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THEORY AND DESIGN SCHEME OF ROAD ENGINEERING STRUCTURES FROM PIPE GROOVE

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Statement of the problem. Designing a welded tubular pile is a new competitive variety of retaining walls used in modern construction. Developing calculation method for designing and investigating such systems is an important issue.
Results. The article provides a description and algorithms of the developed method of calculating engineering structures from pipe groove within road engineering structures. The theoretical basics, description of design diagrams, sequence of the calculation by means of the finite element method, a set of tests to limit state are presented. A calculation example is given.
Conclusions. The solution of practical problems and algorithmization of calculation tribosphenic systems within the road engineering structures is obtained. The results of the study are suitable for use in calculations of other designs of flexible retaining walls of groove type.

Keywords: welded tubular pile, calculation, design, road retaining walls, bridge foundations.

Introduction

The last decade has seen engineering structures developing into a new direction when enveloping systems starting emerging as support walks from tubular welded piles [1—4, 6, 9, 10, 12, 17, 20]. They consist of a steel pipe and welded clutched joints (Fig. 1). An internal vacuum of the pipe is filled with sand-cement mix (5:1 ratio), monolith ferroconcrete or soil nuclear that is designed considering the length within the base.

The advantages of tubular welded piles is a high level of ready-made quality, strength and simplicity of aligned joints, suitability for quick construction and operation in severe climate conditions. All of these make them particularly attractive for the use in construction as well as road industry: edge supports of bridges, supporting walls of the base, ramp areas of tonnels and other types of enveloping systems.

In the guidelines [5, 8, 16—19] there are theoretical foundations and general principles of calculating piled supporting walls requiring specification and extra information to be employed in projects. This article deals with practical tasks and algorithms of the developed engineering method of calculation for designing and studying engineering structures using tubular welded pipes.

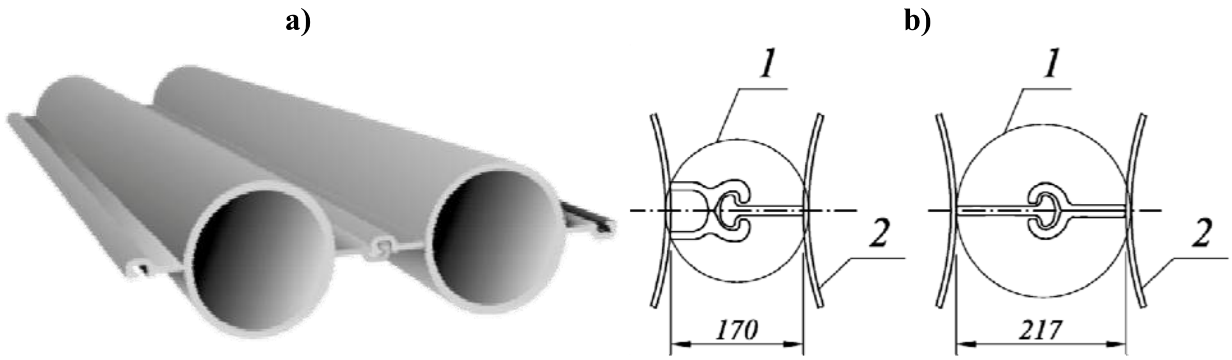

Fig. 1. Structure of a tubular welded pile:

a) schemes of elements of welded tubular piles; b) examples of highly efficient clutch joints 1 [10]; 2 — tube

1. Theoretical foundations and description of calculation schemes. Calculations of road engineering structures are performed using limit states in two groups in accordance with GOST 27751-2014: in the first group (strength and bearing capacity) using calculation loads and strength characteristics of soils, in the second group (using transformations) by means of normal laods and strength characteristics of soils.

Calculations are performed in accordance with the conditions of a flat task (flat deformation). The calculation area (Fig. 2) is a segment of a designed structure with the width of 1 m restricted side vertical faces. Calculation schemes of tubular pile supporting walls 1 are replaced with flat rods of finite stiffness 2 with the calculation width of 1 m consisting of two areas: underground *AB* and deepened into the base *BC*.

The area *AB* takes the active pressure of the soil from the side of the back face of a tubular welded pile, loads *P*, *H*, *M* applied to the head of an abutment (Fig. 2a) and eigen weight of supporting wall structures.

