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FRICTION PILE BEARING CAPACITY BASED ON THE PARABOLIC DISTRIBUTION OF SKIN FRICTION

Abstract. *The article describes the approach to evaluation of a friction pile bearing capacity based on the parabolic distribution of a skin friction in multi-layer soil bases. The design equationsare obtained for evaluated the ultimate load on an axial loaded pile in multi-layer soil using the new design scheme. The advantage of the proposed approach is to obtain some experimental parameters that take into account the actual interaction of the pile and soil on the construction site. Negative friction forces (from the reaction force under the pile end) negatively affect the pile bearing capacity. The numerical example is given for a friction pile in the soil base with two layers. The proposed equation also allows calculating various parameters: the soil stress under the piletoe, the pile effective length, relative deformations along the pile, etc.*

Keywords: *friction pile, ultimate load, skin friction, shaft resistance, lateral surface, bearing capacity.*

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РАСЧЕТ НЕСУЩЕЙ СПОСОБНОСТИ ВИСЯЧЕЙ СВАИ ПРИ ПАРАБОЛИЧЕСКОМ РАСПРЕДЕЛЕНИИ СИЛ ТРЕНИЯ

Аннотация. *В статье описан подход к оценке несущей способности висячей сваи, основанный на параболическом распределении сил трения по боковой поверхности сваи в многослойных грунтовых основаниях. Получены расчетные уравнения для оценки предельной нагрузки на центрально нагруженную сваю в многослойном грунте с использованием новой расчетной схемы. Преимуществом предлагаемого подхода является получение отдельных экспериментальных параметров, учитывающих фактическое взаимодействие сваи и грунта на строительной площадке. Отрицательные силы трения, возникающие от усилия в виде реакции под нижним концом сваи,негативно влияют на несущую способность сваи. Приведен численный пример расчета несущей способности для висячей сваи в двухслойном грунтовом основании. Предложенное уравнение позволяет также рассчитать различные параметры: напряжение в грунте под нижним концом сваи, эффективную длину сваи, относительные деформации вдоль сваи и др.*

Ключевые слова: *висячая свая, предельная нагрузка, силы трения, боковое сопротивление, боковая поверхность, несущая способность.*

Introduction

Pilesarecommonstructural elementinfoundations of many buildings and structures. As noted in [1], pile foundations are often used for important structures, and thus, reliability evaluation is an important aspect of the design of such structures. It is important to develop reliable mathematical models of pile behavior in multi- layer soils for a subsequent pile reliability analysis.

Friction piles develop most of the pile-bearing capacity by shear stresses along the sides of the pile, and are suitable where harder layers are too deep to reach economically. The pile transmits the load to surrounding soil by adhesion or friction between the surface of the pile and soil.

The paper [2] presents the experimental research of the pile skin friction distribution at the different load levels (Figure 1). The skin friction distribution of a pile is close to the parabolic form.

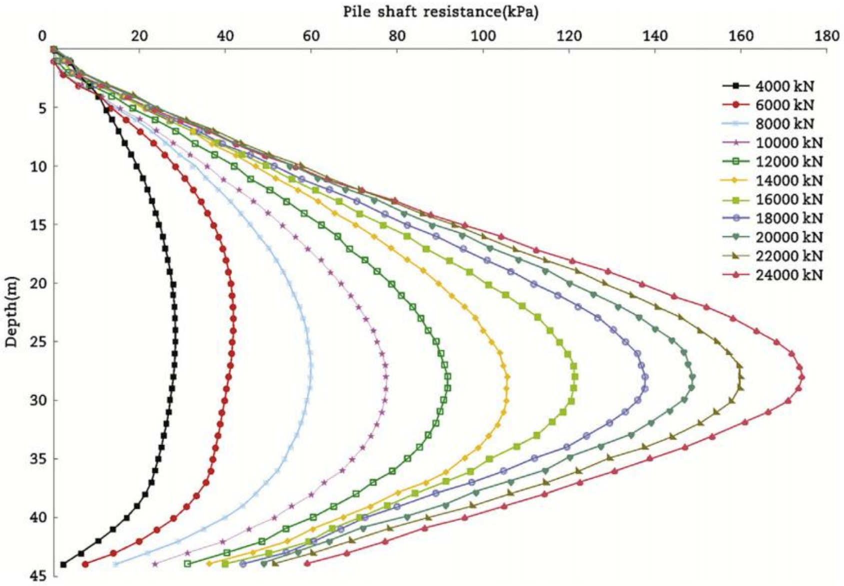

Figure1 –The skin friction (shaft resistance) distributions by experimental researches [2]

