ANALYSIS OF PILES SUBJECTED TO THE COMBINED ACTION OF VERTICAL AND HORIZONTAL LOADS (DISCUSSION)

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UDC 624.131.524.4+531.6

The Editorial Staff of the journal Osnovaniya, Fundamenty i Mekhanika Gruntov has opportunely raised the problem of the unification of the methods of analysis for piles subjected to the action of horizontal loads and bending moments.* The lack of the corresponding instructions in the SNiP norms is the reason why the design organizations at the different departments use different design methods, whose selection is frequently of a subjective nature.

For the same reason, the problem of the action of horizontal loads on piles has been, and is now, the object of many investigations.

A survey of the existing methods of analysis could fill a voluminous book, owing to the extremely large number of problems which must be solved in order to arrive at a sufficiently profound analysis of the phenomena which occur when piles are subjected to horizontal loading (elasto-plastic state of the soil mass in the zone of action of a pile restrained by the soil; influence, upon the deformation characteristics of the soils in the zone adjacent to the loaded pile, of the period of action of repeated and dynamic loads; joint action of horizontal and vertical loads, and of bending moments, under the condition of inapplicability of the principle of independence of the action of the forces during the elasto-plastic stage of the pile; effect of the inclination of the pile and of its embedment conditions in the pile cap; joint action of piles in foundation beds, etc.).

Only such a comprehensive approach to the solution of the problem will permit designing, in a justifiable manner, reliable foundations for the more important structures.

In this connection, investigations are being conducted, in particular, at the Laboratory of Marine Oil-Extraction Structures of the V. V. Kuibyshev Moscow Civil Engineering Institute (MISI).

In order to obtain the complete solution to this problem, it is necessary to carry out research work during long periods and to allocate sufficient funds for this work; in this connection, many investigators endeavor to obtain approximate solutions which can be applied in the near future, with practical results. However, in most cases attention is devoted mainly to the formal methods for integrating the equations for a beam which is elastically restrained in a Winkler foundation bed. The use of different and, sometimes, complex laws of variation of the modulus of subgrade reaction with the depth does not bring the problem closer to the practical conditions.

In multilayer stratified soils, the actual variation of the moduli of subgrade reaction is usally governed by laws which are so highly complex that it is impossible to describe them by means of any analytical relation.

In the cases in which the modulus of subgrade reaction varies with the depth in a triangular or trapezoidal manner, it is acceptable to apply the solutions presented in the articles written by V. V. Mironov, I. Ya. Luchkovskii, and G. S. Lekumovich (Osnovaniya, Fundamenty i Mekhanika Gruntov, No. 3, 1971).

*See comments made by the Editorial Staff and also V. V. Mironov's article "Method of analysis for laterally loaded piles," No. 3, 1971.

Translated from Osnovaniya, Fundamenty i Mekhanika Gruntov, No. 1, pp. 6-8, January-February, 1973.

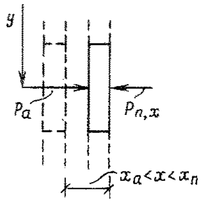

Fig. 1. Analytical scheme.

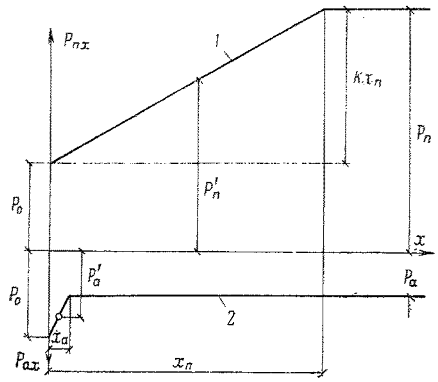

Fig. 2. Schematized graph for the relation between the reactions and the horizontal displacements.

However, it is difficult to establish any substantial advantages of these methods in comparison, for example, with the method described in the "Recommendations for Design of Deep Foundations of Bridges."

The basic direction of further improvement of the methods of pile analysis should be toward a more precise definition of the physical phenomena which occur in the soil mass under the action of a pile loaded by horizontal and vertical forces, as well as by bending moments applied at the head of the pile. Under the action of these forces the pile undergoes displacements. Bending of the pile is affected mainly by the horizontal displacements of its different sections, at different depths. Let us consider which forces act at the different sections of the pile, under the horizontal displacements (Fig. 1).

With a displacement x toward the right, a specific pressure p_{nx}^y acts on the right side over a pile portion at depth y, while a specific pressure p_a^y acts on the left side.

