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EXPERIMENTAL INVESTIGATION OF PILE-SOIL INTERACTION UNDER HORIZONTAL LOADING

L'INVESTIGATION EXPERIMENTALE DE L'INTERACTION DU SOL ET DU PIEU CHARGE HORIZONTALEMENT

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SYNOPSIS Test results obtained when investigating behaviour of horizontally loaded piles at different depths in clay soils are given. The behaviour of piles at different stages of loading is described. The theoretical problems of the analysis of horizontally loaded piles in nonlinear statement, giving more reliable description of the pile-soil interaction, and, hence, considerably increasing the accuracy of design, are considered. The potentialities of the program package for horizontally loaded piles design using personal computers are given.

Characteristic behaviour of a horizontally loaded pile is the change of its design pattern depending on the pile depth in soil. A short pile under horizontal force rotates in soil about a certain point with zero displacements and its bending might be neglected. A longer pile resists to rotation and bending simultaneously, and finally a long pile can resist only to bending. Thus, horizontally loaded piles, depending on their depth in soil, should be subdivided, by their behaviour pattern, as absolutely rigid, of a finite rigidity and slender (infinitely long) ones.

To verify this statement, the writer has carried out static tests of 0,3x0,3m cross-section piles sunk in the soil to the 2, 4, 6 and 12 m depths and instrumented with soil pressure gauges.

Soils of a field test site are represented by alluvial loams and clays of mean density and having a 0,6 consistency index, I_L.

Soil pressure gauges have been fixed in special pockets in piles, provided when casting piles, with a $0,1\ell$ space where ℓ is the pile depth in soil. The soil pressure gauges, before fixing on a pile, have been calibrated by different methods, including calibration in special trial pits made in natural soils of the field test site, and this is very important for obtaining reliable results.

Piles have been tested in pairs, using tension bars and hydraulic jack. The height of a horizontal load application above the ground level was $L = 0,15$m in all cases. The tests were carried out 15 days after pile driving completion.

Because of the risk that a 12 m pile would not get a design depth level, all the tested piles instrumented with soil pressure gauges were driven into the soil through 200mm diameter guiding wells bored to the whole design depth of that or other tested pile, i.e. to 2, 4, 6 and 12 m. The strict vertical position of a pile has been provided by this method as well.

The static horizontal load was applied to piles by increments, every increment acting untill pile got the conventional stabilization of its horizontal displacements not exceeding 0,1 mm for two hours. After that the next load increment was applied. The indications of the soil pressure gauges were recorded and contact stresses along the pile sides were evaluated using calibration charts obtained for each separate soil pressure gauge after the pile reached its conventional displacement stabilization at the end of each load increment application.

Below, the avaraged curves of contact stresses, caused by the reactive soil resistance to horizontal displacements of a pile under horizontal load, are shown in the Fig.1 by the results of the pair tests. The curves are represented as linear loads, their ordinates are in kN/m and have been verified with reference to the equilibrium condition: $\Sigma Q_Z = 0$; $\Sigma M_Z = 0$; and some discrepancies happenning do not exceed 10 per cent.

Plots of horizontal load Q versus horizontal displacement at the ground surface level u_o for static tests of piles, are shown in the Fig.2.

When considering the curves of the reactive soil resistance, $q_{(z)}$, shown in the Fig.1, one could see that values of their ordinates and the shape of these curves depend on the depth of a pile in soil, ℓ, as well as the value of horizontal displacement of a pile, u_o, caused by horizontal force.

The depth of a zero point, ℓ_o, from the ground surface is not constant as well, and depends on the parameters ℓ and u_o

For all pile lengths, ℓ, as u_o increases, the zero point, ℓ_o, moves downwards, as well as a maximum ordinate of the curve q_z