The paper [3] also describes the study of piles effective length based on parabolic frictional resistance. The comparison of results by using the approach [3] and results based on the hypothesis that the pile shaft resistance distribution was triangular-shaped with the experimental data suggest that the [3]approach is closer to the experimental data and more accurate.In order to satisfy the requirements of design and calculation of piles subjected to laterally parabolic distributed loads,the finite difference method and the pole system finite element method of elastic foundation are presented and discussed in the article [4] in order to compute the displacements and internal forces by adopting bi-parameter method of lateral subgrade reaction.The finite difference computing and figure processing of displacements and internal forces of piles are also programmed in [4].The experimental studies [5-8] also confirm the validity of using the parabolic distribution function of a skin friction of piles.

This paper presents the experimental-analytical solution for evaluation the bearing capacity of a friction pile based on the parabolic distribution of skin friction.

Models and methods

Figure 3 shows the design scheme of a friction pile in a single-layer soil base in accordance with the accepted design scheme in the researches [9, 10]. Thepapers [9, 10] established that thedesign loadon a pile F_p is determined in a homogeneous soil primarily by the soil base bearing capacity according to the equation:

$$F_p = \sigma_{soil} A + u \int_0^h f(x)dx - u \int_h^H f_{neg}(x)dx, \quad (1)$$

where σ_{soil} is a soil stress under the pile; A is a cross section area of the pile; u is a perimeter of the pile cross section; $f(x)$ is the function of a pile skin friction; f_{neg} is a function of a pile negative skin friction.

Askinfrictionfunction $f(x)$ onapilelateralsurface can be represented bythe equation:

$$f(x) = \varepsilon(x)q(x)\varphi, \quad (2)$$

where $\varphi = \dfrac{6EA}{u\gamma\xi_0 h_0^2}$ is dimensionless coefficient which takes into account the soil stress state in contact with the pile, the soil properties, the pile surface quality and other factors; h_0 is a length of the skin friction distribution $f(x)$ on the pile length, which is evaluated by the pile test results; γ is a soil density; is a coefficient of a lateral pressure [11].

The diagrams of arelative deformation $\varepsilon(x)$ and a lateralsoil pressure $q(x)$ distribution are shown in Figure 2.

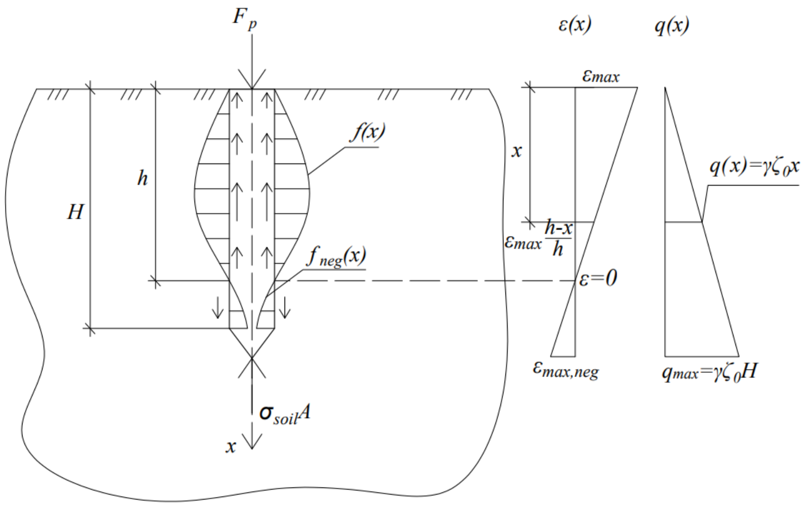

Figure 2 – The design scheme of a frictionpile in a single layer soil base with the design load F_p and the diagrams of deformations and lateral soil pressure of the soil

The*h*valueisset [9] based on the pile test results and the results of relative deformations $\varepsilon(x)$ measurements along the pile length in at least two pile cross-sections by the strain gauges [12] under the assumption of a linear description of the function $\varepsilon(x)$.

The linear distribution of relative deformations $\varepsilon(x)$, adopted in the researches [9, 13, 14] for friction piles, is also used for the design scheme in Figure 1. Asaresult: $\varepsilon(x) = \varepsilon_{\max}\dfrac{h-x}{h}$. Thenegativeskinfriction $f_{neg}(x)$ bytheforce $\sigma_{soil}A$ is proposed to determine by the same equation as (2) in the form: $f_{neg}(x) = \varepsilon_{neg}(x)q(x)\varphi$.

