When dimensioning piles (as is the case with sheet piles and diaphragms), the most common starting point is the differential equation of the elastic line of the pile as a structural element exposed to the effect of vertical and horizontal loads:

$$EI\frac{d^4y}{dx^4} + V\frac{d^2y}{dx^2} + p = 0 \quad (1)$$

where: EI – bending stiffness of the pile,

V – vertical force in the pile,

y – displacement of the elastic line of the pile (deflection),

p – reactive lateral soil pressure (soil reaction).

For practical calculation purposes, the influence of the vertical force V on bending is usually neglected, which is justified in the case of sheet piles and diaphragms, where the vertical force (if present at all) is almost always of low intensity, but not in the case of piles, where V represents the predominant load. However, considering that the presence of vertical force reduces the lateral displacements and bending, and consequently the remaining influences in the pile (bending moment, shear force and lateral soil resistance), its neglect is on the side of safety. Thus, the basic differential equation of the elastic line of the pile takes its final form:

$$-EI\frac{d^4y}{dx^4} = p \quad (2)$$

Figure 1 shows the distribution of basic static quantities along the pile.

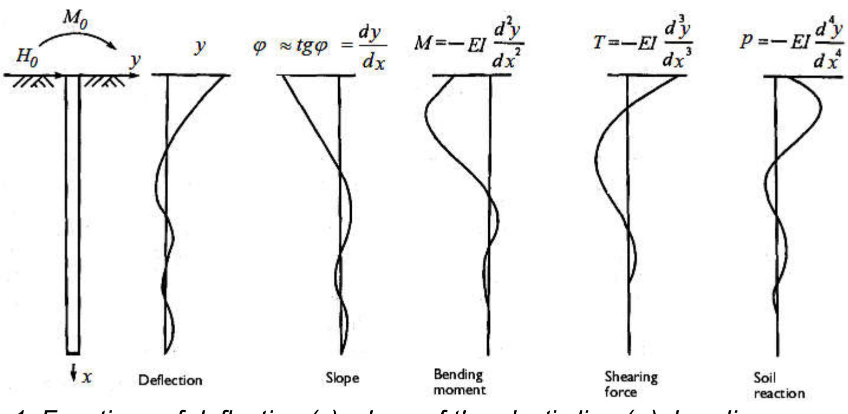

Figure 1. Functions of deflection (y), slope of the elastic line (φ), bending moment (M), shear force (T) and soil reaction (p) along the depth of pile [1]

2. CALCULATION METHODS FOR LATERALLY LOADED PILES

The design of laterally loaded piles primarily depends on the method of soil modeling and the applied calculation method. Commonly applied soil models are:

- ideal-elastic constitutive models (one-parameter and two-parameter models),
- simple elasto-plastic constitutuve models and
- elasto-plastic hardening models.

As for the calculation method, the following are most often applied:

- calculations starting from the differential equation (1) and solving the problem in analytical form,
- calculations based on the concept of discretization of the differential equation (1) or discretization of the pile and the surrounding soil.

The majority of calculation methods found in the literature and design practice treat the soil with the simplest and most easily applicable Winkler's one-parameter model. Here, the soil is represented by a system of independent linear-elastic springs (fictitious struts), where deformations occur only in those springs where the load also occurs. The soil is described by a single parameter – the soil reaction modulus (in the vertical or horizontal direction), which is usually taken as constant or linearly increasing with depth. Using this soil model, a well-known analytical solution, the Hetenyi method (1946), was developed, where the soil reaction modulus is constant with soil depth. The most common analytical solutions where the soil reaction modulus increases linearly with depth include the method of initial parameters (СНиП 2.02.03-85) [2], and the solution of Reese and Matlock [3]. In addition, the Winkler's one-parameter model is widely used in numerous software packages in the field of civil engineering (SAP, STAAD, TOWER, STRESS), based on the principle of discretization of piles and surrounding soil.

