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Engineering kinematic theory in application to the calculation of pile foundations

Инженерная кинематическая теория в приложении к расчету свайных фундаментов

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Key words: pile foundation; lateral pressure; vertical jet pressure; high and low pile grillage; the stiffness coefficient of the soil; dimensionless curve relation from the horizontal and vertical pressure

Ключевые слова: свайный фундамент; боковое давление; вертикальное реактивное давление; высокий и низкий свайный ростверки; коэффициент жесткости грунта; безразмерная кривая связи от горизонтального и вертикального давлений

Abstract. The author has proposed a variant of calculation of pile foundation with the use of the engineerin kinematic theory of ground contact pressure. This calculation uses two separate graph connection, the pressure – vertical or horizontal offset. The diagrams are dimensionless, so is not related to the scale of the building. The absolute values of the end points of the graphs are determined considering the plastic deformation modulus of the soil. Diagram enables the calculation of pile foundation for the entire load cycle. Practical implementation of calculations uses variable from of the depth and the load of the coefficient stiffness soil. The author considered the combined model the stiffness of the soil based on the structural surrounding the pile. The article presents fragments of the calculation of stresses and displacements of pile foundations.

Аннотация. Автор предложил вариант расчета свайного фундамента с применением инженерной кинематической теории контактного давления грунта. Приведено решение по определению сил трения на боковую поверхность сваи дополнительно зависящее от размеров поперечного сечения внедряемой в грунт сваи. Описано решение по определению реактивного давление грунта на острие сваи или условный фундамент для всего цикла нагрузки. Рассмотрено влияние расположения плиты ростверка в свайном основании на несущую способность конструкции. Учтено взаимное влияние свай на распределение усилий в свайном ростверке. Получено решение по определению горизонтального уплотнения и осадки свайного фундамента с использованием относительных кривых связи «давление-перемещение» и «давление-осадка» для всего цикла нагрузки. Приведена комбинированная модель коэффициента жесткости грунта с учетом структурного элемента. Показан прием определения коэффициента жесткости грунта у боковой и торцевой поверхностей сваи от нагрузки. Приведен порядок расчета и его практическая реализация применительно к низкому свайному ростверку городской набережной с использованием программы SCAD.

Introduction

Pile foundation is the most effective, but least studied type of foundation. This is facilitated by a variety of factors affecting its load-bearing capacity while construction and exploitation process. The use of software systems using the theory of continuous media has enabled more fully to describe the work of pile foundation in the ground. However, this theory is for the behavior of structural materials in relation to soils is of the approximate. This is due to different structures of the environments (continuous and discrete), which are more diverse in soil than in metals with larges the intercrystalline by contacts. To adjust the solutions of the theory as applied to soils used various artificial techniques. On the other hand, the use of solutions of the theory of continuous medium at this stage of development of soil mechanics is justified, as the discrete theory soils not quite developed.

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The interaction of piles with soil were considered by scientists: V.A. Barbashov [1], A.A. Bartolomey [2], B.V. Bakholdin [3], S.N. Bezvolen [4], V.S. Glukhov [5], A.V. Savinov [6], V.N. Paramonov [7], V.V. Znamenskiy [8], Y.K. Zaretsky [9], A.B. Fadeev [10], V.G. Fedorovsky [11], D.E. Razvodovsky [12], A.L. Gotman,. [13], К. Terzaghi [14], A. Kezdi, G.P. Chebotarev, B.N. Fellenius [15], D.A. Brown [16], Neil Taylor [17], D.J. White [18], S. Nakajima and others.

Extensive experimental and theoretical studies of the pile foundation works were conducted by A.A. Bartolomey [2]. He studied the propagation process of sealing areas soil, the deformation modulus of the soil, and the nature of the behavior in time of the pore pressure, etc. A.A. Bartolomey received a calculation expression to determine the limit loads and settlement of pile foundations based on the research.

Research in recent decades include both engineering methods of calculation [8], the model using the coefficient, [11], etc. and rigorous solutions using elastic-plastic and visco-plastic model of soil [9, 10], etc.

Researchers conducted numerous experimental investigations of the operation of piles in the estimation of spatial models of continuous soil medium [14–25].

Despite the progress made in the calculation of pile foundations, individual issues cannot be considered fully resolved. For example, the recommended Russian Constructions Normsand Regulations SNiP 2.02.03.85 [26] action of the load and the sediment on pile foundation are not linked together, and their results in some cases, differ substantially from full-scale.

The article aims at linking of the load on pile foundation up to the limit with his draught. Diagram lateral pressure – ground compaction allows defining a variable friction along the length of the pile from the value of the seal. Graph vertical pressure – soil settlement allows you to define a variable jet pressure on the end of the piles from the soil settlement. This allows you to more fully determine the nature of the work piles design in all load range. Recommendations SNiP 2.02.03.85 is a special case of the proposed solution, since they give the maksismum value of the effort.

The author offers a variant of the calculations on the basis of the Engineering kinematic theory of ground contact pressure, for a simplified evaluation of stress-strain state of pile foundations [27].

The main provisions of the engineering kinematic theory of ground contact pressure

The theory assumes that the behavior of soil under load does not depend on a constructive basis of buildings. It integrates and complements the existing special cases of engineering analysis of structures interacting with the soil in the elastic and limit states. This makes for a more clear overall picture of the interaction of soil with the structure [27].

In a soil environment, interacting with any engineering construction (retaining wall, strip foundation, pile) under load is formed by a variable active area. She crosses to the region of shear of the soil at extreme loads (Fig.1). This area is divided into arbitrary strips with the trajectories of moving soil particles. The resistance to compression of the stripes is determined of the stiffness of the soil, the value of which depends on its length and the magnitude of the load.

Load is forming the active region associated with the diagram of compression of the ground in horizontal or vertical directions. The relative nature of the diagram makes it common to describe the behaviour under load of all the strips of ground.

