DESIGN

FINITE-ELEMENT ANALYSIS OF TAPERED PILES UNDER COMBINED VERTICAL AND HORIZONTAL LOADINGS

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A universal method of analyzing tapered piles under the combined action of a horizontal, vertical, and moment loading is developed using the finite-element method and with consideration of their bending stiffness. It is derived on the basis of experimental data that the coefficient of subgrade reaction varies as a function of the horizontal displacement of the pile and the depth of the layer under consideration. Procedures are proposed for determination of the coefficient of subgrade reaction on the basis of data from static probing and for consideration of the non-linearity of the deformation of the soil bed and pile material, which makes it possible to calculate the "load-displacement" curve.

A number of pile designs and pile foundations, which are recognized as most effective, can be isolated on the basis of many years of research and experience with the widespread use of various structural solutions of pile foundations, and a procedure for their installation has been mastered sufficiently by construction organizations and is supported by appropriate equipment. Precast piles (prismatic piles with a solid cross section, shell piles, hollow circular piles, and pyramidal piles with caps and heads), and cast-in-place piles (piles cast in predrilled holes with or without pedestals), which can be concreted in cylindrical holes punched in the ground and pyramidal holes tamped into the ground are classed among these piles. They are distinguished by the sectional shape and taper of the shaft; a different method of analysis must therefore be developed for virtually every design.

One of the most widely used types of tapered piles (pyramidal piles) is described in [1], from which it follows that the majority of methods used for the analysis of these piles for a horizontal load are based on the Fuss-Winkler model. Moreover, the foundation bed is represented as uniform with respect to depth, and the pile is considered "rigid" when subjected to bending. In his working diagram, Mamedov [2] considers the bending "stiffness" of a pyramidal pile, but disregards the multiple-layer character of the foundation bed - the coefficient of subgrade reaction varies linearly with depth within the limits of the entire length of the pile. For a cross section of 0.6 m and more, and a sufficiently large pile length, the foundation bed is included in the functioning at a significant depth (greater than 30 x 30-cm piles) in connection with the fact that the probability of a sudden jumpwise change in the physicomechanical characteristics of the soil increases with depth. To improve the reliability of methods used for the analysis, it is therefore necessary to consider the multiple-layer character of the foundation bed. We had previously proposed a solution with allowance for the multiple-layer character of the foundation bed [3], but it was given for "rigid" piles.
Consideration of the nonlinearity of the deformation of the soil bed and pile material is another problem.

"Linear" methods of analysis are oriented toward convergence with experimental data within a restricted range of displacements (in the region of 8-10 mm). In designing single-pile foundations, however, it is frequently necessary to predict the behavior of the piles for displacements ranging from 3-4 mm to 25-30 mm. Numerous experiments indicate that in this range of displacements, the "load-displacement" diagram assumes a clearly expressed nonlinear pattern; to obtain reliable data, therefore, this nonlinearity should be considered in the analysis.

The actual development of a method of analysis for the combined action of vertical, horizontal, and moment loads on "flexible" and "rigid" piles of constant cross section and tapered piles of any length is therefore presented with consideration given to the nonlinearity of deformations of the soil bed and pile material.

Let us represent the pile as a flexible rod embedded in a multilayer foundation bed, which can be characterized by a coefficient of reaction $C(x)$, and partition the pile (rod) into $n$ finite elements over its length (Fig. 1). An isolated finite element has four degrees of freedom - displacements $U_1$ and $U_2$, and angles of rotation $\varphi_1$ and $\varphi_2$ of the ends of the element at the nodes.

Let us use the element-deflection function in the form of a cubic polynomial, and, having determined the coefficients before the variables with consideration given to the boundary conditions on the ends of the element, write the expression for the displacements in matrix form (the symbol "T" denotes the matrix-transposition operation)

$$U(x)=[r]^T[U], \quad (1)$$

where $[r]^T=[r_1, r_2, r_3, r_4]$;