In practice, soil base often is composed of several layers of a soil with different geological and mechanical properties. For multi-layer soilbase, the designequation (1) will take the form:

$$F_p = \sigma_{soil}A + u\sum_{i=1}^{n}\int_{h_{i-1}}^{h_i} f_i(x)dx - u\sum_{n+1}^{n+m}\int_{h_i}^{h_m} f_{i,soil}(x)dx,$$

where*n*isa number of soil layers with "positive" skin friction; *m*isa number of soil layers with "negative" skin friction.

Firstly , let's consider the calculation of the pile bearing capacity in a two-layer soil base for all ratios h_2иh_1 according to the design scheme shown in Figure3 which built by analogy with the design scheme by Figure2.

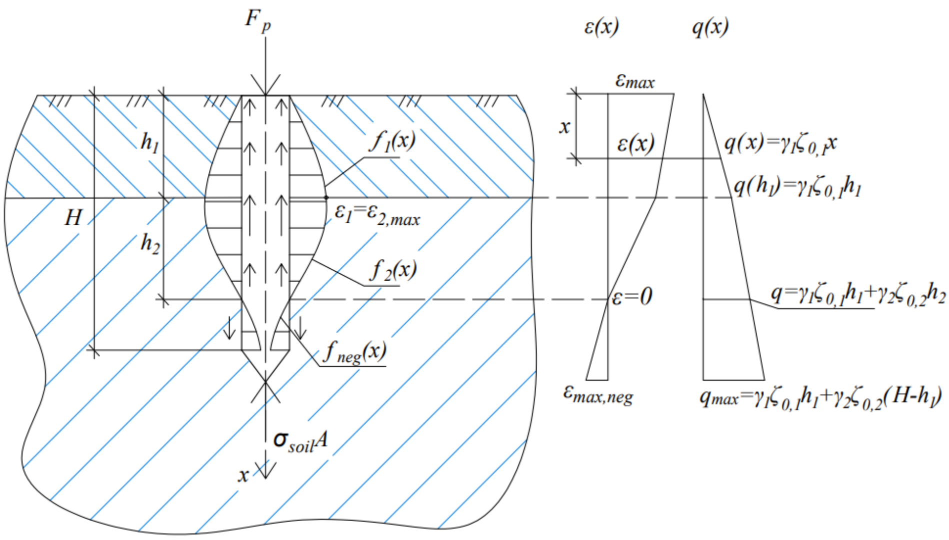

Figure 3 – Design scheme of a friction pile in a two- layer soil base

For the design scheme in Figure 2:

$$F_p=\sigma_{soil}A+u\int_0^{h_1} f_1(x)dx+u\int_{h_1}^{h_2} f_2(x)dx-u\int_{h_1+h_2}^{H} f_{soil}(x)dx,$$

where $f_1(x)=\varepsilon_1(x)q_1(x)\varphi_1$, $f_2(x)=\varepsilon_2(x)q_2(x)\varphi_2$, $q_1(x)=\gamma_1\xi_{0,1}x$ at $0\le x\le h_1$ and $q_2(x)=\gamma_1\xi_{0,1}h_1+\gamma_2\xi_{0,2}(x-h_1)$ at $h_1\le x\le h_2$, where γ_1 and γ_2 aresoil densities. At the pile top (in the cross-section where the pile intersects with the ground surface) $\varepsilon_{\max}=\dfrac{F_p}{AE}$, where*E* is a pile modulus of elasticity.

Resultsandanalysis

Asnotedabove: $\varepsilon(x)$ is linear onall sections of a pile [9, 10]; at the pile top: $\varepsilon_{\max}=F_p/EA$. At the end of the section *h₁*therelativedeformationis $\varepsilon(h_1)$ which can be measured in an arbitrary cross section of the pile x at length h_1 or determined based on test results as $\varepsilon_1(x)=\varepsilon_1+(\varepsilon_{\max}-\varepsilon_1)\dfrac{h_1-x}{h_1}$.

Force perceived by the first layer of a soil is:

$$F_1=u\int_0^{h_1}\left[\varepsilon_1+(\varepsilon_{\max}-\varepsilon_1)\frac{h_1-x}{h_1}\right]\gamma_1\xi_{0,1}x\varphi_1dx.$$

Avalue φ_1 is determined on the first layer of asoil base by pile test results [9, 10] withforce $F_1<F_p$ distributed at the height $h_{0.1}$ asshownonFig. 4. Thefollowingequationused [9, 10]: $\varphi_1=\dfrac{6F_1}{u\varepsilon_{0,\max}\gamma_1\xi_{0,1}h_{0,1}^2}$, where $h_{0,1}\le h_1$ and $h_{0,1}$ isapile length with skinfriction*f*(*x*) as shown in Figure 4; $\varepsilon_{0,\max}$ isamaximum deformation of the pile at the pile intersection with the ground surface.