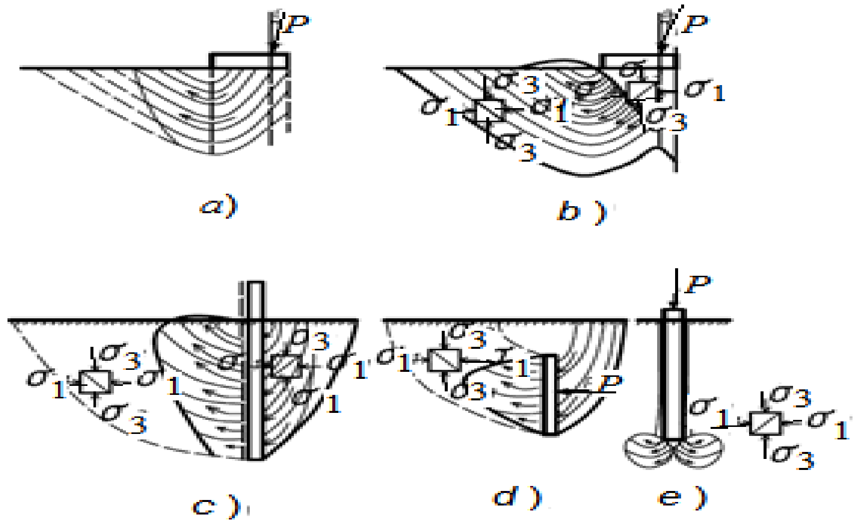

Figure 1. The influence of the degree of the impact of design on the shape of the active zone of the soil

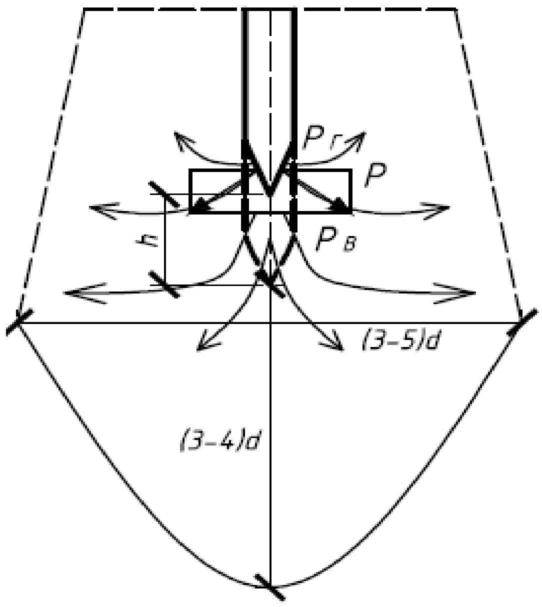

Figure 2. The active area and the trajectory displacement at the pile toe

The soil area in the foundation is active when small loads more or less of the vertical (Fig. 1a). Ground wedge below the foundation from extreme load, similarly, to inclined surface wall pushes ground in the adjacent region (Fig. 1b). Horizontal active area moves at extreme loads in the prism of the shift in the retaining walls, anchor slab (Fig. 1g). In the pile foundation composite region of the ground comprises two of the above areas, acting on the lateral part and the end portion of the piles (Fig. 1d). Earth pressure on the lateral part of the piles is determined by the displacement of soil from the lateral introduction of piles [28], and by the pressure of the soil on the edge of the piles respectively under the sediment the buried piles (Fig. 1e) [29].

The mechanism of the phenomena occurring in the soil when submerged piles

The active region of the soil deformation are formed in the side and in the edge surfaces of the pile [2]. The side seal area of soil to pile is (3÷5)diameter (d), in the strip foundation respectively – (10÷11)d. Vertical active area at the edge of a single pile is (3–4)d and under by number piles, respectively – (4–5)d, Figure 2 [2].

In the pile, submerged in the soil, emerge in the field the tip lateral (Pl) and vertical (PV) components of the forces acting on the foundation soil (Fig. 2). The process of immersion is provided by the excess forces on the components of the reactive resistance of the soil in horizontal and vertical directions. The one concrete rectangular pile, immersed to a depth h, displaces a volume of soil:

$$V =\cdot \int_0^h F_p \cdot dh =\cdot F_p \cdot h,$$

This volume of soil contains the offset in the vertical and horizontal directions. The resistance of the soil in the vertical direction is 3–4 times higher than in the horizontal. Therefore, coefficient the ratio of the horizontal seal equal K_l=0.7–0.8, which takes into account part of the amount of compacted soil in a lateral direction. Therefore, the horizontal lateral displacement of the soil medium per unit height Δ_h = 1.0 m, K_l =0.8 will be:

$$\Delta_l \cdot= 0.25 \cdot K_l \cdot d = 0.2d,$$

where *d* is the side or the diameter of the piles.

Thus, at the piles size 35 × 35 cm each face compresses the soil to 7 cm horizontally and respectively vertically $\Delta_v = 0.05 \cdot d = 1.75$ cm, with K_V= 0.2.

Piles in case dive cause constant horizontal soil compaction. But the calculated value of the maximum horizontal compaction with the depth increases. Hence the magnitude of lateral pressure and thus the friction force on the pile will decrease under the depth. The magnitude of the vertical soil compaction under the pile is significantly less than horizontal. However, the reactive pressure on the end faces piles increases with depth, due to the increase of the higher resistance of the soil. Dive into the soil piles causes arising in the active region does to the change of physico-mechanical characteristics of the soil. These characteristics increase to an average of 30–35 %, and the adhesion and modulus of deformation, respectively several times. This happens is in non-cohesive and a little moist clay soils. [2]. However, during "rest" piles in non-cohesive soils is the dissipation (relaxation) voltage and the resistance of the soil is reduced. In very wet clayey soils the pressure perceives the pore fluid [2]. The unstable condition of the soil gradually approaches to natural stable. In water saturated silty-clay soils during this period, there is dissipation of pore pressure. This leads to an increase of pressure of the solid phase of soil and its strength around the piles to a considerable extent restored. The necessary duration of the "rest" of the pile depends on the type of soil. For sandy loams and sands it is one week. Loam – to clay – at least three weeks.

