The bearing capacity of the explosive piles’ bases: 
geotechnical design of rational structures

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Abstract. The material of the scientific work is presented in two articles: “The bearing capacity of the explosive piles’ bases: the bases granular media geomechanics theory” and “The bearing capacity of the explosive piles’ bases: geotechnical design of rational structures”. The results of the latest innovative achievements in the field of pile foundation engineering are summarized. The explosive single piles-foundations rational designs development of geo-engineering design scientific and technical problem integrated solution relevance is grounded. The goal and objectives of the scientific research are set. The main content of theoretical and practical research is represented by a full demonstration of the scientific results obtained. Geotechnics is based on methodologies that include the computational-theoretical research knowledge geomechanics and methods theory provisions. The proposed geotechnical design of rational designs of explosive single piles-foundations makes it possible to determine their design dimensions from the bases’ bearing capacity values equal to the critical load on the pile.

Introduction
The general problem and relevance of the scientific work is presented in the first article introduction. This second article shows that the lack of a comprehensive solution to the scientific and technical problem of developing the geotechnical engineering for the designing rational structures of stuffed explosive-fused single piles based on the foundations hinders bearing capacity and their widespread use in modern foundation engineering.

Therefore, the purpose of the research work is to create the ramming explosive single piles rational designs geotechnical engineering based on the foundations’ bearing capacity. The implementation and research objectives are:
- obtaining methods for determining the ultimate limit load capacity of the base;
- the pile diameter design size choice, taking into account the structural features of the above-mentioned ground structure;
- the fuse block pile lower end circular cone base limit equilibrium methodology development for calculating the carrying capacity of the five zones areas;
- the methodology for determining the bearing capacity on the stress ejection section length along the lateral surface of the pile shaft creation;
- the methods for calculating the pile shaft side surface carrying capacity against the concrete interaction stresses with the ground development;
- the methodology for the calculation of the foundation pile shaft by the bearing capacity penetration into the soil design length scientific substantiation.
The bearing capacity of the rammed explosive single piles is determined by the normal compressive stresses of the conventional massive foundation trunk and circular cones lateral surface and the lower end of the pile \( \sigma_i \) and the tangential stresses of resistance to immersion of the pile into the ground of the \( \tau_i \) base [1]. The shown stresses \( \sigma_i \) are generated by the shear forces pressure acting on the adjacent compressible plastic contacts slip sites and the shear mineral particles under the pile shaft soil ascending along the lateral surface pressure influence.

The main content of the study is presented in a brief justification of the scientific results obtained. The main significant findings of the study are depicted.

The carrying method-based adjustable explosive-exhaust single pieces-foundations rational-strong constructions design geotechnology

The considered pile foundations rational designs geotechnical design sequence is carried out according to the determined values of the bases’ bearing capacity [2, 3]. The calculated value of the load on a single pile foundation \( P_d \) and the corresponding calculated bearing capacity \( F_d \) is calculated with this purpose. Determination of the critical load on the pile \( P_{cr} \) and the corresponding maximum carrying capacity \( F_{cc} \), corresponding to it, is carried out using the pile bearing capacity factor \( \gamma_z = 1.2 \) for the equalities:

\[
P_{cr} = \gamma_z P_d
\]

\[
F_{cc} = \gamma_z F_d
\]

The pile shaft design diameter size is justified and adopted taking into account the structural features of the structure’s above-ground part.

The following physical and mechanical characteristics of soils are used: \( \gamma \) is the specific gravity of the soil of a natural state, \( \gamma_d \) is the specific weight of the skeleton of dry soil, \( \phi \) is the internal friction angle, \( c \) is the specific adhesion, and \( E \) is the soil deformation modulus.

The values of limiting equilibria states’ five zones internal friction angles [4] are obtained for the elastoplastic properties of clays and loams of a dispersed granular medium with an exponent \( n = 1.0 \) in the function \( \tan^n \phi_i \), whence

\[
\phi_1 = \phi
\]

\[
\phi_2 = 22.5^\circ + \phi / 2
\]

\[
\phi_3 = 45^\circ
\]

\[
\phi_4 = 67.5^\circ - \phi / 2
\]

\[
\phi_5 = 90^\circ - \phi
\]

The elastic-plastic-hardening resistivity properties of loamy clay sands, sandy loams and loamy dusty sands of a dispersed-discrete granular medium with degree indices for clay sands are \( n = 1.13 \ldots 1.50 \), for loamy dusty sands \( n = 1.38 \ldots 1.53 \), for sands the discrete grained environment with \( n = 1.53 \ldots 2.0 \) are in equalities

\[
tg^n \psi_i = tg \psi_i
\]

at inequalities of values \( \psi_i < \psi_i \), where \( \psi_i \) are the elastic-plastic viscosity resistance properties internal friction angles, taking into account the engagement stiffness resistance on the adjacent compressible sliding areas and shift able mineral soil particles in the limit equilibrium states five zones.