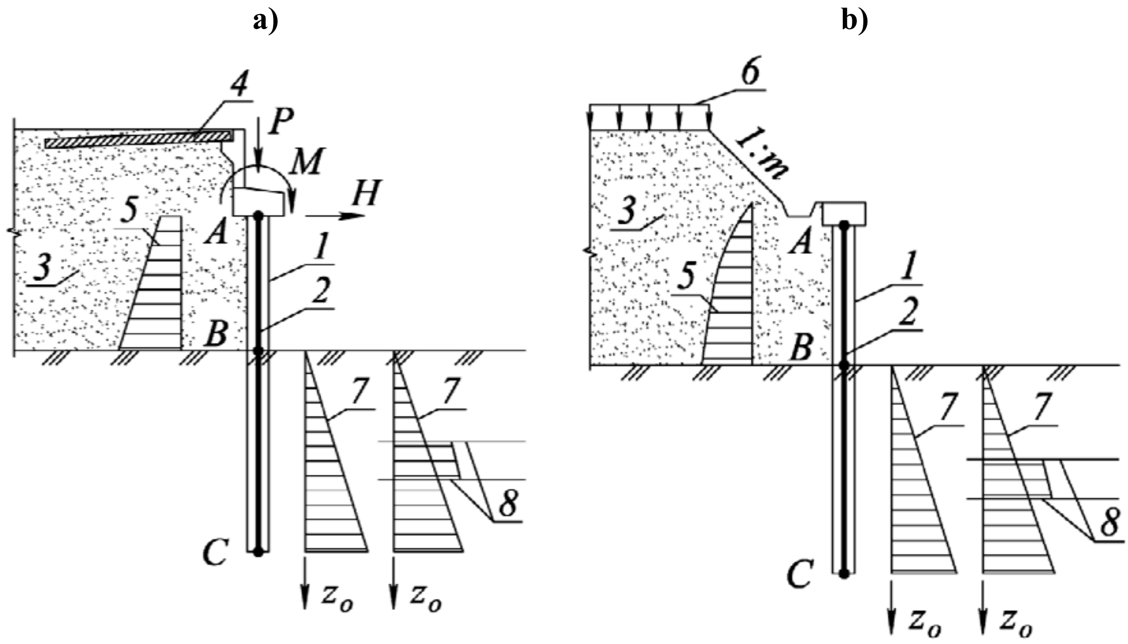

Fig. 2. Calculation schemes of road engineering structures using tubular welded piles:
a) of an abutment of a bridge; b) of a road supporting wall;
1 — abutment (supporting wall); 2 — flat rod; 3 — filling behind the abutment, base of the road;
4 — intermediate plate; 5 — diagram of the active pressure of the soil; 6 —time road vertical load;
7 — distribution of the coefficient of the subbase $C_z = Kz_O$ in a homogeneous and layer bases;
8 — boundaries of geological layers

The deepened lower part of the wall *BC* is an operating area interacting with the base transmitting a horizontal and momentous loads. In order to describe a force impact of the soil and deepened part of tubular welded piles, a calculation scheme is used that combines the theory of the method of local elastic deformations with a triangular shapes of the distribution of the coefficient of the subbase and limit stress-strain of the soil.

The geometric characteristics of the sections are: area *A*, cm^2/m, moment of inertia *I*, cm^4/m, moment of resistance *W*, cm^3/m, in extra calculations per 1 p. m. of a tubular welded pipes are determined depending on identical parameters of the sections of the pipes.

As the pipes are filled with a sand-cement mix or a soil nuclear

$$A = \frac{1000}{D+a} A_D, \; I = \frac{1000}{D+a} I_D, \; W = \frac{1000}{D+a} W_D, \tag{1}$$

where A_D, I_D, W_D are geometric characteristics of the sections of vacuum pipes with the thickness of the walls δ considering losses caused by corrosion; *D* and *a* are the sizes, mm (Fig. 3a).