Depending upon the value of x, the above pressures may have the values shown in the graphs of Fig. 2 at a depth y, in which the abscissas represent the horizontal displacements of the different pile sections, while the upper ordinates represent the passive pressures exerted by the soil, and the lower ordinates represent the active pressures exerted by the soil on the side opposite to the direction of action of the force (to the left of the pile in Fig. 1).

From these graphs it is seen that when the displacements vary from 0 to x, the passive pressure on the right side of the pile varies from p_0 to p_n. Under these conditions the active pressure decreases almost immediately from p_0 to p_a and is maintained at a constant value thereafter. The value of the displacement x_a, at which the active pressure attains its lower value, differs considerably from the value of x_p (usually by not less than one order).

The values of x_n and x_a have been frequently found from experimental and theoretical investigations. Somewhat more complex is the determination of the values of p_a, p_0, and p_n; however, there are some recommendations that can be used for preliminary calculation of these values. For cohesionless soils, p_a, p_0, and p_n are found by Jaky's classical methods and recommendations for the active pressure, the pressure at rest, and the passive pressure.

For determining the passive pressure, it is necessary to take into account the effect of the frictional forces on the pile, as well as the three-dimensional effect. This is done basically by multiplying the limiting forces by a coefficient equal to 3-4, depending on the angle of internal friction of the soil.

For cohesive soils, the active pressure may be disregarded in many cases. The limiting passive pressure of cohesive soils is frequently taken as (2-4)dc, in which d is the pile diameter and c is the cohesion, obtained from triaxial compression tests.

These recommendations are of a preliminary nature. At the present time, investigations are being conducted with a view to arriving at more definite recommendations; however, the above data are sufficiently accurate for constructing approximate graphs for the relation between the pressures and the pile displacements.

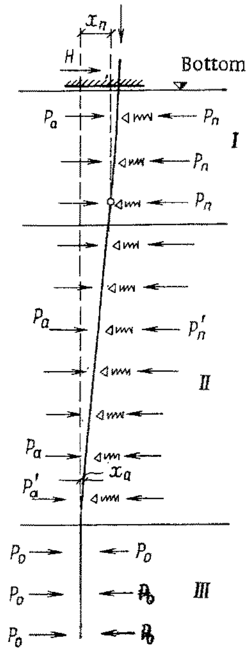

Fig. 3

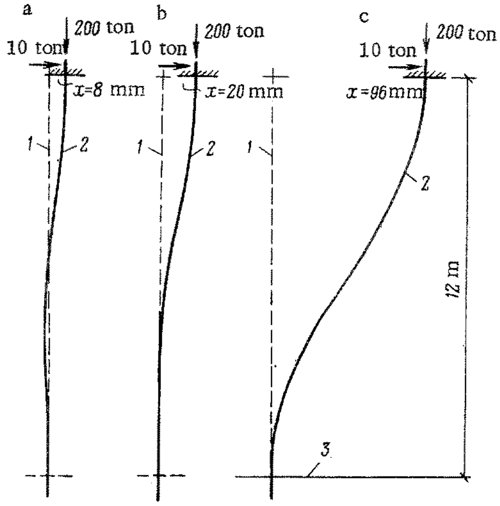

Fig. 4

Fig. 3. Division of long pile into zones.

Fig. 4. Example of pile analysis.

Let us consider a long pile with its head fixed at the elevation of the bottom (Fig. 3). The fixed end permits horizontal motion of the head of the pile. The free portion of the pile above the bottom does not modify substantially the conditions of the problem, and may be easily considered in the analysis.

The long pile is divided vertically into the zones I, II, and III. The lower zone III experiences negligible displacements. For this reason we will consider that the pressure at rest acts on both sides of the pile.

In the upper portion of the pile, the zone I of limiting equilibrium is almost always formed. This is due to the fact that, in the surface zone, small displacements of the pile are sufficient for causing the development of the limiting state in the soil mass near the pile. Between the zone I of limiting equilibrium and the zone III of pressure at rest, there is usually a transition zone II, in which the values of the passive pressures p_n are intermediate between the pressure at rest p_0 and the maximum possible limiting value p_n.

Let us consider the value of the earth pressure on the side opposite to the direction of action of the horizontal force. In the lower zone, as was shown, it is equal to the pressure at rest. In the remaining portion it may be assumed to be equal to the lower, minimum possible value p_a. In fact, in this portion there is a small transition zone. However, the transition between the pressure at rest p_0 and the minimum possible pressure p_a occurs even with very small displacements of the pile, and, consequently, the dimensions of the transition zone are also very small.