Two-parameter soil models also belong to the group of methods based on the ideal-elastic soil model, of which the most widespread is the linear-elastic, homogeneous continuum model. Here the soil properties are defined by two parameters, the modulus of elasticity E_s (which can also be constant or variable with depth) and Poisson's ratio v. Analytical method for solving the problem based on this more realistic, but significantly more complex model for application, has not been commonly used, precisely due to the cumbersomeness of the solution. However, this soil model can often be found in methods based on the concept of discretization of the differential equation (1): the finite difference method, as well as software packages for specialized geotechnical purposes (PLAXIS, GEO-SLOPE, GEO5) and general purposes (ANSYS, NASTRAN and more recently TOWER) based on the finite element method. The well-known analytical–empirical solution of Poulos [4], as well as Randolph's solution [5], are based on this soil model.

Simple elasto-plastic soil models (the Coulomb–Mohr model [6] and the Drucker–Prager model [6], which are the most common in geotechnical engineering) are an integral part of the above-mentioned specialized and general packages, whereas elasto-plastic hardening models (the Cam clay model [7], the modified Cam clay model [8] and similar) are represented only in geotechnical softwares.

In order to compare different calculation methods, calculations performed manually without the use of software packages were selected in this study, as the most commonly used in geotechnical practice: the method of initial parameters (СНиП 2.02.03-85), the method of Poulos and the method of Randolph.

The first two belong to methods based on the Winkler's one-parameter soil model described by the soil reaction modulus. In addition to the basic drawback of this soil model that it does not simulate continuous soil properties, a major difficulty of the model is the determination of the only parameter – the soil reaction modulus. Namely, the modulus does not represent a fundamental property of the soil, but rather the coefficient of linear dependence of the pressure at the observed point of the contact surface and the displacement of the soil at that point. Therefore, in addition to the type of the soil and its condition (in terms of density for coarse-grained soils, or water content, consistency state and consolidation for fine-grained soils), the soil reaction modulus also depends on numerous factors related to the structure itself. These are, primarily, the size and shape of the contact surface of the foundation, the foundation stiffness and depth, the load intensity, etc. Therefore, when designing piles, the values of the soil reaction modulus usually given in tables in the literature should be considered as an approximation, and therefore much more attention should be paid to their precise determination. By applying this simplest soil model, sufficiently good calculation results can be obtained if the value of the soil reaction modulus is determined in such a way that it satisfactorily reflects the behavior of the pile–soil system. In both methods of calculating piles, it is assumed that soil stiffness increases with depth, which primarily corresponds to sands and normally consolidated clays.

The other two methods (of Poulos, as well as the Randolph method) treat the soil with a linear-elastic, homogeneous continuum model. The parameters of this model – the Young modulus of elasticity E_s or shear modulus G_s and Poisson ratio v – can be determined by laboratory or field experiments, and therefore their reliability is higher compared to the soil reaction modulus. In addition to soil homogeneity in depth, these two methods can also be used for soils that are linearly inhomogeneous with depth or for layered soils. They are suitable for simulating soil behavior in the elastic range, which can roughly correspond to the service load of piles.

3. EXAMPLES OF CALCULATION OF LATERALLY LOADED PILES

To analyze the quality of the calculations using the four methods mentioned above, data from field tests of two piles were used. The piles were vertical and loaded with a horizontal force H_0 at the pile cap, whereby the horizontal displacements at the pile cap u_0 were recorded. Both tested piles were Franki reinforced concrete piles; the first one was located near Subotica and the second one was in New Belgrade. Data on soil obtained by cone penetration test (CPT), characteristics of piles and test results were given by Milović and Đogo [9]. Table 1 provides data on the type and dimensions of the tested piles, the type and characteristics of the soil, as well as the maximum applied horizontal loads (H_0) and the corresponding recorded displacements (u_0) at the pile caps.