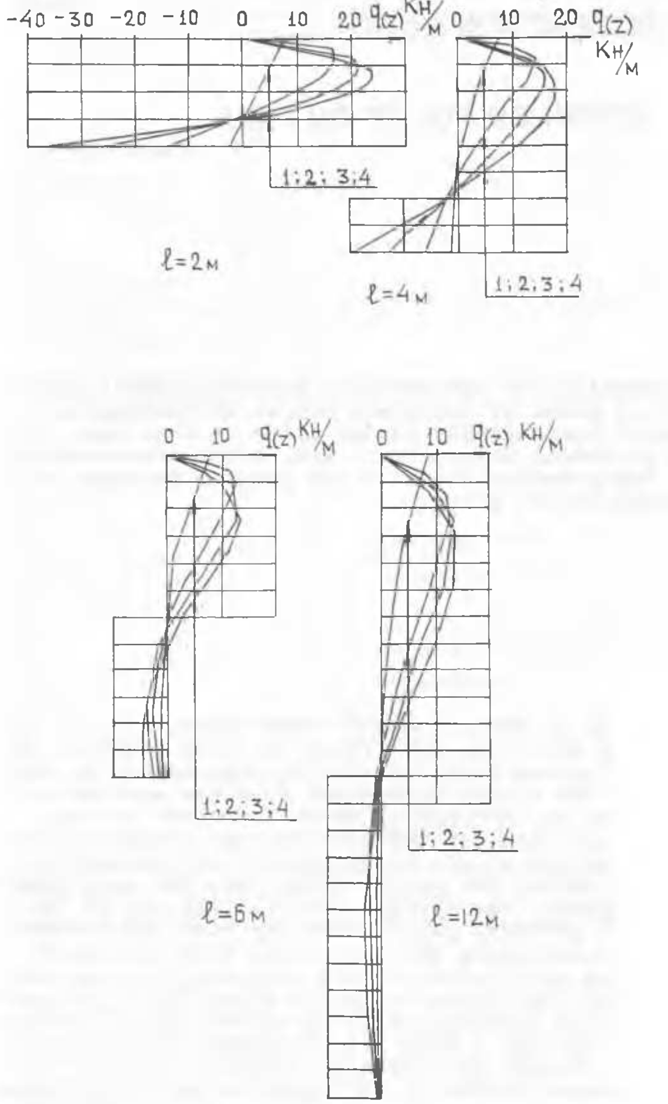

Fig.1. Reactive soil resistance, $q_{(z)}$, related to pile depth in soil, ℓ, and horizontal displacement u_o
1 for u_o =0,002m
2 for u_o =0,01 m
3 for u_o =0,02 m
4 for u_o =0,03 m

It proves that in case of a pile under horizontal load, H, as it develops horizontal displacements, u_o, in the top layer of soil, irreversible plastic deformations occur, extending in the direction of horizontal force and downwards and occupying larger and larger zones. Shapes of the curves $q_{(z)}$ are constantly transforming as more deep soil layers are being involved, still not subjected to plastic deformations and playing an ever-growing role in developing resistance of a pile to horizontal load.

When considering the behaviour of a horizontally loaded pile with reference to the bedding value theory, one might state that $K_{(z)}$ is a variable over depth, X, and depends on the value of horizontal displacement of a pile, $u_{(z)}$.

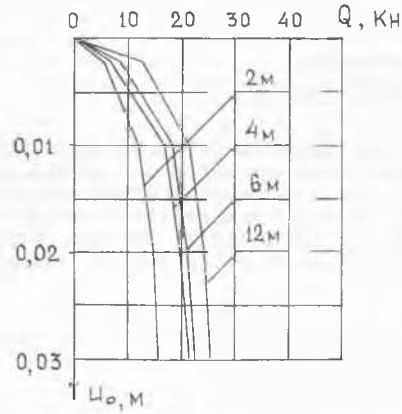

Fig.2. Horizontal loads versus horizontal displacements for ℓ = 2-12m

If $K_{(z)}$ is considered for the specified values of ℓ and u_o, then an absolute bedding value increases nonlinearly with the depth increase. But when considering the changes of $K_{(z)}$ at ℓ constant and $u_{(z)}$ variable, we might state that its integral value is decreasing with the increase of $u_{(z)}$.

It could be seen from the curves in the Fig.1 that for the specified length of a pile $K_{(z)}$, if ever increases depending on the variable Z, nevertheless for different values of ℓ it decreases over absolute value as the depth of a pile in soil increases; and this is proved by the values of ordinates $q_{(z)}$ for different lengths of piles.

The writer earlier, when investigating the behaviour of absolutely rigid piles under horizontal loading, has observed that in such cases the soil bedding value, $K_{(z)}$, is a rather stable characteristic and does not depend (or only slightly depends) on the depth, ℓ, if the pile is an absolutely rigid one.

But as soon as the influence of bending begins to tell on the behaviour of a loaded pile, the value of $K_{(z)}$ begins to decrease the more, the more is the effect of bending, and in case of slender piles (infinitely long) its value can decrease by 2-3 times in comparison with the value for an absolutely rigid pile.

The problem of $K_{(z)}$ is more complicated if the changes in the value are considered as related to $u_{(z)}$, and then it should be written as $K_{(zu)}$. It has been stated above that the integral value of $K_{(zu)}$ decreases as $u_{(z)}$ increases. Thus, it should be stated that the soil bedding value $K_{(zu)}$ is a function of

$K_{(zu)} = f(z, u_z)$. By taking the elastic line equation for a pile, $u_{(z)}$, through the physical parameters of materials of the pile and the soil, as well as the relation $u_{(z)} = f(u_o)$ the changes in $K_{(zu)}$ can be considered in the form of $K_{(zu)} = f(z, u_o)$.