Earth pressure on the pile

The lateral surface of the pile. The Russian Set of Rules SP 24.13330.2011 contains the empirical table limit friction forces on the lateral surface of the pile (ff) [26].The value ff depends on the type of ground and depth of piles. However, friction forces at a certain depth are not permanent, according to the experiments unlike SNIP [26]. They are associated with the value of the jet lateral pressure of compacted soil to the piles. This value will be depending on the shape of the cross section of the pile. The cross-section two piles are shown in Figure 3. The cross-section have the same perimeter: a square cross-section 40x40 cm (fig. 3*a*) and rectangular cross-section 30 x 50 cm (Fig. 3*b*).

The Russian Set of Rules SP 24.13330.2011 contains equal the value of the specific lateral pressure ff on piles with cross-sections *a* and *b* (Fig. 3). In fact, equality the friction force acts only on the square piles, equally compacted the soil in two directions to the cross-sections *a*. The friction force on the sides of reinforced concrete pile will be different due to different values of the compaction parties the cross-sections *b*. This value will depend on the values of the horizontal displacement of the soil. Therefore, the friction force on the lateral the surface cross-section of the piles will be greater than on its front surface (Fig. 3*b*).

In accordance with the article [27] the value of 1rm lateral earth pressure on the pile is equal to:

$$\sigma_{x,\ y} = K_{l\,p} \cdot K_s \cdot u\left(\gamma \cdot h \cdot \lambda(\delta) + c \cdot \lambda_{pc}(\delta)\right) \le \sigma *_{x,\ y}, \qquad (1)$$

where $\sigma_{x,\ y}$, $\sigma^*_{x,\ y}$ – up to of passive and passive lateral pressure 1rm ground on the pile on depth *y*; $K(l\ p)$– coefficient of lateral pressure; Ks = 0.8–1.2 – coefficient taking into account the way of immersion and the perimeter of the pile; *u* – perimeter pile γ – density of soil; λ (δ), λ_{pc} (δ) – power functions-pressure lateral (FLP) and the grip of the clay that describes the relationship diagram "pressure displacement" [28]. The limit value of the seal of the ground along the piles creates a passive pressure and is described by equation (1) with three-dimensional effect. Accordingly, the magnitude of the frictional force on the lateral surface of the pile is equal to:

$$\tau_{x,y} = \sigma_{x,y} tg\varphi \tag{2}$$

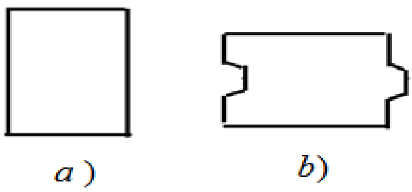

Figure 3. Cross section 2 piles with different cross-sections with the same perimeter

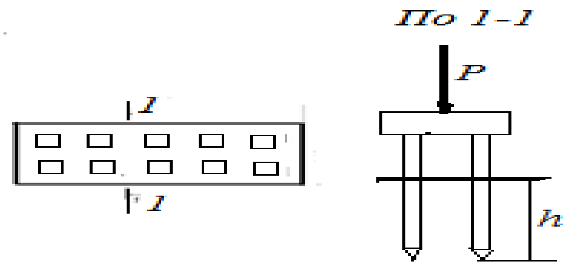

Figure 4. To the determination of the bearing capacity of pile foundation

Example 1. To determine the friction forces on the lateral surface of the single reinforced concrete piles section 30x30 cm, immersed to a depth of 5 m in loamy soils. $I_L = 0.5$, $\varepsilon = 0.7$, $\varphi = 20^0$, $C = 0.02$ MPa; $E = 8.5$ MPa; $\gamma = 16$ kN/m³; $\lambda_p = 2.04$, $\delta = \varphi = 0$; $\lambda_0 = 1.0$ – coefficient of household pressure soil; $\lambda_{pc} = 2.3$, $\delta = \varphi$; $K_s = 0.8$; $u = 1.2$ m is the perimeter of the pile; $K_a = 0.7$ is a coefficient of anisotropy of the soil horizontally; $\Delta_l = 0.2$ d $= 0.06$ m.

Table 1 Comparative data of the calculated and experimental values of shear stress, kPa

Deep	Δ	Δ_i^*,	$\boldsymbol{\delta = (\Delta_i/\Delta_i^*)^n}$ *n =1*	$\boldsymbol{\sigma_{x,y}}$ (1)	$\boldsymbol{\tau_{x,y} = \sigma_{x,y} tg\varphi}$ (2)	Experience [2]	SNIP [26]
1	2	3	4	5	6	7	8
1	0.06	0.0067	1	37.3	13.5	18.0	14.4
2	0.06	0.027	1	55.76	19.5	18.7	20.4
3	0.06	0.06	1	69.0	25.1	19.1	24.0
4	0.06	0.11	0.55	56.3	20.6	19.9	26.4
5	0.06	0.17	0.35	48.46.	18.9	20.0	28.9

Note: If relative offset is more than the limit of δ>1 take δ=1, since lateral pressure is not to exceed of the passive.

In the table 2 the second column shows the horizontal displacement of soil from pile at a value of 0.2*d*, and the third column is accordingly of the limit lateral displacement of soil at depth h, which equal [27]:

$$\Delta^* = K_{h\,d} \cdot \gamma \cdot h^2 \cdot B;$$
$$B = (\lambda_p - \lambda_0) tg\left(45^0 + \frac{\varphi}{2}\right) / К_а E_{PL} (h/h_\delta)^m, \tag{3}$$

where $K_{h\,d} = -0.5 \div 1.5$ coefficient of lateral movement, depending on the type of soil: E_{PL} – plastic soil deformation modulus equal to $E_{PL} = 0.6 E_Y = 0.6\ E(h/\ h_\delta)^m$, $m = 0 - 2$ is the exponent; $h_b = (200 - \lambda_{pc}) / \gamma \cdot \lambda_p = 4.7$ *m* base depth, which corresponds to the regulatory module of deformation, from the load 200 kPa; the remaining dimensions are given in [27].

The fifth and sixth columns are the estimated lateral and shear stress on the piles.