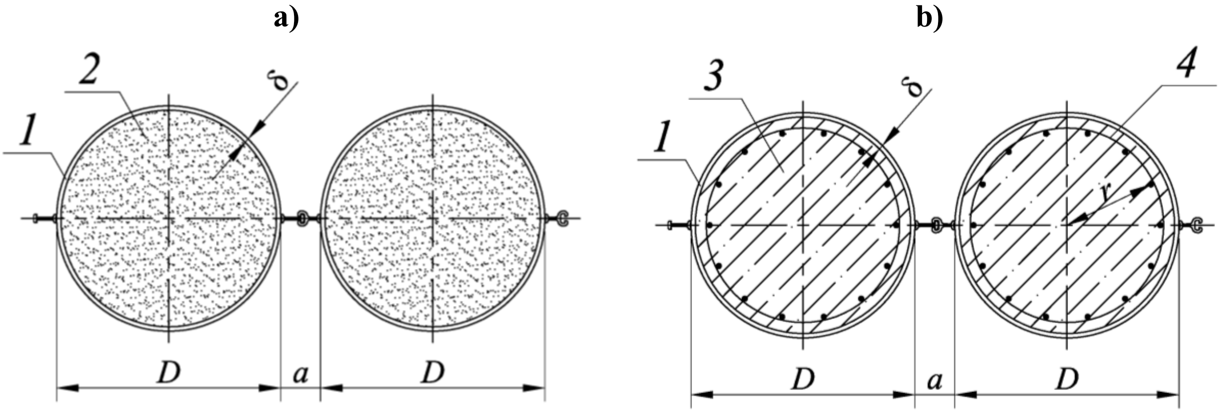

Fig. 3. Schemes of the sections of tubular welded walls:

a) a structure of tubular welded walls with a pipe filled with a sand-cement mix or a soil nuclear;

b) a structure of a tubular welded piles with a tube filled with ferroconcrete;

1 — structure of tubular welded piles; 2 — sand-cement mix (soil nuclear);

3 — monolith ferroconcrete; 4 — reinforced frame

If pipes are filled with monolith concrete or ferroconcrete

$$A = \frac{1000}{D+a} A_{red}\,,\ I = \frac{1000}{D+a} I_{red}\,, \tag{2}$$

where A_{red}, I_{red} are the areas and moments of inertia approximated to steel of sections of the pipes determined using the following formula:

$$A_{red} = \frac{\pi D^2}{4n_{sb}} + \frac{n_{sb}-1}{n_{sb}} A_D + A_{tot}\,,\ I_{red} = \frac{\pi D^4}{64 n_{sb}} + \frac{n_{sb}-1}{n_{sb}} I_D + \frac{1}{2} A_{tot} r^2\,, \tag{3}$$

$n_{sb} = E_s/E_b$ is a ratio of the elasticity modules of steel and concrete; A_{tot} is the area of the section of an operating reinforcement of ferroconcrete used for; r is the radius of a reinforced frame (Fig. 3b).

The calculation of a deepened part of the supporting wall relies on the following assumptions.

1. A deepened rod of finite stiffness replacing the supporting walls in a calculation scheme is divided into two parts: the upper one within which contact impact is determined with the limit resistance of p_{determ} of the base and the lower one with a pressed, bent one according to the solution of a contact task using the method of elastic deformations.

The calculation is performed using the method of subsequent approximations with a step-wise displacement of the boundary between the above parts of a tubular welded wall. At the end of a calculation using the strength (in the first group) the height of a pressed part should be not less than ⅓ of the total height of the pressed part of the pile and not less than 5 m and at the end of the calculation using the displacements (the second group) is no less than ½ of the total height of the deepened part of the pile.

2. A force impact of the pressed part of the rod is assumed to interact with the soil environment and to be described with the function of the coefficient of the subbase C_z according to the equation

$$C_z = Kz_O\,, \tag{4}$$

where K is the coefficient of the proportionality with the dimensionality kN/m^4 depending on a type of a soil in accordance with the appendix V SP 24.13330.2011 of the size 1/3 of the values in Table B.1; z_O is the coordinate of the length of the wall calculated from the surface of the base.

The coefficient of the subbase expresses the ratio of contact pressures p_z and joint horizontal displacements y_z of the pile and soil foundation:

$$C_z = p_z / y_z. \tag{5}$$

The coefficient of proportionality can change at the boundary of geological layers in the base (Fig. 2). At the distance between the pipes a > 1,0 m the coefficient K is multiplied by the coefficient of the operating conditions:

$$\gamma_c = \frac{D+1}{D+a}, \tag{6}$$

where D and a retain its previous values and are expressed in meters.

A horizontal load P_z per 1 meter of the width of the supporting wall is given by the ratio

$$P_z = p_z \times 1 \text{ м} = C_z y_z \times 1 \text{ м}. \tag{7}$$

3. Contact pressures p_z and the linear load P_z are restricted by corresponding limit values p_{determ}, P_{determ} that are capable of perceiving the base:

$$p_z \le p_{determ}, P_z \le P_{determ}\,. \tag{8}$$

The limit resistance of the base from the side of the front side of the piled supporting wall is determined as the difference between the passive pressure p_p from the side of the front face and active pressure p_a from the side of the back face of the supporting wall:

$$p_{determ} = p_n - p_a \tag{9}$$

The limit linear load of the horizontal load on the base is as follows:

$$P_{determ} = p_{determ} \times 1m = (p_n - p_a) \times 1m. \tag{10}$$

4. The pressures p_p and p_a are identified based on the condition of the strength of the soil according to the Moht-Coulomb equation:

$$\frac{1}{2}(\sigma_1 - \sigma_2) - \frac{1}{2}(\sigma_1 + \sigma_2)\sin\varphi - c\cos\varphi = 0,$$

where $\sigma_{1,2}$ the major stresses at the points (elementary volumes) of the soil on the contact (vertical) faces of the tubular piled supporting walls.

