DOI 10.36622/VSTU.2021.50.2.005

UDC 625.7/.8:624.154

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REINFORCEMENT OF SUBGRADE DOUBLE-CONE PILES

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Statement of the problem. The problem of designing the reinforcement method of weak seasonally freezing soils in subgrade base by using double-cone hollow piles and geotechnical materials for roads in the northern regions of the Russian Federation is investigated.

Results. As a result of the study, the construction of the subgrade in the form of pile strip foundation of double-cone piles reinforced by geotechnical materials on weak heaving soils taking into account traffic loads and weight of subgrade is considered. A method has been developed of calculating the road base in the form of pile strip foundation of double-cone piles reinforced by geotechnical materials on weak heaving soils taking into account traffic loads and weight of subgrade is considered. The developed method of calculation is based on the formation of soil compaction zones in the near-pile space as a result of pile driving into the ground, which leads to an increase in the structural strength of the weak soil, and also takes the arch effect that occurs in the soil between adjacent pile heads.

Conclusions. The obtained research results allow us to conclude that the developed subgrade design and its calculation method are of great interest both to scientists and design engineers, and can be used in construction practice.

Keywords: double-cone piles, weak soils, subgrade, frost heaving, porosity coefficient, soil structural strength, pile strip foundation, tridimensional geogrid, geotextile.

Introduction. According to the normative literature [9], it is allowed to build a subgrade on a subsoil reinforced with rigid piles in the construction of highways on soft soils. However, due to the instability of piles to the effects of frost heaving of the soil such a subgrade is not recommended for use in areas of seasonal freezing of soils. The annual soil heaving is 5—10 cm and makes the road impossible to use. Combating this calls for the use of piles with the length of about 10—15 m which is impractical according to economic calculations.

Hence, an urgent task is to develop a new constructive solution including the construction of a subgrade on a soil foundation, reinforced with double-cone piles, resistant to frost heaving of soils. It also seems necessary to develop a method for calculating soil heaving based on the load-bearing capacity. This technique is designed to ensure the reliability of the design and construction of highways in places experiencing seasonal soil freezing.

Double cone piles were developed at the Department of Roads and Bridges of the Perm National Research Polytechnic University (PNRPU) [2, 6, 8, 12, 14—16] and are a hollow structure with a taper towards the pile point and head made by means of centrifugation.

A distinctive feature of these piles is their resistance to frost heaving due to the unique shape of their structure. Unlike prismatic piles, they do not change their design position whose uplift is 6—10 cm annually resulting to the road being impossible to use. Thus prismatic piles were not used in the construction of roads on weak water-saturated clay seasonally freezing heaving soils [8]. The design of a double-cone pile is given in Fig. 1.

As a result of experimental and theoretical studies, an effective construction of the subgrade on the soil foundation reinforced with double-cone piles has been developed (Fig. 2).

Fig. 1. Construction of the pile:

L^B is the length of the upper part;
 d_f is the normative depth of freezing

Fig. 2. Subgrade on a reinforced foundation by double-cone piles:

a and d_i are geometric characteristics of the pile, diameter of the heads and joining of the planes of the upper and lower cones of the pile respectively; B is the distance between the piles based on the diameter of joining of the planes of the upper and lower cones of the piles a

1. Influence of the soil compaction zone around the piles on the change in the load-bearing capacity of a weak subsoil. The foundations for identifying the distance between the piles in the pile foundation is set forth by B. S. Yushkov [1] an analytical method for calculating the soil compaction zone around the piles. One of the major factors affecting the change in the bearing capacity of pile foundations over time is the formation of soil compaction zones caused by pile driving. The compaction zones of water-saturated clay soil depend on its natural density, method of pile driving, number of piles in the cluster, distance between the piles, cross-section of the piles and the natural coefficient of porosity.

In order to identify the size of the soil compaction zone around the piles, due to symmetry, it will suffice to consider $\frac{1}{4}$ of the selected pile foundation. As a result of pile driving, soil particles displaced by the pile are displaced in the horizontal layer Δh . The soil displaced by the driven pile compacts the adjacent soil, as a result of which the porosity coefficient in the near-pile space decreases from ε to $\varepsilon_{\min}$. The soil is squeezed out of the pile into a zone of the width L . This zone includes the sections — I, II (Fig. 3).