The coefficients of maximum \( K_1 \), minimum \( K_3 \), and the total principal normal compressive stresses \( K_i \) at sliding sites of shifted mineral soil particles are:

\[
K_1 = \cos \phi
\]

\[
K_3 = \sin \phi
\]

\[
K_i = \cos \phi + \sin \phi
\]

The maximum \( \sigma_1 \) and minimum \( \sigma_3 \) main compressive stresses are generated from the pressure stress of the dry soil skeleton specific weight \( \sigma_d \) and the specific adhesion to resist the dispersed granular
medium limit equilibrium states five zones clays and loams elastic-plastic viscosity properties are determined by the equalities:

\[ \sigma_1 = (\sigma_d + c) \cos \varphi, \]  \hspace{1cm} (12) 
\[ \sigma_2 = (\sigma_d + c) \sin \varphi. \]  \hspace{1cm} (13)

The resistance tangential stresses to the pile piling into the ground:

\[ \tau_{1,1} = \sigma_1 \tan \varphi_1 = (\sigma_d + c) \cos \varphi \tan \varphi_1, \]  \hspace{1cm} (14) 
\[ \tau_{1,5} = \sigma_1 \tan \varphi_5 = (\sigma_d + c) \cos \varphi \tan \varphi_5, \]  \hspace{1cm} (15)

Specific grip

\[ c = C_w + C_{s,1}, \]  \hspace{1cm} (16)

where \( C_w \) is the physicochemical nature specific connectivity in the plastic sliding contacts; \( C_{s,1} \) - is the specific adhesion in contacts of the mineral particles sediment gels onto the surface continuous cementation bonds destruction and shear;

\[ \tau_{3,1} = \sigma_3 \tan \varphi_1 = (\sigma_d + c) \sin \varphi \tan \varphi_1, \]  \hspace{1cm} (17) 
\[ \tau_{3,5} = \sigma_3 \tan \varphi_5 = (\sigma_d + c) \sin \varphi \tan \varphi_5, \]  \hspace{1cm} (18)

For the dispersed-discrete and discrete granular media, normal stresses limiting equilibria state five zones loamy clayed sands, sandy loams, loamy dusty sands elastic-plastic-hardness properties resistance is determined by the equalities for \( \sigma_1 \) - (12) and for \( \sigma_3 \) - (13), considering the shear stresses on the lateral surface of the pile shaft from \( \sigma_1 \):

\[ \tau_{1,1} = \sigma_1 \tan \varphi_1 = (\sigma_d + c_z) \cos \varphi \tan \varphi_1, \]  \hspace{1cm} (19) 
\[ \tau_{1,5} = \sigma_1 \tan \varphi_5 = (\sigma_d + c_z) \cos \varphi \tan \varphi_5, \]  \hspace{1cm} (20)

where \( c_z \) is the specific adhesion taking into account the stiffness of the gearing for loamy clayed sands, sandy loams and loamy dusty sands.

\[ c_z = C_w + C_{s,1} + C_{s,2} + C_Z, \]  \hspace{1cm} (21)

\( C_{s,2} \) - is the mineral particles surfaces irregularities cut contacts specific connectivity; the stiffness specific connectivity

\( \Delta \psi \) – is an excess of the angle of internal friction \( \psi \) with respect to the angle \( \varphi \); specific grip for sands

\[ c_z = C_w + C_{s,2} + C_Z. \]  \hspace{1cm} (22)

Tangential stresses along the side surface of the pile shaft from \( \sigma_3 \):

\[ \tau_{3,1} = \sigma_3 \tan \varphi_1 = (\sigma_d + c_z) \sin \varphi \tan \varphi_1, \]  \hspace{1cm} (23) 
\[ \tau_{3,5} = \sigma_3 \tan \varphi_5 = (\sigma_d + c_z) \sin \varphi \tan \varphi_5. \]  \hspace{1cm} (24)

The total main normal stresses of dispersed granular medium limiting equilibria five zones of the states clays and loams elastoplastic-viscosity resistance properties the compression with \( K \), (11)

\[ \sigma_i = (\sigma_d + c)(\cos \varphi + \sin \varphi). \]  \hspace{1cm} (25)

Tangential total stresses of resistance to the pile immersion in the ground:

\[ \tau_{t,1} = \sigma_t \tan \varphi_1 = (\sigma_d + c)(\cos \varphi + \sin \varphi) \tan \varphi_1, \]  \hspace{1cm} (26) 
\[ \tau_{t,5} = \sigma_t \tan \varphi_5 = (\sigma_d + c)(\cos \varphi + \sin \varphi) \tan \varphi_5. \]  \hspace{1cm} (27)

For the discrete medium loamy dusty sands, sandy loams and loamy clayed sands dispersion-discrete granular media and sands elastic-plastic-hardness properties resistance the total normal compressive stresses of the limiting soil equilibria state five zones are determined by the formula (25).