The fraction on the contact sides is neglected. Strains acting on these faces are major ones.

The active p_a and passive p_p pressures of the soil on the vertical faces of the piled supporting walls is determined depending on the vertical pressure p_v of the soil behind the lower supporting wall and natural pressure p_{zg} of the soil of the base from the side of the front face of the supporting wall.

While determining the active pressure σ_2 is replaced by p_a, σ_1 by на p_v:

$$p_a = p_v \frac{(1-\sin\varphi)}{(1+\sin\varphi)} - 2c\frac{\cos\varphi}{(1+\sin\varphi)} = p_v tg^2\left(45° - \frac{\varphi}{2}\right) - 2c \cdot tg\left(45° - \frac{\varphi}{2}\right). \quad (11)$$

While determining the passive pressure from the side of the front face of the supporting wall of the tubular welded pile in the base, σ_1 is replaced by p_n, σ_2 by the natural pressure p_{zg}:

$$p_n = p_{zg} \frac{(1+\sin\varphi)}{(1-\sin\varphi)} + 2c\frac{\cos\varphi}{(1-\sin\varphi)} = p_{zg} tg^2\left(45° + \frac{\varphi}{2}\right) + 2c \cdot tg\left(45° + \frac{\varphi}{2}\right). \quad (12)$$

5. The distribution of the vertical pressure p_{zg} from the weight of the soils of the base is accepted as specified in the schemes in Fig. 4 [7, 14]. In the upper layer as well as if the base is made more complicated by homogeneous soils with an evenly distributed specific weight,

$$p_{zg} = \gamma z_O. \quad (13)$$

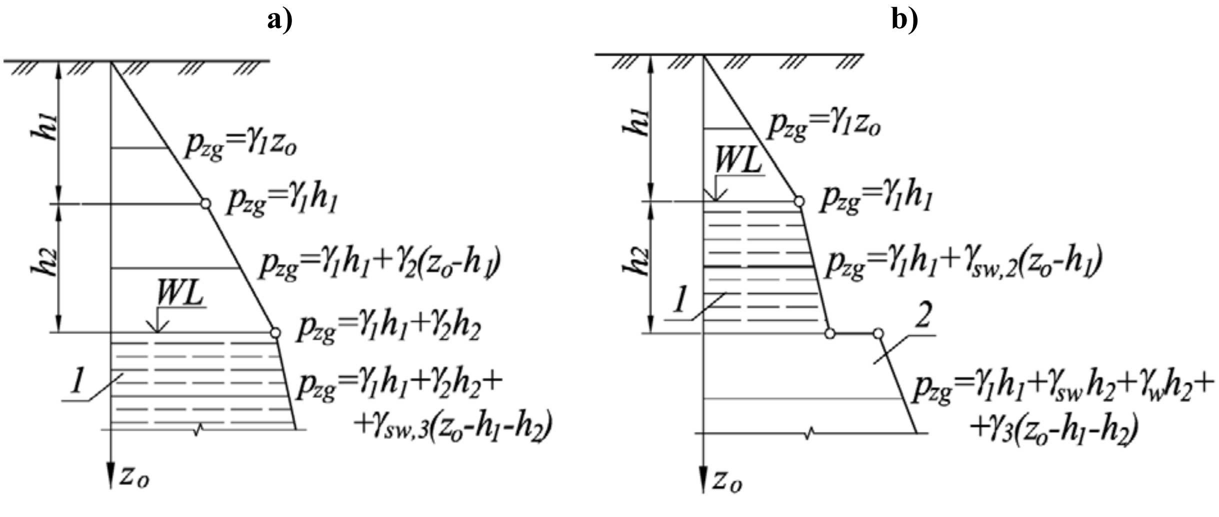

Fig. 4. Diagrams of the distribution of the vertical pressure p_{zg} from eigen weight of the soils:
a) in the bases with a varying specific weight along the depth if there are underground waters;
b) in the bases partially weighed soil waters if there is a water-absorbing layer;
1 — water-absorbing soil; 2 — water-resistant layer of the base; *WL* is the level of underground waters

In the layer foundations with a varying specific weight and water absorbing soils if there are underground waters (Fig. 4a)

$$p_{zg} = \gamma_1 h_1 + \gamma_2 (z_O - h_1),$$
$$p_{zg} = \gamma_1 h_1 + \gamma_2 h_2 + \gamma_{sw,3} (z_O - h_1 - h_2), \qquad (14)$$

where h_1, h_2 are the thickness of the layers of the base within the depth z_O; γ_1, γ_2 are specific weights of the bases of the layers of the base above the underground waters, $\gamma_{sw,3}$ is a specific weight of the layer of the water-absorbing soil determined as the weight of mineral particles, the indices 1, 2, 3 relate to the numbers of the layers of the soil.