Table 1. Pile test data [9]

Tested pile	Pile properties	Maximum horizontal load applied	Maximum horizontal displacement	Soil properties
Franki	• Pile length: 16.0 m • Pile diameter: 0.52 m	H_0 = 100 kN	u_0 = 10 mm	• Silt and silty sand. • The result of ili cone penetration test: recorded cone resistance q_c = 1.5–6.5 MPa.
Franki	• Pile length: 10.0 m • Pile diameter: 0.60 m	H_0 = 100 kN	u_0 = 7 mm	• Silty sand and sand with gravel. • The result of cone penetration test: recorded cone resistance q_c = 5.0–12.0 MPa.

4. CALCULATION RESULTS

As already mentioned, in order to compare different calculation methods with the results of field tests of horizontally loaded test-piles, calculations according to the method of initial parameters (СНиП 2.02.03-85), the method of Poulos and the method of Randolph were selected. The results of this analysis are presented in the diagrams in Figures 2 and 3.

All the listed methods treat the soil with an ideal-elastic linear model, whereby the method of СНиП 2.02.03-85 belongs to the group of one-parameter soil models, whereas the calculation method according to Poulos and the Randolph method belong to the group of two-parameter soil models.

The method according to СНиП 2.02.03-85 represents the analytical solution of the basic differential equation (2) by the method of initial parameters, and the soil is represented by the Winkler's model with a single parameter – the soil reaction modulus, which increases linearly with soil depth and is equal to zero on the ground surface.

In the calculation method according to Poulos, the soil is treated as an ideal, homogeneous, elastic and isotropic half-space that simulate continuous soil properties and is defined by the Young modulus of soil elasticity E_s and Poisson ratio v_s.

In the Randolph calculation method, the soil is also treated as an ideal, homogeneous, elastic and isotropic half-space and is defined by the soil shear modulus *Gs* obtained from a field pressuremeter test (PMT) and Poisson ratio v_s. To develop this calculation method, Randolph used the finite element method in numerous examples analyzing homogeneous and inhomogeneous soil.

The conducted analysis and its graphic presentation show a good agreement between the results obtained by applying the developed analytical solutions and the recorded displacements of the pile caps during the experiments.

From the given diagrams (Figure 2 and Figure 3), it can be seen that the Randolph method results in pile cap displacement values that were smaller than the measured displacement values of the tested piles for all applied load levels. On the other hand, the displacement values obtained by applying the method of СНиП 2.02.03-85 are larger than the experimentally recorded ones also for all load levels. The Poulos method, as the third one considered in this analysis, gives results that were closest to the experimental ones during the entire loading of the piles. Almost up to half of the test load intensity, the results did not differ from the magnitude of the measured displacements, whereas up to a magnitude of approximately two-thirds of the test load intensity, the differences were less than 20%.

However, for the generalization of such conclusions, it is necessary to make a significantly larger number of such theoretical–experimental comparisons.

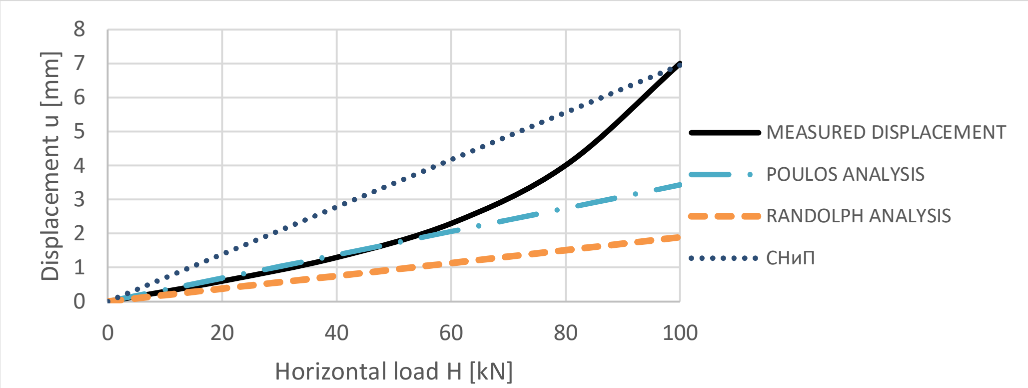

Figure 2. Diagram comparing horizontal displacements at the pile cap of the first pile

