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EVALUATION OF BEARING CAPACITY OF DRIVEN PILES, BASED ON THE RESULTS OF SOLUTION OF THE CYLINDRICAL CAVITY EXPANSION PROBLEM

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This paper describes an analytical method for evaluating the bearing capacity of piles, installed with no soil excavation. It describes a process of pile insertion into soil and a method of pile side bearing capacity evaluation, based on a solution of the cylindrical cavity expansion problem. Analysis of analytical and test data shows the validity and applicability of the proposed method.

Introduction

The broad variety of pile types and fabrication methods, depending on the pile-soil interaction mode, include either soil extraction or soil displacement. Although piles are applied everywhere, the current foundation engineering practice faces many issues of pile bearing capacity evaluation.

As compared with precise but expensive in-situ methods that require special equipment, the methods for pile bearing capacity analysis do not demonstrate adequate compatibility with real data, especially for soil displacement piles. The engineering method [1] based on correlations of design resistances and soil physical properties is far from perfect either.

This paper presents an analytical model for pile installation into a leader hole. The authors did their best to make the model valid so that the model input parameters and relationships would be a part of the on-site geological survey report.

The known pile analysis techniques consider a pile as just being in soil with no data on how the pile got there and what changes in the soil characteristics could happen. Therefore, it is necessary to develop an analytical model for a rigid pile forced into a plastically compactable soil. Among current publications on the analysis of pile (probe) penetration into soil, the paper by Fedorovsky and Grevtsev [2] should be mentioned.

The present paper employs axisymmetric solutions, which are realistic due to the following facts.

Firstly, the symmetry does not consider the issue of stress and strain incompatibility in the case of complex loading.

Secondly, the actual velocity fields can be simulated by kinematically admissible fields of horizontal velocities that define the powers of internal forces; this assumption is realistic and enables allocation of the upper bearing capacity boundary according to the Gvozdev theorem.

Finally, the mathematical problem reduces to a simple solution of just one nonlinear first-order differential equation.

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As in many other methods, including the practical one included in Russian construction codes, the authors solved two problems: one for the pile tip and another one for its lateral surface.

When analyzing driven pile bearing capacity, a dynamic method based on the energy conservation law is often applicable. The bearing capacity so evaluated appears to be close to the actual one, which demonstrates the adequacy of the applied method. However, the dynamic method of pile bearing capacity analysis requires pile dynamics test data.

In order to solve the first problem, the volume conservation law was applied, i.e., the pile volume in the soil was assumed to be equal to the reduction of the total pore volume around the pile. We neglect the complicated soil compaction phenomena around the pile tip during the pile driving and assume that the soil around the pile is compacted in the radial direction alone.

The solution of the problem of the limit (stabilized) porosity and stress distribution around the cylindrical cavity in terms of the plastically compacted soil model [3] boils down to a system of four equations (1)-(4) with four unknown functions σ_1, σ_3, b, e. The argument of the functions is $r^* = \ln r$ with r as distance from the pile axis:

$$\begin{cases} \dfrac{d\sigma_3}{dr^*} + \sigma_3 - \sigma_1 = 0; & (1) \\ \sigma_3 = -C = AC_1 + b\sigma_1^2; & (2) \\ e = \Gamma - 1 - \mu \ln \dfrac{C + A^2/4b}{P_0}; & (3) \\ \dfrac{de}{dr^*} = (1 + e_A)(1 - \dfrac{1}{A + 2b\sigma_1}). & (4) \end{cases}$$

In the main system, Eq. (1) is an equilibrium equation, and Eq. (2) is a simplified limit state condition, i.e., normal flow inside the soil sample due to one-dimensional compression. If $b \to 0$, then stress (2) complies with the Coulomb-Mohr strength criterion, in which $C = 2c\cos\varphi(1 - \sin\varphi)$, $A = (1 + \sin\varphi)/(1 - \sin\varphi)$, where φ is the angle of internal friction, and c is the cohesion.