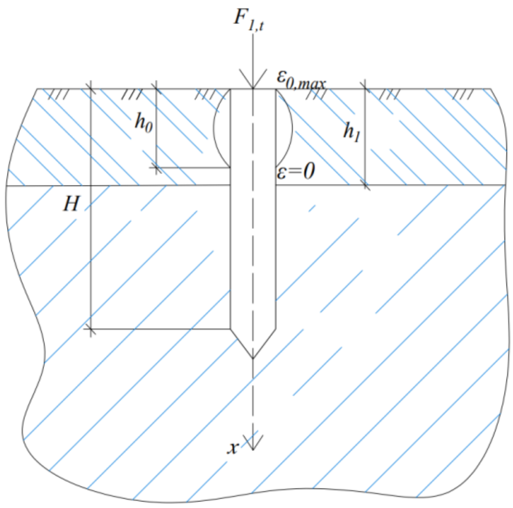

Figure 4 - Design scheme of the friction pile behavior within the upper soil layer under test load $F_{1,t}$

Avalueofthetestload $F_{1,t}$ is selected in such a way as to cause pile deformations only on the length $h_1$of the upper soil layer.

Let's consider the pile statics on the second layer of the soil base at $x \geq h_1$ as shown on Figure 4.

The skin friction function is $f_2(x) = \varepsilon_2(x)\gamma_2\xi_{0,2}\varphi_2 x$ with $\varepsilon_2(x) = \varepsilon_{2,\max}\dfrac{h_1 + h_2 - x}{h_2}$, $q_2(x) = q_1(h_1) + q_2(x - h_1)$.

Force perceived by the second layer of a soil (Figure 5) is:

$$F_2 = u\int_{h_1}^{h_2}\varepsilon_{2,\max}\frac{h_1 + h_1 - x}{h_2}\left[\gamma_1\xi_{0,1}h_1 + \gamma_2\xi_{0,2}(x - h_1)\right]\varphi_2 x dx .$$

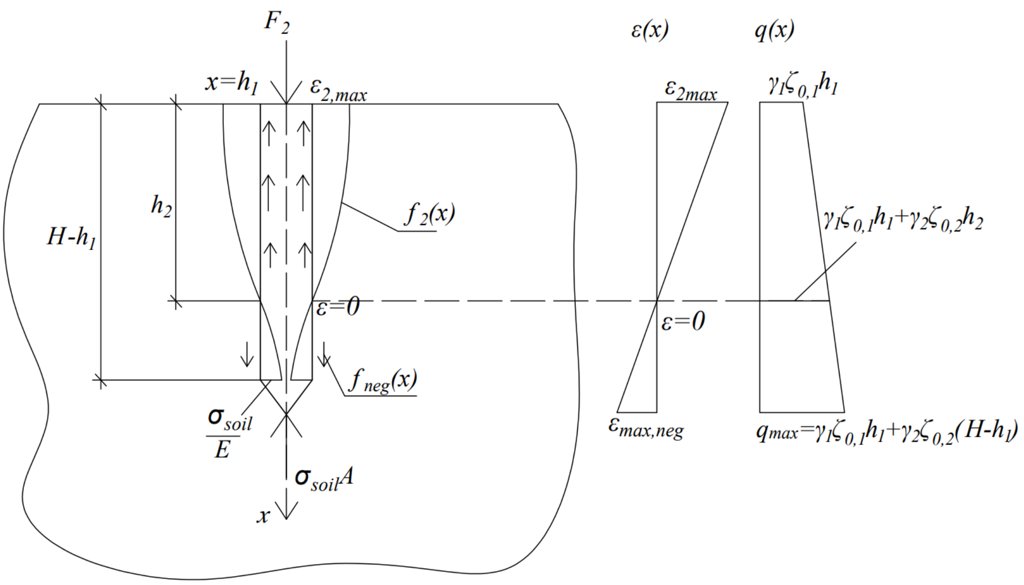

Figure 5 - Design scheme of the lower part of afriction pile in the second soil layer

By Figure 4, the dimensionless coefficient φ_2 is $\varphi_2 = \varphi_1\dfrac{\gamma_2\xi_{0,2}}{\gamma_1\xi_{0,1}}$.