The analysis table 1 shows that the horizontal limit displacement of soil from pile and corresponding friction force occur to a depth of 3 M (3rd column). Less the value of stress occurs when a further increase in depth.

Calculations show that in the table the SP 24.13330.2011 consists into a single column of values of ground resistance at the side surfaces are of the sand and clay soils is not correct. The large difference in the behavior of these soils under load, especially if the soils are with water.

For example, physico-mechanical characteristics of soil silty sand and clay at the rate of I_L= 0.4. In the Russian Constructions Norms and Regulations SNiP 2.02.03.85: silty sands have φ = 26^0– 36^0 depending on the porosity ratio E = 11–39 MPa and clay (loam absent), respectively φ =11^0–18^0, clutch 32–57 kPa, the soil deformation modulus E = 9–21 MPa.

Value $\tau_{x,y}$ obtained by the proposed solution, for these soils will be different, which is confirmed by the data of natural experiments [2].

Therefore, the table of the limiting values of friction forces on the lateral surface of the pile in the SP 24.13330.2011 are a particular case of solutions of the maximum the horizontal shift of the soil. Limit values of the friction forces recommended by the SP, if significant depths of immersion, as a rule, do not spring up [2].

The edge of the piles. After mobilization of the friction forces begin towork more actively the force the resistance of the soil under the tip piles. For disclosure of the behavior of the soil under the pile tip is used dimensionless chart vertical compression of the soil, presented in the form of nonlinear function [27]. The relative nature of this chart is not associated with a scale factor, allowing use of a single curve.

The values of vertical earth pressure on 1rm to the axis of symmetry of the piles on the entire range of action of the load is equal to [27]:

$$\sigma_{y,x} = K_{\text{v p}} \cdot K_s \cdot a[q_{\text{br}} + q_{1\text{br}} + \gamma \cdot x/tg(45^o - 0.5\varphi)]\lambda_v(\delta) \le \sigma^*_{y,x}, \tag{4}$$

where $\sigma_{y,x}$, $\sigma^*_{y,x}$ – vertical and the limit vertical pressure of the soil on the edge of the pile to the axis of symmetry (the first index "y" indicates the direction of stresses, the second "x" coordinate by the width of the piles; $K_{\text{V p}}$= $4 \div 6$ – coefficient of the vertical pressure, the larger value refers to dense soils; K_s = 0.8 - 1.2 – coefficient taking into account the immersing of piles, and is the largest dimension of the pile section, q_{br} , $q_{1\text{br}}$ – additional weight of the overlying soil and at the expense of the adhesion forces; γ – specific weight of soil; x is the horizontal coordinate of the considered point, counting from the face of the piles in the range $0 \le x \le 0.5b$ (b is the smallest dimension of the pile section; $\lambda_v(\delta) = \lambda_{pa}/\lambda_{aa}$ – function diagram of the vertical deformation [27].

Taking in the expression (4) $\lambda_v(\delta) = \lambda_v$ (where λ_v – limit value) get the limit value of the vertical pressure on the tip of the pile to the axis of symmetry.

Due to the small width of the piles, it is possible to take a rectangular plot of reactive ground pressure. Then taking into account (4) limiting of the resultant vertical pressure on the end piles is equal:

$$N = K_{\text{v p}} \cdot K_s \cdot a \cdot b[q_{\text{br}} + q_{1\text{br}} + 0.5\gamma \cdot b/tg(45° - 0.5\varphi)]\lambda_v \tag{5}$$

Example 2. To determine the ultimate bearing capacity of high pile grillage of reinforced concrete piles sunk 6m, section 30 x 30 cm. Soil base: φ = 20°; C = 0.022 MPa; γ = 19.7 kN/m3; λ_{pa} = 4.05, δ = φ; λ_{aa} =0.59; λ_v =6.86, $K_{\text{v p}}$ = 5, K_s = 1.0. Using the expression (5), with of the calculation friction forces on the lateral surface of the piles F_{fr} obtains (Fig. 4):

$$N = \cdot K_{\text{v p}} \cdot K_s \cdot n \cdot a \cdot b[q_{\text{br}} + q_{1\text{br}} + 0.5\gamma \cdot b/tg(45° - 0.5\varphi)] \cdot \lambda_v + n \cdot F_{\text{fr}} = 5 \cdot 1.0 \cdot 10 \cdot 0.09 =$$
$$= [118.4 + 60.43 + 0.5 \cdot 19.7 \cdot 0.3/0.7] \cdot 6.86 + \cdot 1145.6 = 6796.4 \text{ кН}$$

The experimental ultimate bearing capacity the high pile grillage was not achieved [2]. At sediment equal 70 mm the bearing capacity was of the order of 5100 KN. The bearing capacity on SNIP amounted to 4500 KN. On the experimental curve the sediment-load this corresponds of the sediment order of 55 mm .

The effect of construction of pile foundation at its carrying capacity

Low pile grillage (combined pile-slab foundation – PCB) increases the load carrying capacity due to the additional reactance of the ground from his slab. This is confirmed by experimental data [2]. This foundation is recommended to count as plate on elastic foundation with a variable in terms of the coefficient of elastic resistance of the soil in the SP 24.13330.2011. Depending on the position plate design relative to the surface of the soil it load-bearing capacity will be different (Fig. 5).

On the Figure 5, a and b bearing capacity of single pile or high pile grillage related to heaving soil from under the end of the pile and with by friction of soil on its side surface

Work low pile cap occurs in two stages. At the first stage it works similar to high pile grillage taking into account the additional resistance of the soil on the slab of the raft foundation (Fig. 5c). The second stage begins, when the proportion of pile cap to bearing capacity of pile foundation is about 30 – 35 %. Then the work included the compacted soil mass between the piles. (Fig. 5*d*). The author proposes determine the bearing capacity of low raft foundation with piles step ≤ 3*d* in the form of a conditional soil mass with the piles. The nature of its work is confirmed by the experiments of A. A. Bartolomey at extreme loads [2].