Through investigation of a horizontally loaded pile under the effect of horizontal force in the most general case when the pile, depending on its depth in soil, could sequentially experience all the three abovementioned behaviour patterns: from an absolutely rigid to a slender (infinitely long) pile, and having at his disposal representative test results, the writer has managed, on the two-parameters model basis for locally deformed foundation, to obtain design expressions for piles under the effect of horizontal force with account of the vertical component, proceeding from the nonlinear representation of the relation $Q = f(u_o)$.

The expression describing the nonlinear relation between Q and horizontal displacements due to u_o has the form:

$$Q = bK_{(\ell)} u_o \ell \left[\frac{1}{\nu + 1} - \frac{1}{(\nu+2)\alpha} - \frac{F_r \cdot F\alpha_2 (1-\alpha)}{\alpha(1-\alpha + F_r \cdot F\alpha_1)} \right] \quad (1)$$

where

- b is the breadth of a pile, m;
- $K_{(\ell)}$ is the bedding value at the level of the lower end of a pile, kN/m^3, evaluated by the formula: $K_{(\ell)} = \alpha_K K_o$
- K_o represents bedding values, obtained in the experimental investigation, for absolutely rigid piles and different soils in different physical states, given in the Tables;
- α_K is the coefficient, evaluated using the Tables developed by the writer, taking account of $u_o, K_{(\ell)}$ changes related to the slenderness ratio F_r;
- F_r is the slenderness ratio of a pile described by the expression:

$$F_r = \frac{bK_o \ell^4}{360EI} \quad (2)$$

- EI is the cross section stiffness of a pile;
- ν is the coefficient of plastic deformation development in the soil near pile, taken according to the Tables as a function of u_o;
- $F\alpha_1$ is a nondimentional function depending on:

$$F\alpha_1 = 26 - 33\alpha - F\alpha_3$$

$$F\alpha_2 = F_1 + F_2 - F_3 + F_4 - F_5$$

$$F\alpha_3 = 45\alpha - 80\alpha^2 + 30\alpha^3 - 2\alpha^5$$

$$F_1 = \frac{F\alpha}{\nu+2}; \quad F_2 = \frac{60\alpha - 45}{\nu+3};$$

$$F_3 = \frac{30\alpha - 20}{\nu+4}; \quad F_4 = \frac{3\alpha}{\nu+6};$$

$$F_5 = \frac{1}{\nu+7}$$

- α is a relative depth of a zero point location for a pile, $\alpha = \ell_o/\ell$ obtained by the equation:

$$\frac{(\lambda+1)(\nu+2)-1}{(\nu+1)(\nu+2)} - \frac{(\lambda+1)(\nu+3)-1}{(\nu+2)(\nu+3)\alpha} - \frac{F_r(1-\alpha)}{\alpha(1-\alpha+F_r F\alpha_1)} \cdot F\nu + \frac{N(u_L + u_b + \ell - \frac{b}{2})}{bK_{(b)} u_o \ell^2} + \frac{m_o}{bK_{(\ell)}\ell^2 u_o} = 0 \quad (3)$$

where $F\nu = F\nu_1 + F\nu_2 - F\nu_3 + F\nu_4 - F\nu_5$

$$F\nu_1 = \frac{F_1[(\lambda+1)(\nu+3)-1]}{\nu+3}; \quad F\nu_2 = \frac{F_2[(\lambda+1)(\nu+4)-1]}{\nu+4};$$

$$F\nu_3 = \frac{F_3[(\lambda+1)(\nu+5)-1]}{\nu+5}; \quad F\nu_4 = \frac{F_4[(\lambda+1)(\nu+7)-1]}{\nu+7};$$

$$F\nu_5 = \frac{F_5[(\lambda+1)(\nu+2)-1]}{\nu+8}.$$

- λ is a relative height of a horizontal load application above the ground surface level, equal to $\lambda = \frac{L}{\ell}$
- M_o is the moment applied to the pile head;
- N is a vertical load applied to a pile;
- ℓ is the eccentricity of the application of the forces N relative to the geometrical axis of a pile;
- u_L is a horizontal displacement of a pile at the height L above the ground surface, obtained from the expression:

$$u_L = u_o + \varphi_o L + \frac{Q\ell^3}{3EI} + \frac{M_o \ell^2}{2EI} \quad (4)$$