In the water-absorbing layer of the bases the weight of the above layers and the weight of the layer of water are considered according to the scheme in Fig. 4b:

$$p_{zg} = \gamma_1 h_1 + \gamma_{sw,2} h_2 + \gamma_w h_2 + \gamma_3 (z_O - h_1 - h_2), \qquad (15)$$

where $\gamma_w = 9.8$ kN/m^3 is a specific weight of water, γ_3 is a specific weight of the water-absorbing layer.

6. The distribution of the vertical pressures p_v behind the face of the supporting wall of the abutment of a bridge (Fig. 5a) is determined according to the following formulas:

— within the filling behind the abutment (above the level of the planned surface):

$$p_v = \gamma_n z, \qquad (16)$$

where γ_n is a specific weight of the abutment soil; z is a vertical coordinate calculated from the top of the filling behind the abutment according to the scheme in Fig. 5a;

— within the base (below the level of the planned surface):

$$p_v = \gamma_n h + p_{zg}. \qquad (17)$$

The distribution of the vertical pressures p_v behind the lower face of a road supporting wall in Fig. 5b is given by the following formulas:

— within the filling (above the level of the planned surface):

$$p_v = \gamma_n z + p_{open}, \qquad (18)$$

— within the base (below the level of the planned surface):

$$p_v = \gamma_n h + p_{open} + p_{zg}, \qquad (19)$$

where h is the height of the underground part of the supporting wall (Fig. 5b); p_{open} is a vertical pressure of the soil behind the lower face of the supporting wall from the weight of the sloped part of the abutment with the height d distributed according to the below expressions (21) that were obtained in the following way.

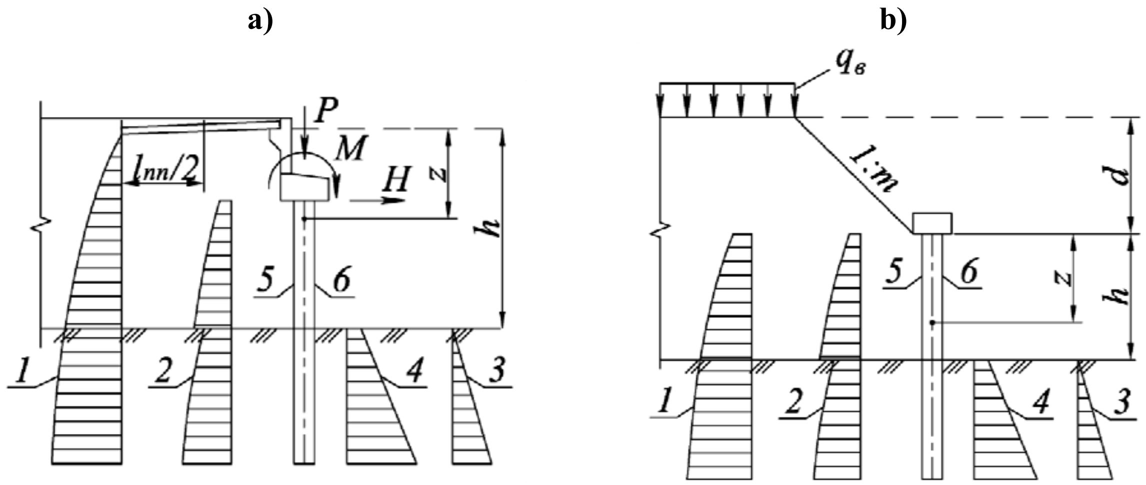

Fig. 5. Distribution of the pressures p_v (1), p_a (2) on the back (5) and p_{zg} (3), p_f (4) on the front (6) faces of the piled supporting walls

Let us denote the intensity of the distributed load at the level *AB* on the left from the point *D* (Fig. 6):

$$q_{open} = \gamma_n d + q_b. \tag{20}$$

where $q_в$ is a temporary vertical load that is agreed to be evenly distributed on the surface of the base according to the GOST 32960-2014.