The expression of the resultant ultimate bearing capacity of the soil:

$$N = K_m \cdot a \cdot b[q_{br} + q_{1br} + 0.5\gamma \cdot b/tg(45° - 0.5\varphi)]\lambda_v + K_n \cdot E_b \cdot tg\varphi - \gamma \cdot V, \tag{6}$$

where K_m= 1.0–1.2 – generalized coefficient array; q_{br}, q_{1br}, λ_v – conventional sign is given in equation (4); K_N=1.0–1.2 - coefficient of uneven friction forces, depending on the step of the piles; E_b – resultant pressure on the side of the pile foundation, *V* – volume of the conditional foundation.

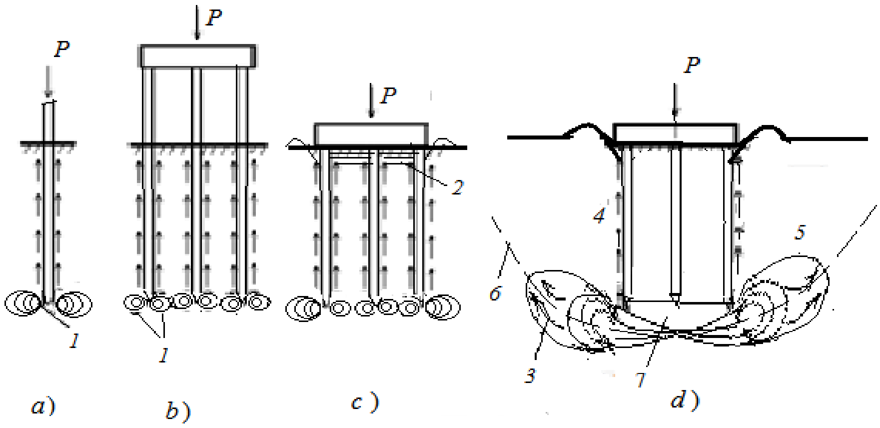

Figure 5. The active region constrained deformation of soil from variable loads:
***a*) single pile; *b*) high pile grillage; *c*, *d*) low-pile grillage**

Legend: 1 – boundary of the const-rained deformation of a bottom single and group of piles from the variable load; 2 – boundary of the zone of compaction of soil under the slab of the raft foundation. 3 – trajectories of movement of particles; 4 – the friction forces on the lateral surface; 5 – the boundary of the constrained deformation of conditional array; 6 – origin curve move; 7 ▯ lower boundary soil of the wedge sealing.

Example. 3. The constructions from example 2 to determine the bearing capacity of low pile grillage . The slab of the size in terms of *a* = 4.0 m; *b*= 1.3 m. The Length of pile 6 m. the foundation. Soil: K_m =1,1; φ = 20°; C = 0.022 MPa; γ = 19.7 kN/m³; α = 35⁰; λ_{pa}=4.05, δ=φ; λ_{aa}=0.59, δ=0.5 to φ; λ_v=6.86; K_n =1.2.

Lateral pressure on a conditional array have of the hydrostatic law. Limit load including self weight of the array, and the structures (6):

$$N = K_m \cdot a \cdot b[q_{br} + q_{1br} + 0.5\gamma \cdot b/tg(45° - 0.5\varphi)]\lambda_v + K_n \cdot E_b \cdot tg\varphi - \Sigma\gamma_i \cdot V_i, \\ = 1.1 \cdot 4{,}0 \cdot 1.3[19.7 \cdot 6 + 22/0.364 + 0.5 \cdot 19.7 \cdot 1.3/0.364]6.86 + \cdot\ 1641.8 \\ - 668{,}4 = 9364.3\ кН$$

Experienced the load on the foundation is not reaches carrying capacity and reaches 6000 KN. This load corresponds to the draught of the order of 70 mm [2]. Limit load on the Russian Constructions Normsand Regulations SNiP 2.02.03.85 is about 7000 KN. The comparison examples no. 2 and no. 3 shows that in the lower pile grillage plate increases the bearing capacity of pile foundation up to 30 %. In fact, this effect will be more, but there are restrictions on the offset.

The influence of the location of piles on effort into them

Load on pile grillage causes shear stresses in the area along the height of the piles. Intermediate lateral resistance of the pile decreases from the overlay plots of the shear stresses of the neighbouring piles (Fig. 6).The other thing is the voltage under the tip of the piles. On the one hand, the seal space during pile driving, have increases of the bearing capacity. On the other hand, the overlay plots of the voltages from the intermediate piles increases the reactive presure under its. This creates conditions of greater precipitation and thus a reduction of effort due to redistribution to other piles.

Experience shows, that in clay ground and silty and fine sands, bearing capacity of piles in the bush, generally reduced in comparison with the bearing capacity of single piles. The sands with medium-sized and large have it increases. The use of method of angular points in the determination of additional stresses within the edge of the piles, shows that the influence of adjacent piles leads to redistribution of effort of approximately 30 % [30]. Data full-scale have bearing capacity of the intermediate piles are lower than from the outside of the piles in from 20 to 40 % [2].

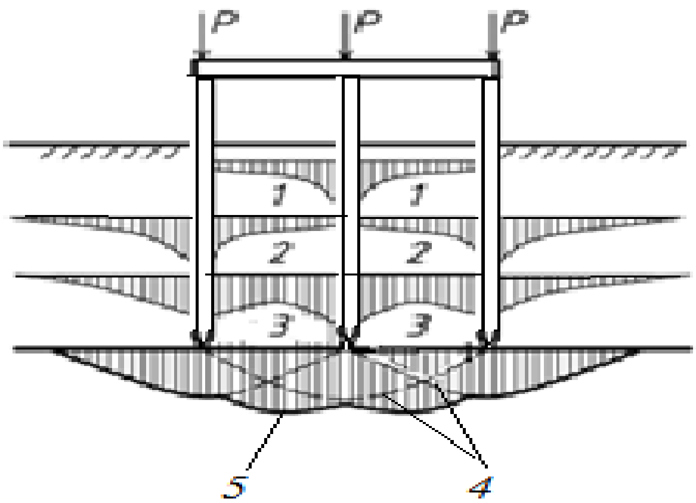

Figure 6. Summary plots of the tangential (1+2=3) and vertical stress (4+4=5).
Legend: 1, 2 – a plot of the tangential stresses in the cross-section for the central and outer piles;
4 – plot of the normal stress beneath the central and outer piles;
3, 5 – plot the resulting shear and normal stresses