The odometer test results in terms of Terzaghi's logarithmic law are as follows:

$$e = \Gamma - 1 - \mu \ln(P_k/P_0), \tag{5}$$

where P_k is the odometer pressure, Γ and μ are parameters of the Terzaghi equation, and $P_0 = 0.1$ MPa.

If condition (2) is fulfilled for limited normal plastic flow in compression [3], then

$$P_k = A^2/4b - C. \tag{6}$$

Inserting (6) into (5), we obtain (3). Eq. (4) follows from the associated flow law [4].

Then the solution of the system reduces to just one equation. In order to do this we exclude σ_3 from Eqs. (1) and (2) and e from (3) and (4), then exclude r^* from the obtained equations.

After these transformations, we introduce the main equation, which defines the first principal stress as the soil porosity functions:

$$\frac{d\sigma_1}{db} = k \frac{C - (A-1)\sigma_1 - b\sigma_1^2}{(A - 1 + 2b\sigma_1)(4Cb + A^2)b} - \sigma_1^2 \frac{1}{A + 2b\sigma_1}, \tag{7}$$

where $k = \mu A^2/(1 + e_i)$, and e_i is the initial (natural) porosity coefficient.

In order to obtain the upper limit of the pile tip bearing capacity, we apply the second Gvozdev theorem to the radially directed velocity field, which enables application of the results of the solution of

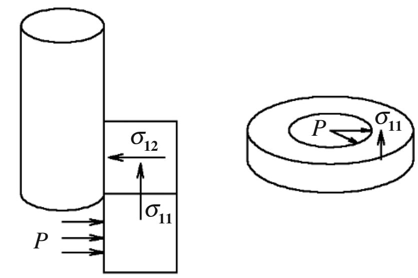

Fig. 1. Analysis of pile lateral surface bearing capacity.

TABLE 1

Test No.	Pile type	Pile length, m	Max pull-out force, kN	Max push-down force, kN
1	Steel pile, ∅ 159 mm	5.6	80.57	–
2		6.1	90.64	–
3	Concrete pile, 150×150 mm cross section	5.6	111.83	–
4		4.6	109.87	–
5	Steel pile ∅ 159 mm	6.1	–	191.35
6		6.1	–	141
7	Concrete pile, 150×150 mm cross section	5.6	–	181.21
8		5.6	–	181.29

the one-dimensional cavity expansion problem. The work of the unknown force (that of bearing capacity) on an arbitrary displacement h is made equal to the work of the respective horizontal soil layer having h thickness.

The relevant extra parameters for the solution of the problem such as the final void ratio and the Terzaghi equation parameters are borrowed from the compression test data such that the Terzaghi equation best fits the actual soil compression curve.

Solving the system of equations (1)-(4), we obtain stress and void ratio distributions in the radial direction if the pressure P is applied to the cylindrical cavity. This pressure corresponds to the pressure at which the volume displaced by the pile is equal to the reduction in the surrounding soil voids volume.

Pile side surface bearing capacity is equal to the friction force due to soil compression. The lateral surface normal pressures are evaluated as active ones, generated by passive pressure from the lower soil layers on the upper ones during pile penetration (Fig. 1).

It is assumed in the model that the pile moves together with the soil stuck on it against the massif; therefore, the soil-soil friction ratio is assumed according to [5] as the tangent of the internal friction angle. The pile lateral surface bearing capacity

$$N_b = \sigma_{11}(\tan\varphi)S, \tag{8}$$

where σ_{11} is the normal pressure on the pile side surface; $\tan\varphi$ is the soil-soil friction ratio; S is the lateral surface area.

The model was tested under specific geological conditions of the Saratov downtown. The geological cross-section contains soft plastic loams with γ_{Sb} = 9.21 kN/m^3; e = 0.88; S_r = 0.86; I_p = 0.16; I_L = 0.53; φ = 18-21°; c = 18-20 kPa; ν = 0.26; $E_s = E_p$ = 12.8 MPa.