The vertical strains p_{open} behind the back face of the supporting wall are determined depending on q_{open} using the following approach that is similar to that in construction mechanics (the method of boundary elements). The essence of this method is to agree to expand the calculation area to the size and shape where there are ready-made solutions and to apply new boundaries of such a system of forces so that the distribution of strains on an actual surface of the calculation area with an acting load.

Let us show an example. The calculation area and an acting load are replaced with the equivalent system where the level of a horizontal face *AB* is displaced to the top at the height of ½*md* into the position *A'B'*. The acting load of a trapezoid shape is replaced by a band with the intensity q_{open} and is placed according to the scheme in Fig. 6. The total weight of the sloping part of the abutment and the equivalent load replacing it.

Let us draw two rays from the point *E* at the angle of 45^0. One of them crosses the point *B* and the other one the point *F*. Let us assume that at the level *AB* the intensity of the load on the left of the point *F* is $q_{\ open}$ and on the right of the point changes according to the linear law to zero at the point *B*. Then the shape of the distribution of the load coincides with an actual shape of a part of the abutment.

Let us assume that the effect of a band load in the system restricted with a horizontal plane *A'B'* is the same as that of an actual load on the lower semi-space. Continuing both rays we get vertical strains on the line *BMN* within the filling part of the calculation area:

$$q_{open} z / (md + 2z), \tag{a}$$

within the base:

$$q_{open}(h + z_o) / [md + 2(h + z_o)]. \tag{b}$$

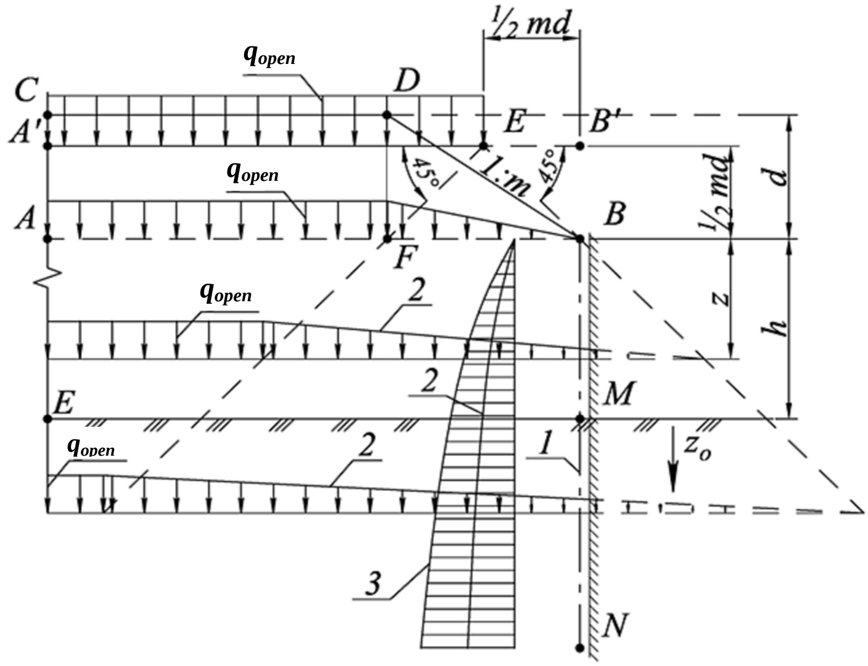

Fig. 6. Scheme of determining vertical strains behind the back supporting wall from the weight of the sloping part of the base:

1 — back face of the supporting wall;

2 — diagrams of distribution $q_{open} z / (md + 2z)$ and $q_{open}(h + z_o) / (md + 2(h + z_o))$;

3 is a diageram of distribution of P_{open}

The obtained expressions correspond with free distribution of strains in the soil without a supporting wall. If we neglect horizontal displacements of the supporting wall, the back face is considered supported. In order to obtain p_{open} "the imaging method" can be employed [11, p. 400] according to which under the effect of a one-sided system of the forces, a motionless wall is replaced by a symmetry plane. Hence in order to obtain p_{open} the expressions (a) and (b) should be doubled:

$$\begin{aligned} p_{open} &= 2q_{open} z / (md + 2z), \\ p_{open} &= 2q_{open}(h + z_o) / [md + 2(h + z_o)]. \end{aligned} \tag{21}$$

2. Sequence of the calculation. The calculations of supporting walls in accordance with the above guidelines should be performed using the finite element method. It is possible to use the software such as *LIRA*, *SCAD*, *MicroFe*, *Midas civil* or other verified (tested) software recommended for use in the Russian Federation. Calculations are performed in the below sequence.

1. Creating a finite element scheme [13—15] by dividing (in the underground and deepened parts) of a vertical rod depicting the pile supporting wall, on the finite elements with the step t of no more than 1 m and no more than 0.1 of the heights of the over- and underground parts.