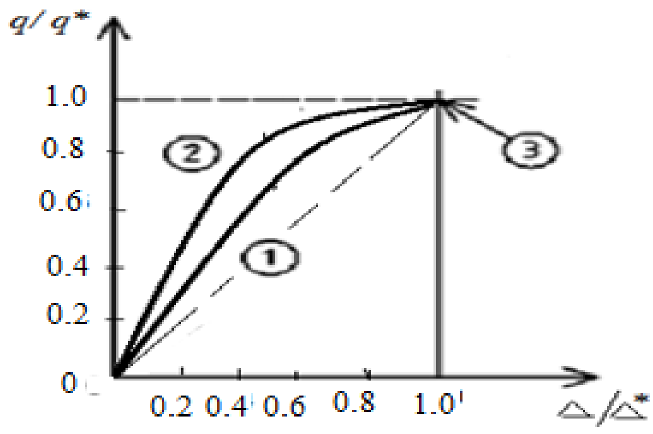

Figure 7. Schedule dimensionless relationship diagram precipitation subgrade from t he load depending on soil density of the base in dimensionless terms.
Legend 1 – loose soil; 2 – dense soil; 3 – coordinate of the point limit load

The sediment pile foundation

Sediment, wich implements the friction forces on the lateral surface. The force Friction in pile foundations involves in the work in two stages [2]. In the first stage, consolidation soil mass with the piles is of 10–15 mm. However, the load of perceived by the end face of the pile increases slightly to full mobilization of the friction forces on the lateral surface of the pile.

The second phase of the work from the lateral surface observed from the draught from 10–15 mm to 30–35 mm. At this stage, is as if "failure" of the piles foundation. It leads to an increase of the friction forces. Therefore, of the external load exerted on the pile at the beginning perceive the friction force of the side surface. To them requires a smaller offset than for the mobilization of reactive pressure on the tip of the piles. Maximum draught of a soil mass or a single pile, which implements the friction forces on the lateral surface are equal [27].

$$\Delta^*_{\mathrm{f}} = E_l \cdot tg\ \varphi\ / U \cdot \Sigma L_{\mathrm{i}} \cdot K_{b\ d\,\mathrm{i}},$$

where E_l is the resultant lateral pressure on the pile; U is the perimeter and L_i is the areas of the conventional length of an array or piles to the ground, $K_{b\ d\,\mathrm{i}} = 0.7 \cdot K_{\mathrm{a}} \cdot K_{\mathrm{pl}} \cdot K \cdot y$ – variable in depth coefficient of bed shear (K_{a} – anisotropy factor, K_{pl} is the factor of the plastic properties shear, K – coefficient of proportionality, y – the depth of the considered layer).

The vertical sediment that implements the force on an end face of the piles or piles of the array soil. After the exhaustion of the forces of friction, holds the load, the edge of the piles. Vertical pressure begins to rapidly increase until a complete loss of bearing capacity.

In the conventional array of draught of the basement increases gradually and it is impossible to distinguish clearly the ultimate load [2]. In connection with sediment limit necessary to limit the load for the maximum allowable precipitation. Analysis of pile foundation shows that whatever the design of single pile or pile grillage, the nature of their work is similar**.**

In the both of the application cases there is restricted from the subsidence of soil.

The relative diagram connection (8) based (4), (7) and (8) allows to determine direct and inverse problem using the maximum allowable draught of pile foundation (Fig. 7).

The marginal precipitation conditional massif (piles), (Fig. 5).

The marginal precipitation piles or conditional array to the width 1пог m, (Fig. 5, point 3) equals [27]:

$$\Delta^* = \mathrm{K}_g \cdot \gamma \cdot b^2 B;$$
$$B = (\lambda_{pa} - \lambda_{aa}) tg^2(45^0 + 0.5\varphi)/K_a \cdot E_{pl}[1 + \left(\frac{y}{y_1}\right)^m] tg^2\,(45^0 + 0.5\varphi), \tag{7}$$

where $K_{\mathrm{g}} = 0.4–0.8$ – generalized coefficient taking into account the closeness of the calculated scheme; b is the width (smallest dimension) of a conditional pattern (piles); λ_{pa}, λ_{aa} – pressure coefficients of passive and active pressure of the compacted soil wedge inclined at an angle ($45^0 - 0.5\varphi$) to the vertical; $E_{pl,y} = 0.8E[1 + \left(\frac{y}{y_1}\right)^m$ – the plastic deformation modulus of soil at depth y; y and y_1 – considered and adopted a single depth; m is the exponent, $0 \le m \le 1$. The rest of the notation is given in equation (3).

The author believes that the sediment pile foundation (piles) includes the of sediment that implements the friction force at the lateral surface. The marginal precipitation (7) and the load (4) (point 3 on the chart Fig. 7) allow to determine the values of precipitation throughout the load range.

$$\Delta_{pl} = \Delta^* \left(\frac{q}{q^*}\right)^n \tag{8}$$

where n is the exponent (n =1–3). When $n = 1$ is a linear dependence (dotted line, Fig.7), the weaker the soil has a smaller curvature (curve 1, for $n = 3$).

Example 4: Determine the limit for sediment in pile foundation shown in example 3. The value of modulus of deformation with depth is $E_{\mathrm{pl.y}} = 36.7$ MPa.

$$\Delta^* = \text{K}_g \cdot \gamma \cdot b^2 B = 0.4 \cdot 19.7 \cdot 1.3^2 \cdot 0.007 = 0.093\ m,$$

The value of precipitation of the pile cap at 40% load limit 9364.3 KN is equal to:

$$\Delta_{pl} = \Delta^* \left(\frac{q}{q^*}\right)^{1.5} = 0.093 \cdot 0.25 = 0.023\ m$$

The sediment of the low pile grillage with this load amounted to 0.025 m [2]. Specifying the maximum permissible amount of displacement of the foundation structures from equation (8) we get the desired maximum load.