- φ_o is an angle of rotation of a pile cross-section at the level of soil surface, calculated by the formula:

$$\varphi_o = \frac{u_o}{\alpha\ell}\left[1 + \frac{F_r(1-\alpha)}{1-\alpha_r F_r F\alpha_1} \cdot F\alpha_3\right] \quad (5)$$

u_ℓ is a horizontal displacement of a pile lower end, calculated by the formula:

$$u_\ell = \frac{u_o(1-\alpha)^2}{\alpha(1-\alpha+F_r F\alpha)} \qquad (6)$$

To construct curves of geometrical forces $\varphi_{(z)}$ and moments $M_{(z)}$, the expressions (7) and (8) are recommended for use:

$$Q_{(z)} = Q - bK_{(\ell)}\ell u_o\left\{\frac{1}{\nu+1}\left(\frac{z}{\ell}\right)^{\nu+1} - \frac{1}{(\nu+2)\alpha}\left(\frac{z}{\ell}\right)^{\nu+2} - \frac{F_r(1-\alpha)}{\alpha(1-\alpha+F_r F\alpha_1)}\cdot\left[F_1\left(\frac{z}{\ell}\right)^{\nu+2} + F_2\left(\frac{z}{\ell}\right)^{\nu+3} - F_3\left(\frac{z}{\ell}\right)^{\nu+4} + F_4\left(\frac{z}{\ell}\right)^{\nu+6} - F_5\left(\frac{z}{\ell}\right)^{\nu+7}\right]\right\} \qquad (7)$$

$$M_{(z)} = m_o + Q(L+Z) + N\left(u_L + u_\ell + b - \frac{6}{2}\right)\cdot bK_{(\ell)}\ell^2 u_o\cdot\left\{\frac{1}{(\nu+1)(\nu+2)}\left(\frac{z}{\ell}\right)^{\nu+2} - \frac{1}{(\nu+2)(\nu+3)\alpha}\left(\frac{z}{\ell}\right)^{\nu+3} - \frac{F_r(1-\alpha)}{\alpha(1-\alpha+F_r F\alpha_1)}\cdot\left[\frac{F_1}{\nu+3}\left(\frac{z}{\ell}\right)^{\nu+3} + \frac{F_2}{\nu+4}\left(\frac{z}{\ell}\right)^{\nu+4} - \frac{F_3}{\nu+5}\left(\frac{z}{\ell}\right)^{\nu+5} + \frac{F_4}{\nu+7}\left(\frac{z}{\ell}\right)^{\nu+7} - \frac{F_5}{\nu+8}\left(\frac{z}{\ell}\right)^{\nu+8}\right]\right\} \qquad (8)$$

When considering expressions (1), (3), (4-8) one can see that in the case of an absolutely rigid pile when $EI \to \infty$ they reduce to a particular case and take the form shown in Refs /1/, /2/, i.e.

$$Q = bK_{(\ell)}\ell u_o\left[\frac{1}{\nu+1} - \frac{1}{(\nu+2)\alpha}\right] \qquad (9)$$

$$\alpha = \frac{[F\nu_1 K_o\ell^2 - N(\lambda+1)]\,u_o}{F\nu_2 K_o\ell^2 u_o + N\left(\ell - \frac{\ell}{2}\right) \pm M} \qquad (10)$$

$$F\nu_1 = \frac{b[(\lambda+1)(\nu+3)-1]}{(\nu+2)(\nu+3)};$$

$$F\nu_2 = \frac{b[(\lambda+1)(\nu+2)-1]}{(\nu+1)(\nu+2)};$$

$$Q_{(z)} = Q - bK_o\ell u_o\left[\frac{1}{\nu+1}\left(\frac{z}{\ell}\right)^{\nu+1} - \frac{1}{(\nu+2)\alpha}\left(\frac{z}{\ell}\right)^{\nu+2}\right]. \qquad (11)$$

$$M_{(z)} = N\left(\frac{\lambda+1}{\alpha}u_o + \ell - \frac{b}{2}\right) + H(L+Z) - bK_o\ell^2 u_o\left[\frac{1}{(\nu+1)(\nu+2)}\left(\frac{z}{\ell}\right)^{\nu+2} - \frac{1}{(\nu+2)(\nu+3)\alpha}\left(\frac{z}{\ell}\right)^{\nu+3}\right] \qquad (12)$$

Analyses of piles by these formulae have a good agreement with test results and have passed an evaluation test at the design and construction of heating-system pipe-lines (with 1000 mm and 1520 mm diameter pipes) in Minsk, Gomel, and Grodno.

The method of analysis developed by the writer for horizontally loaded piles, in a non-linear formulation, has become a basis for the package of pile design programs using personal computers. The programs are very easy to use, and besides the analysis of piles for deformations in the range of displacements of u_o from 0 to 3cm, construction of $Q_{(z)}$ and $M_{(z)}$, $u_{(z)}$ and $q_{(z)}$ curves, they automatically select longitudinal and transverse reinforcement for concrete piles and verify their crack resistance.

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