The coordinates and the number of the finite elements and nodes on their boundaries start from the lower end of the supporting wall (Fig. 7).

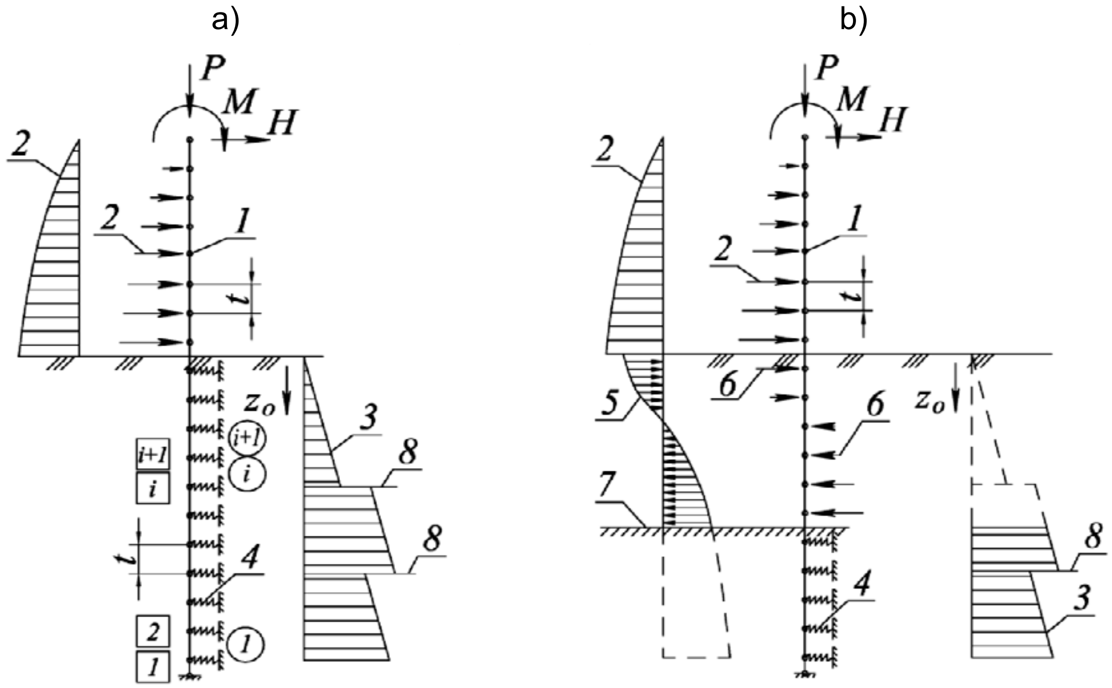

Fig. 7. Scheme of the calculations of the walls of the method of finite elements:
a) the first step of calculations (boundary of the pressed part at the level of the planned surface);
b) the second and subsequent steps of the calculation; 1 — piled supporting wall;
2 — diagram p_a and the force F_{ai} in the overground part of the supporting wall;
3, 4 — diagram of the coefficient of the subbase $C_z = Kz_O$
and its replacement with conditional “spins” with the stiffness $B_{zi} = K_j\, z_{Oi}\, t \times 1$ m;
5, 6 — linear load $P_{determi}$ and its replacement with the node forces F_{determ}
7 — boundary of the pressed part of the tubular welded pile;
8 — boundary of geological layers; [i] — numbers of the nodes; (i) — numbers of the finite elements

2. Replacing a triangular or stepwise diagram of distribution with the coefficient of the subbase with conditional horizontal stiff rods (“spins”) with the length of 1 m with the compressive and tension stiffness $B_z = C_z t \times 1$ m. The conditional “spins” are placed into the nodes of the finite element system. The stiffness of the conditional spin in the i-th node:

$$B_{zi} = K_j z_{oi} t \times 1m, \quad (22)$$

where z_{Oi} is the coordinate z_O i-th node; K_j is the coefficient of proportionality of j-th layer of the base where there is the i-th node.

3. Applying a horizontal pressure p_a to the nodes of the underground part of the back face of the tubular welded pile of the supporting wall. The load p_a is transformed into the node forces of the force F_{ai} using the formula

$$F_{ai} = p_{ai} t \times 1m \quad (23)$$

where p_{ai} is the pressure p_a at the level of the i-th node of the overground part of the supporting wall.

Determining equal horizontal forces H and a moment M of loads applied to the head of the abutment and its application to the upper node of the system. There is no scuh operation in a road supporting wall.