Model the combined stiffness coefficient of the soil

Each strip in Figure 1 due to the variable length has a different degree of resistance to compression of the soil. In design scheme that corresponds to the different stiffness of the soil (variable coefficient).Variable coefficient better reflects the work of the foundation. Picking up the variation of the ratio bed, we provide the right character of precipitation.

Using the program CROSS procedure of successive approximations as applied to foundations can more accurately determine the stiffness coefficient of the soil [31]. The program CROSS is part of the package SCAD Office and provides both stand-alone operation and communication with integrated system of strength analysis of structures Structure CAD (SCAD) [32]. This procedure of successive approximations, according to the author, it is permissible for light loads on the foundation. Because there is no law of variation of stiffness of soil from the full load cycle and is not considered redistribution of the contact pressure of the marginal plastic areas.

The author proposes a mechanical model of the soil with a structural element acting on the lateral surface (Fig. 8 a) and of the low end the piles (figure 8 b). In the model, except of elastic Hooke body (H) and of plastic body of the Saint Venant (SV) , also have a structural element (S).

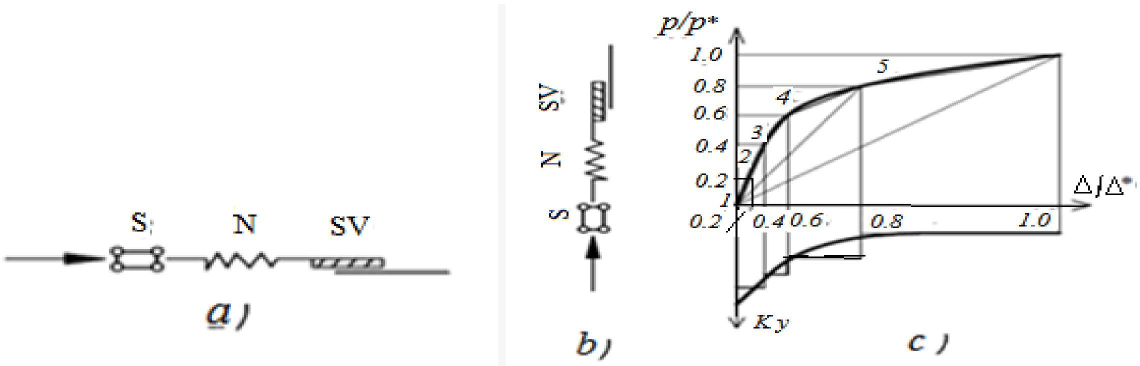

Figure 8. Mechanical model of compression of the soil taking into account the structural element in the side (*a*) end (*b*) surfaces of the piles. Dimensionless curve pressure – lateral displacement (pressure – vertical offset) and a variable coefficient of stiffness of the soil correspond to the model (*c*).

This element functionally connects of the curve pressure-displacement according the type of connection (Fig. 8). This model is similar to the adopted model for the aoundation [29].

The springs located both on the lateral surface of the pile (Fig. 8, *a*) and on its end face (Fig.8, *b*). The number of turns of the spring depends on the depth of the active zone of the soil. The springs resist compression more or less elastically under small external loads. The load increases to the limit value changes the value of resistance to compression of the springs due to the structural element (S). This leads to a nonlinear dependence of the "pressure-displacement".

Dimensionless curve "pressure-displacement (pressure-draught") is shown in Figure 8, in the upper part. Schedule of changes in relative stiffness between the level of load shown in Figure 8*b*, the lower part. The dimensionless character of the two curves is similar, but the degree of curvature is different. The dimensionless nature of the relationship allows you to use the curve to describe the interaction of the side or end portions of the pile with the soil from the load irrespective of the scale of the building. The conditional transfer of the stiffness coefficient of the soil in absolute value sets the regularity of this change on the side or lower surfaces of the piles. For example, each length segment of the lateral surface of the pile or the width of its edge, depending on the load will correspond to a specific area of the connection curve of the contact and hence of the curve the stiffness of the soil (Fig. 8, *c*).

Expressions (1–7), in addition to independent values, according to Figure 8 allow us to determine the coefficients of stiffness of the soil elements to pile foundation. These coefficients are used as source data in the proposed calculation of pile foundation using the software complex "SCAD". For this of the purpose, calculated ultimate horizontal and vertical loads and the corresponding ultimate displacements.

The author believes that the coefficient of stiffness is in some respects is the type of the discrete model of the environment. So reducing the length of the element to the minimum size allows to obtain a family of discrete independent coefficients, whose values can be described the necessary desired function or set numerically.

In relation to the design scheme of pile grillage is used of the frame rack with different stiffness of the rigel and racks. The nature of the work structures in the soil is determined by its stiffness characteristics of the system elements: beams, uprights and ground.

Example 5. To calculate the reconstructed embankment on the canal Griboedova in St Petersburg. Original data: The old quay was built in the beginning of the last century (Fig. 9). In front of the old embankment to the form of rigid raft foundation of rubble concrete which masonry is based on three rows of wooden piles, and erected a new hard grillage. It has a crossbar of variable cross section of reinforced concrete on pile foundation of two rows of bored piles, 16 m long, with a diameter of 0.6 m. Step piles across the cordon line is 2.35 m, and respectively along the line of the cordon 1.4 m. Characteristics of the soil include four layers of the loam from the fluid (Kb = 350÷1750 kN/m^3) up plastic (Kb = 21300÷39700 kN/m^3), layer of sandy loam (Kb = 58000÷70000 kN/m^3), sand (Kb = 73000÷75000 kN/m^3), the coefficient on the tip of the piles, Kb v= 14792 MP/m3. The calculation with using the program SCAD performed by student of A. Melentiev. Results of the comparison of calculations are given in table 2.