The condition of the balance of particles displaced in the horizontal layer enables one to obtain an expression for the width of the compaction zone L через ε и $\varepsilon_{\min}$:

$$L = \frac{(\varepsilon - \varepsilon_{\min}) \left(1.5 \sqrt{\frac{1 + \varepsilon}{\varepsilon - \varepsilon_{\min}}} - 3.5 \right)}{(1 + \varepsilon)(1 + \varepsilon_{\min}) \mathcal{I}} d_0, \quad (1)$$

where $\mathcal{I}$ is the value describing the quadratic law of decreasing the coefficient of soil porosity from ε to $\varepsilon_{\min}$:

$$\mathcal{I} = \frac{1}{2\sqrt{1 + \varepsilon} \sqrt{(\varepsilon - \varepsilon_{\min})}} \ln \frac{\sqrt{(\varepsilon - \varepsilon_{\min})} + \sqrt{1 + \varepsilon}}{\sqrt{1 + \varepsilon} - \sqrt{(\varepsilon - \varepsilon_{\min})}} - \frac{1}{1 + \varepsilon}. \quad (2)$$

The porosity in zone L decreases from ε at the border of the compacted zone to $\varepsilon_{\min}$ at the border of the pile.

Fig. 3. Calculation scheme for determining the compaction zone: d_0 is the diameter of the pile

Having obtained the width of the compaction zone L , the distance between the piles in the pile foundation can be calculated using the formula:

$$B = 2L, \quad (3)$$

where B is the distance between the piles in the light.

Using the analytical method for calculating the soil compaction zone around the piles, the soil compaction zone around the double-cone pile is determined with the following dimensions:

- diameter at the top and bottom ends $d_{01} = 30$ cm;
- diameter along the line of conjugation of the planes of the upper and lower cones $d_{02} = 50$ cm;
- the full length of the double-cone pile taken equal to 3 m (the upper double-coned part — 1 m, lower cone part — 2 m).

We set and the Let us take the coefficient of soil porosity to be $\varepsilon = 0.80$ and at the maximum density obtained by driving the piles to be $\varepsilon_{\min} = 0.65$.

Using formula (2), the value characterizing the quadratic law of decreasing the coefficient of soil porosity is found from ε to $\varepsilon_{\min}$.

The frost resistance coefficient is represented by the regression equation:

$$\begin{aligned} \mathcal{I} &= \frac{1}{2\sqrt{(1+\varepsilon)}\sqrt{(\varepsilon-\varepsilon_{\min})}} \ln \frac{\sqrt{(\varepsilon-\varepsilon_{\min})} + \sqrt{(1+\varepsilon)}}{\sqrt{(1+\varepsilon)} - \sqrt{(\varepsilon-\varepsilon_{\min})}} - \frac{1}{1+\varepsilon} = \\ &= \frac{1}{2\sqrt{(1+0.8)}\sqrt{(0.8-0.65)}} \ln \frac{\sqrt{(0.8-0.65)} + \sqrt{(1+0.8)}}{\sqrt{(1+0.8)} - \sqrt{(0.8-0.65)}} - \frac{1}{1+0.8} = 0.0152. \end{aligned}$$

The width of the soil compaction zone in the pile space at $d_{01} = 30$ cm is

$$L_1 = \frac{(\varepsilon - \varepsilon_{\min 1}) \left(1.5 \sqrt{\frac{1+\varepsilon}{\varepsilon - \varepsilon_{\min}}} - 3.5 \right)}{(1+\varepsilon)(1+\varepsilon_{\min 1})\mathcal{I}} d_{01} = \frac{(0.8 - 0.65) \left(1.5 \sqrt{\frac{1+0.8}{0.8-0.65}} - 3.5 \right)}{(1+0.8)(1+0.65)0.0152} 30 = 173 \text{ sm.}$$

The width of the soil compaction zone in the space adjacent to the pile at $d_{02} = 50$ cm is given by the following:

$$L_2 = \frac{(\varepsilon - \varepsilon_{\min}) \left(1.5 \sqrt{\frac{1+\varepsilon}{\varepsilon - \varepsilon_{\min}}} - 3.5 \right)}{(1+\varepsilon)(1+\varepsilon_{\min})\mathcal{I}} d_{02} = \frac{(0.8 - 0.65) \left(1.5 \sqrt{\frac{1+0.8}{0.8-0.65}} - 3.5 \right)}{(1+0.8)(1+0.65)0.0152} 50 = 282 \text{ sm.}$$

Considering the obtained results of identifying the values of the widths L_1 and L_2 , the width of the soil compaction zone in the space adjacent to the pile as a result of putting up a pile is plotted (Fig. 4).