The negativeskinfriction $f_{neg}(x)$ can be found by next equations $\varepsilon_{\max, neg} = \frac{\sigma_{soil}}{E}$ and $\varepsilon_{neg}(x) = \varepsilon_{\max, neg} \frac{x - h_1 - h_2}{H - h_1 - h_2}$.

In accordance with (2): $f_{neg}(x) = \frac{\sigma_{soil}}{E} \frac{x - h_1 - h_2}{H - h_1 - h_2} \left[\gamma_1 \xi_{0,1} h_1 + \gamma_2 \xi_{0,2}(x - h_1)\right]\varphi_2$.

Force perceived by the third layer (“negative” layer) of a soil is:

$$F_{neg} = u \int_{h_1+h_2}^{H} \frac{\sigma_{soil}}{E} \frac{x - h_1 - h_2}{H - h_1 - h_2} \left[\gamma_1 \xi_{0,1} h_1 + \gamma_2 \xi_{0,2}(x - h_1)\right]\varphi_2 dx .$$

In expanded form, the equation (1) for determining the friction pile bearing capacity can be represented as:

$$F_p = \sigma_{soil} A + u \int_0^{h_1} \varepsilon_{\max} \frac{h_1 - x}{h_1} \gamma_1 \xi_{0,1} x \varphi_1 dx + u \int_{h_1}^{h_2} \varepsilon_{2,\max} \frac{h_1 + h_2 - x}{h_2} \gamma_2 \xi_{0,2} \varphi_2 x -$$

$$- u \int_{h_1+h_2}^{H} \frac{\sigma_{soil}}{E} \frac{x - h_1 - h_2}{H - h_1 - h_2} \left[\gamma_1 \xi_{0,1} h_1 + \gamma_2 \xi_{0,2}(x - h_1)\right]\varphi_2 dx . \quad (3)$$

Asolution of (3) is more convenient to perform based on the results of numerical calculation in computer programs. Astress σ_{soil} to check asoil strength,a permissible load value F_p, the maximum deformation $\varepsilon_{\max}$, etc. are can be found by (3).

The ultimate load on a pile F_d can be evaluatedreplacing the soil stress σ_{soil} under the pile lower end to the pile design resistance*R*in (3) and neglecting a slight change in the deformation of the pile material under the pile lower end.

Let*R*=3.0 MPa;*A*=0.126 m^2; *u*=1.256 m; h_1=3 m; $\varepsilon_{\max} = 0.001$; $\gamma_1 = 15$ kN/m^3 (poorly graded sand); $\xi_{0,1} = 0.2$; $E = 15000$ MPa; $h_{0,1} = 2$ m; h_2=3 m; $\varepsilon_{2,\max} = 0.0004$; $\gamma_2 = 18$ kN/m^3 (elastic silt); $\xi_{0,2} = 0.4$; *H*=7 m; $\varphi_1 = 1.25 \cdot 10^5$; $\varphi_2 = 1.69 \cdot 10^5$ with $\varepsilon_{0,\max} = 0.00002$; $F_{1,t}$=0.050 MN.

By the numerical calculation of (3) in MathCAD:

$$F_d = 0.377 + 0.707 + 0.753 – 0.690 = 0.993 \text{MN}.$$

Let’s compare the result with result by the traditional approach:

$$F_d = RA + u \sum f_i h_i ,$$

where the values of taken by SP 22.13330.2011 “Pile foundations”.

$$F_d = 3 \cdot 10^6 \cdot 0.126 + 1.256 \cdot 10^3 (2 \cdot 35 + 1 \cdot 38.5 + 2 \cdot 33 + 2 \cdot 42) = 0.377 + 0.327 = 0.704 \text{ MN}.$$

The results are close enough. However, some of the values in the example are set theoretically. Experimental researchesare required for a more objective comparison of the proposed approach and the normative approach.

Conclusions

1. The article describes the behavior of afriction pile with the new design scheme.The designequation is obtained for evaluated the ultimate load (bearing capacity) F_d ofanaxial loaded pile.

2. Negativeskinfrictionforces adversely affectsonthe F_d value. Thenegativeskinfrictionis more than greater the reaction RA at the pile lower end. To reduce this impact, the direct contact of the pile at the length $H - h_1 - h_2$ can be partially or completely isolated from the soil;

3. With a larger number of different layers of soil base, the equation (8) will retain its appearancebut with increasing the number of members.

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