ANALYSIS OF TAPERED PILES UNDER COMBINED ACTION OF VERTICAL, HORIZONTAL, AND FLEXURAL LOADS

A. L. Gotman

During the last few years, in the industrial construction field wide use has been made of single-pile foundations, which have significant technicoeconomic advantages in comparison with traditional foundations on natural bases and piles.

Along with shell piles and bored-cast-in-place piles of large diameters [1], single-pile foundations have been used recently which consist of punched-cast-in-place tapered piles of large cross section, for example under pipeline supports [2]. On the foundations of industrial buildings and structures, in addition to the vertical loads significant horizontal loads and flexural moments act also (especially at the supports of pipelines). Hence, the questions of analysis of such piles under these factors are of great practical importance.

The existing methods of analysis of piles, including tapered piles [3], are based on the theory of local deformations (Fuss-Winkler) and take into account the soil resistance only on the lateral faces perpendicular to the plane of action of the load. Moreover, in the total resistance of pile to the horizontal load action a definite share is taken by the resistance of the lateral faces as a result of the soil friction on them. Thus, experimental investigations have shown that the share of the resistance to a horizontal load as a result of friction on the lateral surfaces of tapered piles may reach 30-45% of the total [4], and that this component increases as the vertical load increases [5].

In [6] an attempt is made to work out a procedure for analysis taking into account the above-mentioned factors, but it makes possible to find only the forces in the foundation, whereas for the design practice the question of determination of the displacements and angle of rotation of the pile head is of great importance also.

Let us consider a more universal method for analysis of tapered piles under a horizontal load and a bending moment, taking into account the friction on the lateral faces.

Let us adopt the following premises (Fig. 1).

1. The soil base is heterogeneous with depth, of multiple layers, and divided into n layers with moduli of subgrade reaction \( K_i \) and friction resistances \( f_i \) constant within the limits of each layer.

2. The dimension of the pile section side \( d_x \) varies with depth according to the linear relation

\[
\frac{d_x}{d_o} = \frac{d_x}{d_b} = \frac{1}{1 + \xi} \, \xi = \left(1 - \frac{d_x}{d_b}\right) \xi_0,
\]

in which \( d_o \) and \( d_b \) are the dimensions of the section sides at the pile top and bottom, respectively; \( \xi \) is the pile length embedded in the soil; and \( x \) is the distance from the ground surface to the pile section under consideration.

3. In the same way as for a rigid bar and an elastic medium, the variation of the pile...
Fig. 1. Analytical schematic of tapered pile. a) Schematic of load and soil resistance for pile; b) the same, i-th pile portion.

Displacement $Z_x$ with depth is assumed to have the form

$$Z_x = Z_0 \left( \frac{1 - x}{L_0} \right),$$

in which $Z_0$ is the pile displacement at the ground surface level; $L_0$ is the depth at which the point of zero displacement is located; $Z_0 = Z_0/\varphi_0$; and $\varphi_0$ is the angle of rotation of the pile at the ground surface level.

4. The soil pressure $q_{x}^{*}$ on a unit length of the pile is proportional to its displacement $d_{x} = dxZ_{x}$.

5. The specific friction developed in the horizontal direction on the lateral surface of the pile for the horizontal load action is determined by the relation $f = \tau \gamma$, and the soil resistance on a unit length of the pile as a result of the friction $f$ is $q_{x}^{*} = f_{x}d_{x}$, in which $\tau$ is the limit friction resistance of the soil at the interface with the lateral surface of the pile in the horizontal direction; and $\gamma$ is a coefficient which takes into account the vertical load action.

The value of $\tau$ is most conveniently determined by using the static penetration test data $\tau = \beta f d$, in which $f_{d}$ is the soil resistance on the lateral surface of the device, obtained from penetration tests with the S-832 device; and $\beta_{f}$ is an experimental coefficient determined in conformity with [7] from the equation $\beta_{f} = 0.26 + 0.73(x/\ell)^{2}$, where $x$ refers to the middle of the area under consideration in the lateral surface of the pile at the interface with the $i$-th layer of the soil base.

The value of $\gamma$ is

$$\gamma = a + b N_0 / S,$$

in which $N_0$ is the vertical compressive load acting on the pile; $S$ is the limit strength of the pile under a vertical load, determined by any of the well-known existing methods in conformity with the SNiP II-17-77 Norms; and $a$ and $b$ are experimentally established dimensionless coefficients; in the absence of experimental data, these coefficients can be taken as $a = b = 0.5$.

The modulus of subgrade reaction $K_i$ is found from the condition of equality of the settlements, determined from the theory of local deformations and an elastic half-space by applying the equation

$$K_i = \omega \frac{E_{oi} A_{g}}{(1 - \mu^2_{i}) d_{mn}},$$

in which $\omega$ is a dimensionless coefficient which depends on the ratio $l/d_{mn}$, taken from Table 5 in [8]; $E_{oi}$ is the modulus of deformation of the $i$-th soil layer, determined from plate test results; $\mu_{i}$ is the Poisson ratio of the $i$-th soil layer; $A_{g}$ is a dimensionless coefficient taken as 3.5 for driven piles and for bored piles concreted in holes formed by punching; $d_{mn}$ is the mean dimension of the pile section side; and $d_{mn}$ is the mean dimension of the pile section side within the limits of the $i$-th layer.