The width of the soil compaction zone as a result of putting up the pile in the plane of the upper end of the pile (on the surface of soft soil) is $L_1 = 282$ cm. This is due to the passage of a larger pile diameter $d_{02} = 50$ cm through the surface of soft soil in the process of putting it up.

Fig. 4. Diagram of the width of the soil compaction zone as a result of putting up a pile:

d_{01} is the diameter at the top and bottom of the pile;

d_{02} is the diameter along the line of joining of the planes upper and lower pile cones;

L_1 is the width of the soil compaction zone by the diameter of the lower end of the pile d_{01} ;

L_2 is the width of the soil compaction zone by diameter d_{02} and on the soil surface

As the coefficient of soil porosity drops from ε to $\varepsilon_{\min}$ in the space adjacent to the pile as a result of putting up the pile, the structural strength of the soil increases:

$$\text{from } P_{str1} \text{ to } P_{str2} \quad (P_{str1} < P_{str2}). \quad (4)$$

where $P_{str1} = 1.0 \text{ kg/cm}^2$ is the natural structural strength of soft soil at the maximum porosity coefficient ε ; P_{str2} is the highest structural strength of soft soil with the minimum coefficient of porosity $\varepsilon_{\min}$ obtained as a result of putting up the pile in the space adjacent to it.

The structural strength of the soil is inversely proportional to the change in its porosity coefficient [1] using the ratio:

$$\begin{aligned} \frac{\varepsilon}{\varepsilon_{\min}} &= \frac{P_{str2}}{P_{str1}}, \\ P_{str2} &= \frac{\varepsilon \cdot P_{str1}}{\varepsilon_{\min}}. \end{aligned} \quad (5)$$

When the coefficient of soil porosity changes from $\varepsilon = 0.80$ to $\varepsilon_{\min} = 0.65$, the structural strength $P_{str1} = 1.0 \text{ kg/cm}^2$ changes to P_{str2} using the formula (5):

$$P_{str2} = \frac{\varepsilon \cdot P_{str1}}{\varepsilon_{\min}} = \frac{0.8 \cdot 1.0}{0.65} = 1.23 \text{ kg/sm}^2.$$

2. Identifying the distance between the piles in the pile foundation. After obtaining the values of the width of the compaction zones L_1 and L_2 , the distance between the piles in the pile foundation is identified according to the formula (3):

$$B_1 = 2L_1 = 2 \cdot 173 = 346 \text{ sm},$$

$$B_2 = 2L_2 = 2 \cdot 282 = 564 \text{ sm}.$$

Using the two obtained values B_1 and B_2 , the distance between the piles is taken to be $B_2 = 564$ cm. Within the space B_2 , the soil will have a structural strength $P_{str2} = 1.23$ kg/cm² (Fig. 5).

Fig. 5. Section of the subgrade

along the axis of the pile foundation:

1 — subgrade; 2 — geocellular material;

3 — geotextile material;

4 — the gap formed during putting up the pile between the upper cone and natural soil

filled with sand or gravel;

5 — solid ground rocks;

d_{01} — diameter at the top and bottom of the pile;

d_{02} — diameter along the line of the joining of the planes of the upper and lower pile cones;

L_1 — width of the soil compaction zone by the diameter of the lower end of the pile d_{01} ;

B_2 — the distance between adjacent piles

Reinforcement of the subgrade structure with double-cone piles increases the load-bearing capacity of a weak subgrade by increasing its structural strength from $P_{str1} = 1.0$ kg/cm² to $P_{str2} = 1.23$ kg/cm² as a result of the formation of soil compaction zones in the pile space during putting up the pile. For the normal operation of highways, without the development of unacceptable deformations, the following condition must be met:

$$\delta_{zh} \leq [\delta_{zh}]; \quad (6)$$

$$[\delta_{zh}] = \frac{P_{str2}}{[n]}, \quad (7)$$

where δ_{zh} is the value of the total stress from the load during the movement of transport and the own weight of the subgrade, kg/cm²; $[\delta_{zh}]$ is the maximum permissible stress on the surface of soft soil, kg/cm², which is given by the formula:

$$[\delta_{zh}] = \frac{P_{str2}}{[n]} = \frac{1.23}{1} = 1.23 \text{ kg/sm}^2 \quad (8)$$

where $[n] = 1.0$ is the safety factor; P_{str2} is the highest structural strength of soft soil in the space adjacent to the pile with a minimum porosity coefficient ε_{min} obtained as a result of putting up the pile.