For known relations between the deformations and the displacements, subsequent analysis may be carried out by the method of successive approximations, using an electronic computer, in the following order:

1) The shape of the deflection curve of the pile is established; 2) from graphs similar to those of Fig. 2, the passive pressures corresponding to this deflection curve are determined; 3) for the given load, the corrected shape of the deflection curve is drawn; 4) the corrections and the load values are introduced, etc.

The calculations are repeated until a sufficiently close convergence between the successive approximations is obtained.

To reduce the computing time, it is desirable that the shape of the deflection curve adopted in the first approximation be as close as possible to the final one. For this purpose, it is recommended that a

TABLE 1

Soil conditions	Maximum deflection, mm	Maximum bending moment, ton-m
Dense soils	8	28.3
Soils of medium density.	20	37.6
Weak soils, underlain by dense soils	96	79.2

TABLE 2

Load, tons		Deflection at pile head, mm	Bending moment, ton-m
horizontal	vertical		
10	0	72	60
10	100	82	68,2
10	200	96	79,2
10	300	114	94,2

preliminary analysis, starting from simplified analytical schemes, be carried out. Equations obtained for such schemes, for long, medium, and short piles, have been included in the draft of the instructions for design of laterally loaded piles, prepared by the Laboratory of Marine Oil-Extraction Structures of the MISI.

The recommended procedure was used for analyzing a metal tubular pile, 500 mm in diameter with a wall thickness of 20 mm, driven to a depth of 24 m, and subjected to the action of a horizontal force of 10 tons and a vertical force of 200 tons. This is a characteristic case in the construction of marine structures. Three types of soils were considered: relatively dense with a coefficient of increase of the modulus of subgrade reaction, with depth, of 40 tons/m^4; of medium density (20 tons/m^4), and weak to one half the embedded depth of the pile (< 5 tons/m^4); and dense in the underlying layers. All these types of soils are common in marine deposits. In Fig. 4, the heavy lines represent the pile deflections for all the three cases (a for dense soils, b for medium-dense soils, and c for weak soils) under the action of the loads shown. Table 1 shows the values of the maximum deflections and bending moments at the head of the pile.

For the third case, four values of the vertical force were used in the analysis: 0, 100, 200, and 300 tons (Table 2).

The above results indicate a substantial effect from the physical and geometrical nonlinearity of the phenomena which occur in piles subjected to the combined action of vertical loads, horizontal loads, and bending moments.

It is important also to take into account the changes in the pile deformations under repeated and variable loads, and, in some cases, under loads acting during long periods. This is especially important in connection with the fact that when the piles undergo large displacements the plastic deformations of the soil start playing an important role. According to the investigations conducted by Gill, the limiting deformation of piles, for which this phenomenon becomes important, is 2-3 cm.

The above data indicate that this value may be exceeded; for this reason, the effect of repeated loads should be taken into account. The limited extent of this article does not permit treating this aspect nor examining the characteristics of the analysis of piles of medium and short length. However, investigations are being conducted in this direction.

From the Editorial Staff. The Editorial Staff found it necessary to include B. F. Goryunov's article, which agrees with the conclusion that at the present time it is hardly possible to develop a strictly theoretical method of analysis for laterally loaded piles taking into account all the important factors governing the behavior of piles. For this reason, it is entirely justifiable to apply other more practical engineering methods for solving this problem, such as that proposed by the author, which contains many interesting concepts. However, the Editorial Staff considers that in this article the proposed data for the relation between the soil pressure and the displacements have not been sufficiently substantiated by experimental research. The author considers that for cohesionless soils the pressures may be determined as active or passive pressures. Yet it is known that the pressure at the end of a short or rigid pile may be considerably higher than the passive pressure calculated from Coulomb's theory, since the soil cannot maintain its firmness in this case. The author considers that in the lower portion of the pile the soil reaction is insignificant and equal to the pressure at rest. However, the justification of this point is questionable: the pile displacements in this portion may be small because of high resistance of the soil. The author is right only in the case of a very long pile, when its length is determined on the basis of the vertical loads. Since the author does not give recommendations for the analysis of medium-length and short piles, it is not possible to arrive at a conclusion about the extent to which the proposed method of analysis is admissible in these cases.