Tangential total stresses of resistance to the pile immersion in the ground:

\[ \tau_{t,1} = \sigma_t \tan \varphi_1 = (\sigma_d + c_z)(\cos \varphi + \sin \varphi) \tan \varphi_1. \]  \hspace{1cm} (28)
4

\[ \tau_{i,5} = \sigma_d \tan \varphi (\cos \varphi + \sin \varphi), \]

The total principal normal and tangential stresses are used to determine the physically maximum resource carrying capacity of the piles’ bases.

The pile shaft lower end circular cone base limiting equilibrium state five zones bearing capacity is:

\[ F_{K,1} = A_k \tau_{0-1}, \]
\[ F_{K,5} = A_k \tau_{0-5}, \]

where \( A_k \) is the circular cone lateral surface area; consistently the tangential stresses in five zones total values:

\[ \tau_{0-1} = 0 + \tau_{r,1}, \]
\[ \tau_{0-2} = \tau_{0-1} + \tau_{r,2}, \]
\[ + \ldots + \tau_{0-5} = \tau_{0-4} + \tau_{r,5}. \]

Total limiting equilibria states five zones tangential stresses (26, 27), (28, 29): \( \tau_{r,1}, \ldots, \tau_{r,5} \)

The total critical load on a circular cone

\[ F_{K,1} = F_{K,1} + \ldots + F_{K,5}, \]

The bearing capacity of the pile length section at the tip at the height of the truncated cone of the stress plot around the pile shaft is determined by the extreme soil equilibrium state fifth zone radius following calculations.

\[ R_5 = \sqrt{2A_e / \pi}, \]

where \( A_e \) - is the pile shaft cross-sectional area. The limiting equilibria states five zones total stresses values are used to calculate the radius of their boundaries:

\[ R_4 = R_5 \tau_{0-5} / \tau_{0-4}, \]
\[ R_1 = R_5 \tau_{0-5} / \tau_{0-1}. \]

Each soil layer compressible strata thickness between the zone boundaries

\[ \Delta h_5 = R_5 - R_e, \]
\[ \Delta h_4 = R_4 - R_5, \]
\[ \Delta h_1 = R_1 - R_2. \]

The voltage collapse sections length of the five zones on the side to the pile top:

\[ l_2 = \Delta h_2, \]
\[ l_5 = \Delta h_5. \]

Ejection section length

\[ l_0 = l_2 + \ldots + l_5, \]

Critical load bearing capacity at a voltage sprint section of length \( l_0 \)

\[ F_0 = 0.5A_0 \Sigma \tau_{3,j}, \]

where \( A_0 = ul_0 \) - is the pile shaft side surface area; amount of stress

\[ \Sigma \tau_{3,j} = \tau_{3,2} + \ldots + \tau_{3,5}. \]

Critical bearing capacity for the pile shaft remaining length \( l_z \), surrounded by the compression and shear stresses of cylindrical form

\[ F_z = F_{\sigma_p} - F_0 - F_{K,i} - F_{b,i}, \]

where \( F_{b,i} \) is the base bearing capacity part of the falling on the section length \( l_0 \) from the stresses of interaction between the pile concrete and the ground \( \tau_b \).
\[ F_{b0} = ul_0 \tau_b. \]  
(48)

Critical bearing capacity on the length of the pile shaft \( l_z \)

\[ F_z = ul_z \tau_i + ul_z \tau_b. \]  
(49)

The pile shaft stress length of the section of cylindrical form

\[ l_z = F_z / u(\tau_i + \tau_b). \]  
(50)

Design pile length

\[ l_c = l_0 + l_z. \]  
(51)

The state equations choice for tangential stresses \( \tau_i \) within the limiting equilibria states five zones boundaries involved in the project is determined by the field experimental investigations results of the bearing capacity of the piles’ bases, which is a significant disadvantage. In this regard, the proposed theoretical-calculation method for determining the tangential stresses \( \tau_i \) values involved in the limiting equilibria linearly state five zones and proportionally depending on the sizes of pile diameters \( d_{c,i} \) according to the schedule \( \tau_i = f (d_{c,i}) \), shown in Figure 1 for specific grounds.