3. Collection of the loads acting on the subgrade. The total stress due to the own weight of the subgrade and the load during vehicle movement considering the correction factors f_{fs} and f_q , is given by the formula (8):

$$\sigma'_c = f_{fs} \gamma h + f_q W_s, \quad (9)$$

where $f_{fs} = 1.0$ is the correction factor for the load from the weight of the subgrade on the specific gravity of the soil; f_q is the correction factor for an external applied load (traffic load); $\gamma = 1.3 \text{ т/м}^3$ is the average specific gravity of the subgrade; $h = 0.5 \text{ м}$ is the height of the subgrade; $W_s = \delta_z$ is the uniformly distributed additional traffic load identified by means of the soil mechanics formula (Boussinesq's formula) [4]).

The last formula enables one to identify the stresses in the soil mass from the action of a vertical concentrated force applied to the surface of a linearly deformable half-space according to the diagram below (Fig. 6). The stresses on the surface of soft soil from the load during the movement of transport, presented in the form of a concentrated force, will be greater than those from the uniformly distributed load over the area of the wheel track, i.e. considering the most unfavorable combination of loads.

$$\delta_z = \frac{K \cdot P}{z^2}, \quad (10)$$

where K is a coefficient depending on the ratio r/z , $K = f(r/z)$ as taken from Table 6.1 [4]; $P = 10 \text{ т}$ is the design axle load of the vehicle; $z = 0.5 \text{ м}$ is the vertical distance for points on the surface at which the stress δ_z is identified (at a subgrade height of 0.5 m).

Fig. 6. Scheme for calculating voltages on the surface of soft soil from the load during the movement of vehicles: M is a point on the surface of soft ground, in which the voltage δ_z is identified; z is the vertical distance to point M ; r is the horizontal distance to point M

The results of identifying the values of stress δ_z at various points on the surface of soft soil are presented in Table.

Table

Identifying the stresses δ_z

Number of the point of identifying the stress	$r, \text{ m}$	$z, \text{ m}$	r / z	K	$\delta_z, \text{ t/m}^2$
1	0	0.5	0	0.4775	19.1
2	0.5	0.5	1	0.0844	3.376
3	1.0	0.5	2	0.0085	0.34
4	1.5	0.5	3	0.0015	0.06
5	2.0	0.5	4	0.0004	0.016
6	2.5	0.5	5	0.0001	0.004

Using the obtained δ_z values, the maximum $\delta_z = 1.9 \text{ kg/cm}^2$ is selected, which corresponds to the place under the load application point (No. 1) and is given by the formula (9):

$$\delta_z = \frac{K \cdot P}{z^2} = \frac{0.4775 \cdot 10}{0.5^2} = 19 \text{ t / m}^2 = 1,9 \text{ kg / sm}^2; \quad (11)$$

$$\sigma'_c = f_{fs} \gamma h + f_q W_s = 1.0 \cdot 0.13 \cdot 0.5 + 1.0 \cdot 1.9 = 1,965 \text{ kg / sm}^2 = 196,5 \text{ kN / m}^2. \quad (12)$$

4. Consideration of the arched effect in soils. Due to considerable differences in the deformation characteristics of piles and the surrounding soft soil, the distribution of vertical stresses along and across the base of the subgrade is uneven. Therefore an arched effect might be observed.

The arched effect that occurs in the soil between adjacent pile heads causes additional vertical stresses on the pile heads. The ratio of vertical stresses at the pile heads to the average vertical stresses at the base of the subgrade P'_c / σ'_c can be estimated by means of the Martson formula [17] for the designed underground water pipelines:

$$\frac{P'_c}{\sigma'_c} = \left[\frac{C_c d_{01}}{h} \right]^2, \quad (13)$$

$$P'_c = \sigma'_c \left[\frac{C_c d_{01}}{h} \right]^2, \quad (14)$$

where P'_c is the additional vertical stress on the pile head arising between adjacent heads as a result of the arched effect in soils, kN/m^2 ; $\sigma'_c = 196.5 \text{ kN/m}^2$ is the total stress from the own

weight of the subgrade and the load during traffic considering the correction factors; C_c is the arch coefficient for rack piles:

$$C_c = 1.95 \frac{h}{d_{01}} - 0.18 = 1.95 \frac{0.5}{0.3} - 0.18 = 3.07.$$

Let us insert certain values σ'_c and C_c into formula (13) and get additional vertical stresses on the pile heads as a result of the arched effect that occurs in the soil between the adjacent pile heads:

$$P'_c = \sigma'_c \left[\frac{C_c d_{01}}{h} \right]^2 = 196.5 \left[\frac{3.07 \cdot 0.30}{0.50} \right]^2 = 666.7 \text{ kN / m}^2.$$