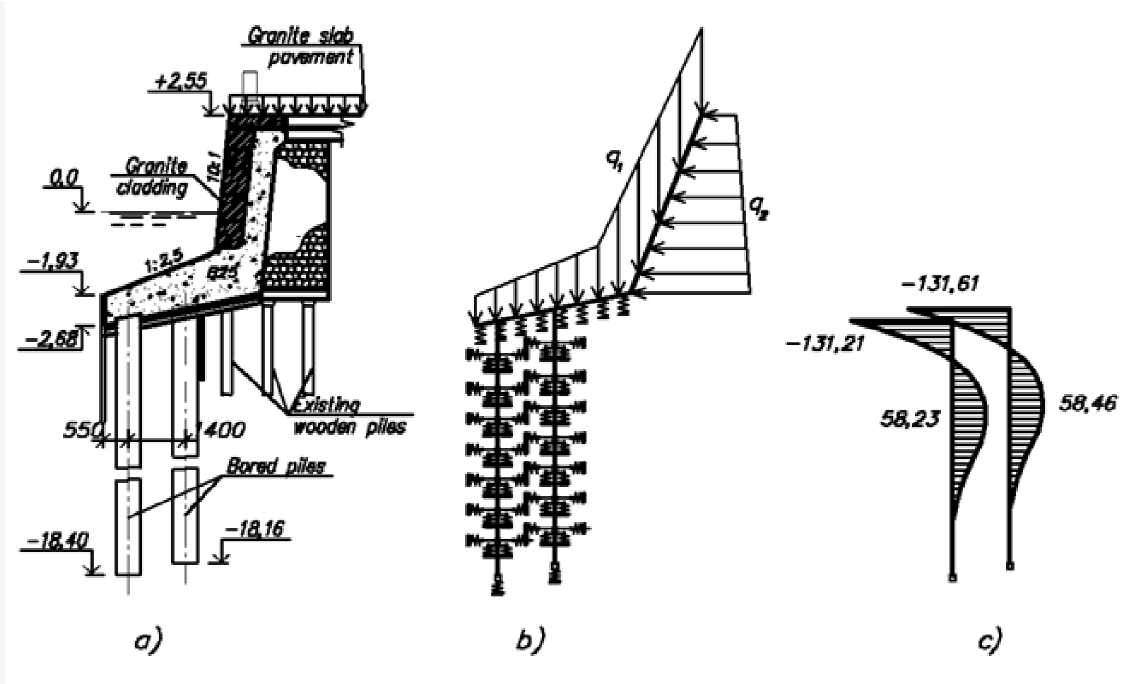

Figure 9. To the calculation of the city's waterfront. a) Cross section. b) design scheme. b) Plot bending moment in the piles

Table 2. Results of calculations

Name	Calculati for a SNP [26]	The calculation for a generic method
Moment in the topic sealing of the first pile, kNm	-135.23	-131.21
Moment at the topic sealing of the second pile, kNm	-135.23	-131.61
Moment in the span of the first pile, kNm	-	58.23
Moment in the span of the second pile, kNm	-	58,46
The effort in the first pile, kN	-470.0	-417.92
The effort in the second pile, kN	64.16	12.02
Horizontal displacement of the top, mm	-	4.87

Results and Discussion

Pile when submerged in the soil condenses it in the transverse and longitudinal directions. Seal give the effect on the piles lateral and vertical pressure of soil. The friction force along the length the piles depends on the value of lateral pressure. Analysis of example 1 shows that the maximum friction force occurs at a depth up 3 the meters. Further increase in depth does not implements the maximum force of the lateral pressure of soil. This leads to a decrease in the values of the tangential stresses along the length of the pile. The Russian Building Regulations SNIP [26] recommends a limiting value of the friction forces along the length of the piles, which usually is not confirmed by experimental data.

The work of pile foundation depends on the load, position of the grillage and the distance between the piles. The author gives of the engineering solution, in which the limit load and the sediment pile foundation, depending on conditions, determined by the number piles or by the ground massive. The analysis of examples No. 2 and No. 3 shows that the calculated values are comparable with experimental data A. A. Bartholomew [2]

Bearing capacity of pile foundation in the Russian Set of Rules SP 24.13330.2011 is below the limit load, so as by the limited by it sediment. However, in the proposed method of taking into account the allowable residue it is 15–25 % higher than in the SP 24.13330.2011.

Analysis of example No. 4 showed that the efforts in the pillars of the city's waterfront in the form of lower pile grillage in the proposed method, and SNIP [26] practically coincide.

Chart of the load-displacement allows solving in the proposed method direct and inverse problems for the entire load range.

Conclusions

1. The author proposed the variant of calculation of pile foundation using of the engineering theory of ground contact pressure.
2. This variant uses the mechanism of influence of piles in the ground on the magnitude of lateral and vertical seals.
3. The friction force on the lateral surface of the pile is variable and depends on the magnitude of lateral soil pressure on it. The normative document Russian Set of Rules SP 24.13330. 2011 gives the maximum value of the friction force. The maximum value, trenie can not occur at depths greater than 3–4 mm. In addition, SP 24.13330.2011 gives the joint values the calculated resistance of sands and clayey soils. This are the basis for criticism, as each type of soil has its own physical and mechanical characteristics associated with the friction forces.
4. The proposed option determines the jet pressure of the soil on the edge of the piles or on a conditional piler foundation for the entire load cycle.
5. Bearing capacity of pile Foundation additionally depends on the location of the plate grillage. The influence of the plate begins to emerge, usually with a load more friction forces on piles.
6. In the proposed calculation takes into account the mutual influence of piles on the distribution of forces in pile grillage.
7. The value of the precipitation of pile foundation gets from a dimensionless curve the "pressure-settlement" for the entire load cycle.

8. The author proposed a mechanical model of the ratio of stiffness of soil with the influence of the structural element. The stiffness coefficient of the soil load is determined based on a curve of deformation.

9. Analysis of sample data showed that the efforts in the pillars of the city's waterfront in the form of lower pile grillage in the proposed method, and SNIP [26] practically coincide.

10. In the calculation of structures using the model of the stiffness of the soil, special attention must be paid to the reliability of this characteristic, which substantially depends on the efforts and peremescheniya structural members. Each of those values recommended in the standards, have a broad range of values and require adjustment.

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