**Figure 1.** Graph of the tangent stresses \( \tau_i \) at the border of the limiting equilibrium state involved zones versus the pile diameter \( d_c \)

The tangential shear forces \( \tau_i \) are generated by the minimum main normal compressive stresses \( \sigma_3 \) for the medium-sized piles with diameters from \( d_a = 0.2 \) m - initial to \( d_c = 0.8 \) m - average and total values of the minimum \( \sigma_3 \) and maximum \( \sigma_i \) main normal compression stresses for the large-sized piles with diameter from \( d_{c,i} = 0.8 \) m to \( d_{c,r} = 2.8 \) m - the final one, at which the studied pile base bearing capacity physically maximum possible is realized.

Normal \( \sigma_b \) and tangential \( \tau_b \) stresses from the concrete interaction with the surrounding soil take part in the explosive piles bases bearing capacity formation.

\[ \sigma_b = \sigma_{b0} + \sigma_k, \]  
(52)

\[ \tau_b = \sigma_{b0} \tan \phi_3, \]  
(53)

where \( \sigma_{b0} \) - is the normal stress of compression of the pile shaft from the swelling of the concrete mix; \( \sigma_k \) - is normal stress compression with the maximum carrying capacity on the side surface of the pile shaft; \( \phi_3 = 45^\circ \) according to the formula (5).

The limiting bearing capacity of the base, taking into account the soil interaction with the pile shaft lateral surface concrete, is equal to the critical loads on the pile at the boundaries of the limiting equilibria states five zones:
\[ F_1 = F_{1c} + F_{K,1} + F_b = P_1, \]  
\[ F_2 = F_{2c} + F_{K,2} + F_1 = P_2, \]  
\[ F_5 = F_{5c} + F_{K,5} + F_4 = P_5. \]  

The vertically loaded filling-up explosive-functioned single piled foundations sedimentary mechanical loading in ground-reconfigurable bases

The soil deformation modulus \( E_i \) and its nonlinear total deformation \( E_i^0 \) for the first, second, and first half of the third zones of the ultimate equilibrium states of the soil compaction phase A at the circular cone base of the pile under consideration are determined using the conventional pile foundations with a diameter \( d_c \).

\[ E_i = E_i^0 / K_i^0, \quad (88) \]  
\[ E_i^0 = (1 - \nu^2)P_i / d_y S_1, \quad (57) \]

where \( K_i^0 \) defines the non-linear total soil deformation reference proportional coefficients.

From the second half of the third, fourth and fifth zones of the limiting equilibria state of the basics of soil B decomposition \( E_i \), \( E_i^0 \) the deformation moduli are determined at the pile shaft lower end circular cone base with the diameter \( d_c \)

\[ E_i^0 = EK_i^0, \]  
where \( E \) is the soil deformation modulus.

The final compressibility of the soil between the limiting equilibria states five zones boundaries:

\[ S_1 = (1 - \nu^2)P_1 / d_y E_i^0, \]  
\[ S_2 = (1 - \nu^2)P_2 / d_y E_2^0, \]  
\[ S_3 = (1 - \nu^2)P_3 / d_y E_3^0, \]  
\[ S_4 = (1 - \nu^2)P_4 / d_y E_4^0, \]  
\[ S_5 = (1 - \nu^2)P_5 / d_y E_5^0. \]  

Based on the obtained values \( P_1 \) (54) ... (56) and \( S_i \) (59) ... (63), a calculation-theoretical non-linear-linear graph is plotted as a function of setting the load \( S_i = f (P_i) \). According to the design load on the pile \( P_d \) value, the corresponding design stabilized sediment \( S_d \) is graphically determined (see the first article).

The development of scientific substantiation and scientific and the effective explosive tube-filled tubular shells technical support of constructive and technological production, as well as no less effective hinged single-pile-slab foundations are considered as a promising study area [5].

Summary

The packed explosive single piles-foundations rational structures geotechnical design positions are based on the foundations’ granular media geomechanics theory.

The structures design of the piles under consideration is based on the principle of their own bases limiting load-bearing abilities determining their dimensions from the values .

The basics of the methodologies, methods and means of computational and theoretical studies of the explosive-high explosive single piles-foundations foundations non-existent ability are shown.

A method for determining the critical loads along the boundaries of the limiting equilibria state five zones is presented.

The method of calculating the sediment values from the critical loads action along the explosive piles bases soils limiting equilibria states five zones boundaries is shown.

It is noted that it is possible to build a theoretical-theoretical graph of the draft dependence on the load, with the help of which the maximum stabilized draft is graphically determined by the value of the design load on a single pile foundation.
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