Then using the formula in [17], the distributed load was calculated, which is perceived by the geocell material between the adjacent pile heads:

$$W_{T1} = \frac{s \cdot \sigma'_c}{s^2 - d_{01}^2} \left[s^2 - d_{01}^2 \frac{P'_c}{\sigma'_c} \right], \quad (15)$$

where $s = B_2 + d_{02} = 5.64 + 0.5 = 6.14 \text{ m}$ is the the distance between the axes of the adjacent piles.

$$W_{T1} = \frac{s \cdot \sigma'_c}{s^2 - d_{01}^2} \left[s^2 - d_{01}^2 \frac{P'_c}{\sigma'_c} \right] = \frac{6.14 \cdot 196.5}{6.14^2 - 0.3^2} \left[6.14^2 - 0.3^2 \frac{174.74}{196.5} \right] = 1199.60 \text{ kN / m}.$$

The reaction of the underlying soil under the geogrid between the heads of adjacent piles is given by the formula:

$$W_{T2} = P_{str2} \cdot (s - d_{01}) = 123 \cdot (6.14 - 0.3) = 718.3 \text{ kN / m}. \quad (16)$$

The distributed load, which is perceived by the geogrid between the adjacent pile heads, is calculated as:

$$W_T = W_{T1} - W_{T2} = 1199.60 - 718.3 = 481.28 \text{ kN / m}. \quad (17)$$

Knowing the magnitude of the load that is perceived by the geocell material between the adjacent heads of the W_T piles, the total tensile force in the geocell material can be identified using the formula:

$$T_{rp} = \frac{W_T}{2d_{01}} \sqrt{1 + \frac{1}{6\epsilon}}, \quad (18)$$

where $\epsilon = 4\%$ is the maximum possible ultimate stretching of the geocell material, which is given by the formula:

$$\epsilon = 0.04(s - d_{01}) = 0.04(614 - 30) = 23.36 \text{ sm}, \quad (19)$$

$$T_{rp} = \frac{W_r}{2d_{01}} \sqrt{1 + \frac{1}{6\epsilon}} = \frac{481.28}{2 \cdot 0.30} \sqrt{1 + \frac{1}{6 \cdot 0.2336}} = 805 \text{ kN/m}^2 = 8.05 \text{ kg / sm}^2.$$

After obtaining the value of the total tensile force in the geocell material T_{rp} , the maximum tensile force per unit of the reinforcing geocell material T_r can be given by the formula:

$$T_r = T_{rp} \cdot \delta = 8.05 \cdot 0.12 = 0.97 \text{ kg / sm}, \quad (20)$$

where $\delta = 0.12 \text{ sm}$ is the wall thickness of the geogrid taken based on [13].

Let us check the tensile strength condition of the geocell material according to the formula:

$$\frac{T_D}{f_n} \geq T_r, \quad (21)$$

where $T_r = 0.97 \text{ kg/cm}$ is the maximum tensile force per unit of reinforcing geocell material; $T_D = 5 \text{ kg / cm}$ is the tensile strength of a geocell material (a spatial geogrid of the «ST» brand with a cell size of $20 \times 20 \text{ cm}$ and a height of 15 cm) taken based on [13]; $f_n = 1.0$ is the coefficient of reliability considering the class of the structure (road) is taken based on [11].

At $f_n = 1 \rightarrow 5 \text{ кг / см} \geq 0.97 \text{ кг / см}$ the condition is met.

The efficiency of the structure is improved considerably if the geocell material is laid on top of the geotextile material, which prevents the aggregate particles from passing through the geocell material into soft ground.

Conclusions. As a result of experimental and theoretical studies, an effective construction of the subgrade has been developed, protected by a patent for a useful model No. 156221 [7], which ensures the reliability of the design and construction of highways in spots experiencing seasonal freezing of soils. Considering domestic and foreign experience in the construction of highways on soft soils [3, 5, 10, 11, 18—29], it can be concluded that strengthening the structure of the subgrade with double-cone piles reinforced with geotechnical materials is of special interest. This is due to the novelty of the approach to addressing this engineering problem in the construction of highways in severe climatic and engineering and geological conditions. The structure of the subgrade on a reinforced subsoil with double-coned piles reinforced with geotechnical materials can be considered one of the alternative viable options for constructing the subgrade by replacing soft soil.

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