The results of pile static tests, performed by A.V. Savinov, are given in Table 1. We tested steel (tube concrete) piles 159 mm in diameter and 150×150 mm square section reinforced concrete piles. The piles were tested on a construction site by static axial pullout and pushdown loads up to the ultimate soil bearing capacity [6].

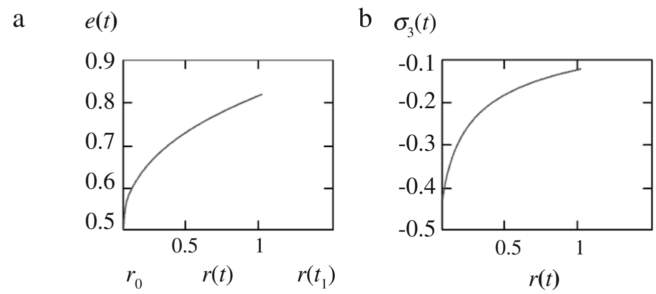

Fig. 2. Distribution of porosity (a) and principle stresses (b) depending on the radius of action; $t = b$ is a parameter.

TABLE 2

Evaluation method	Bearing capacity, kN		Total
	lateral surface	pile tip	
Construction Code	266.22	79.05	345.3
The proposed method, kN	249.6	195.2	444.8
Compression load test	402.5		

We measured porosity and radial principal stress distributions (Fig. 2) as well as pile tip and pile side surface bearing capacity values. The calculated pile tip bearing capacity was 113.07 kN (with 5.7 MPa pile tip soil resistance), and the pile lateral surface bearing capacity was 101.013 kN (with 33.2 kPa unit bearing capacity of the surface).

According to the tests, the bearing capacity of the piles to compression load was 191.35 kN, the pullout bearing capacity was 90.64 kN (pile lateral surface bearing capacity); hence, according to the tests, the pile tip bearing capacity was 100.71 kN.

The value of the pile bearing capacity calculated by the proposed method differs from the experimental one by 11.9%.

Also, the pile bearing capacity was calculated for the geological conditions provided by the Construction Industry and Geotechnical Engineering Chair of PNIPU. The subsoil geological cross section included soft plastic loams and semihard clays having the following parameters: $e = 0.763$, 0.718; $I_L = 0.6$, 0.15; $\varphi = 10$, $17°$; $c = 14$, 49 kPa.

Table 2 shows the analytical results of the pile bearing capacity obtained by different methods and the pile bearing capacity data from tests conducted on a construction site and provided by the Construction Industry and Geotechnical Engineering Chair of PNIPU.

Driven concrete piles 300×300 mm square cross section were tested. The analytical pile bearing capacity calculated by the authors differs from the test data by 10.5%. The comparison demonstrates the adequacy and prospects of the model for driving piles into soil.

REFERENCES

1. SP 22.13330.2011 "Subsoils of buildings and structures."
2. A. A. Grevtsev and V. G. Fedorovsky, "Analysis of probe tip resistance from soil mechanical properties," *Osn. Fundam. Mekh. Gruntov*, No.6, 2-5 (2014).
3. V. P. Dyba and M. P. Shiryaeva, "Simulation of soil base slump under strip footing," *University News. North Caucasian region. Technical sciences*, app. 12, 18-25 (2006).
4. V. P. Dyba, *Footing Bearing Capacity Evaluations* [in Russian], YuRGTU, Novocherkassk (2008).
5. A. V. Savinov, "Evaluation of material friction ratio on the side surface of pressed-in piles," Proc. Deep Footings and Underground Space Development Conf, PGTU, Perm', 181-189 (2011).
6. A. V. Savinov, "Experimental investigation of steel and reinforced concrete small cross section piles, pushed into saturated clay soils by static penetration and pullout loads," Urban agglomeration on landslide prone areas, Proc. III Intern. Sci. Conf., VolgGASU, Volgograd, 64-67 (2005).