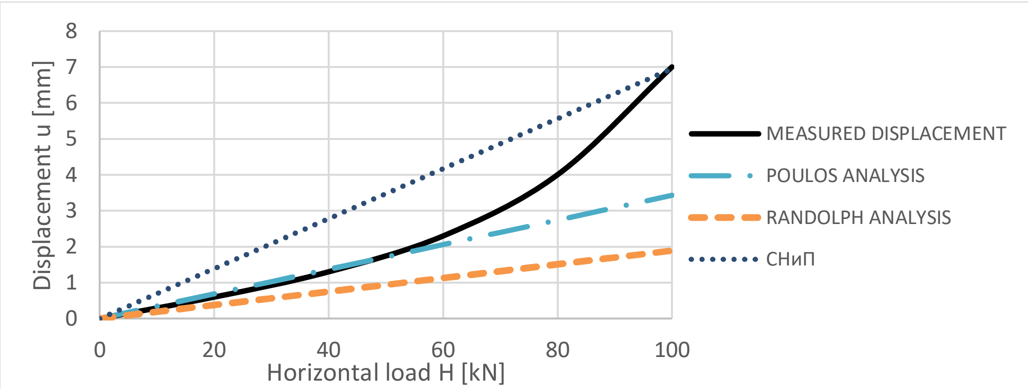

Figure 3. Diagram comparing horizontal displacements at the pile cap of the second pile

5. CONCLUSIONS

The main drawback of the presented analytical solutions, which are based on the application of ideal-elastic linear soil models, is that they do not account for the more realistic nonlinear soil behavior. However, for load levels that can significantly exceed the service load levels, the obtained results show very good agreement with the results of pile test loading. This idealization of soil behavior is justified when calculating displacements due to the action of transverse forces of intensities that are far bellow the ultimate value, which is a condition that is always met when it comes to service loads of piles. For these load levels, it can be considered with sufficient accuracy that the pile behavior is in the linear-elastic region.

ACKNOWLEDGMENTS

The authors thank the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš - Registration number: 451-03-137/2025-03/200095 dated 04/02/2025.).

REFERENCES

[1] Murthy, V.N.S.: **Geotechnical Engineering, Principles and Practices of Soil Mechanics and Foundation Engineering**. *CRC Press*, New York, 2002.

[2] **Проектирование и устройство свайных фундаментов,** Сп 50-102-2003, Москва, 2004.

[3] Tomlinson M., Woodward J.: **Pile Design and Construction Practice**. *Taylor & Francis*, New York, 2007.

[4] Poulos, H.G.: **Behavior of laterally loaded piles: I—Single piles**. *Proceedings of the American Society of Civil Engineers*, Vol. SM5, 711-31, 1971.

[5] Randolph, M.F.: **The response of flexible piles to lateral loading**. *Géotechnique*, Vol., No. 2, 247-259, 1981.

[6] Potts D.M., Zdravković L.: **Finite element analysis in geotechnical engineering Theory**. *Imperial College of Science, Technology and Medicine*, ThomasTelford Publishing, London, 1999.

[7] Roscoe K.H., Schofield A.N.: **Mechanical behaviour of an idealised 'wet' clay**. *2nd ECSMFE*, Wiesbaden, Vol. 1, 47-54, 1963.

[8] Roscoe K.H., Burland I.B.: **On the generalised stress-strain behaviour of 'wet' clay**. *Eng. Plasticity*, Cambridge Univ. Press, 535-609, 1968.

[9] Milović M.D., Đogo B.M.: **Greške u fundiranju**. *FTN Izdavaštvo*, Novi Sad 2005.