4. Determining a specific linear horizontal load $P_{determ,\ i}$ in the nodes of the pressed part:

$$P_{determ,i} = (p_{ni} - p_{ai}) \times 1m \quad (24)$$

where p_{ni}, p_{ai} are linear loads p_n and p_a at the level of the i-th node of the pressed piled supporting wall.

5. The first (initial) step. The boundary of the pressed part of the piled supporting wall is accepted to be at the level of the planned surface.

Designing and solving the system of equations of the method of finite elements expressing the balance of the nodes. The solution is horizontal displacements y_{zi} and rotation angles φ_{zi} of the piled supporting wall in the nodes.

Determining the linear load in the nodes using the formula

$$P_{zi} = p_{zi} \times 1m = y_{zi} K_j z_{oi} \times 1m, \quad (25)$$

and node forces in the conditional “spins”:

$$R_{zi} = P_{zi} t. \quad (26)$$

Comparing P_{zi} and $P_{determ,\ i}$ in the nodes of the system, identifying nodes where $P_{zi} > P_{determ,\ i}$. $P_{zi} \leq P_{determ,\ i}$, and displacing the boundary of the pressed part of the piled supporting wall by one level.

6. The second and subsequent steps. The level of the pressed part of the piled supporting wall based on the results of the previous step is identified in the node where $P_{zi} \leq P_{determ,\ i}$. In the above nodes instead of R_{zi} the following loads are applied

$$F_{determ,i} = P_{determ,i}t = (p_{ni} - p_{ai})t \times 1m. \tag{27}$$

Repeating calculations and logical operations with a new level of pressing and corrected loads.

The latter is the approximation where the ratios $P_{zi} \leq P_{determ,\ i}$ in the nodes of the system. Testing the conditions $P_{zi} \leq P_{determ,\ i}$ at all the levels of the pressed part of the tubular welded pile.

7. Calculation of the first group completes obtaining the node forces $R_{zi} = P_{zi}t$ in the conditional "spins", designing the diagrams of longitudinal forces and moments for each combination of loads.

Calculation of the seconв group completes designing the axis of the piled supporting wall and determining a horizontal displacement in the node of the support of a span structure on the abutment (with combined functions) of a bridge structure for each combination of loads.

Calculations of structures of tubular pile in the composition of abutments of bridges and road supporting walls include the following tests performed in compliance with the current guideline (SP 35.13330, SP 24.13330, etc.)

The first group:

— calculation of longitudinal sections for bending or outercentral compression (if a piled system perceives a longitudinal force besides a horizontal pressure);

— calculation of the sections of a pipe on the longitudinal force by comparing calculation and tangent strains;

— calculation of the strength for a complex stress-strain in the sections of a pipe where there are both normal and tangent strains;

— calculation of the strength of circular sections of a ferroconcrete filling for bending and a longitudinal force;

— testing a tubular piled abutment using the bearing capacity of the base group.

The second group:

— testing of structures of deformation stitches and supporting parts on the capacity to perceive horizontal displacements of the abutments in joints with wardrobe walls and supporting nodes of bridges.

— comparing horizontal displacement of the upper road supporting wall with a specific value.

3. Calculation example. Fig. 8 shows the section of a wall of tubular welded pile, the calculation scheme for the last displacement of the initial level and results of calculations of the supporting wall with the total length of 6.7 m supporting the soil in the road butt with the depth of 10 m. The label of a tubular welded pile is ShTS-820×13 ZSG1, the external diameter of the pipes is 820 mm, the thickness of the wall is 13 mm, the geometric characteristics are

$$A = 0.0304m^2 / m, I = 0.0025m^4 / m, W = 0.0061m^3 / m.$$

The label of steel is 09G2S-12 according to the GOST 19281-89*, calculation resistance R_y = 295 MPa, elasticity module E = 2.06×10^5 MPa. The bearing capacity of the tubular welded pile: in the moment M_{determ} = 1798 kNm/m, in the longitudinal force $Q_{пред}$ = 2727 kN/m.

The calculations were performed twice: the first group in the strength (the second using displacements) of the group using the calculation (normal) loads and mechanical characteristics of soils (Table). According to the above, the calculations were performed by means of the method of subsequent approximations with a stepwise displacement of the boundary of the pressed part of the piled supporting wall. At the first stage the boundary of the pressed part was placed at the level of the planned surface.

Table

Mechanical characteristics of soils

Name of the soil	Standard/calculated			
	Specific adhesion $C_{norm}/c_{investig}$, kPa	Angle of the internal friction $\Phi_{norm.}/\varphi_{investig}$ degrees	Specific weight, $\Gamma_{norm.}/\gamma_{investig}$, kN/m^3	K, kN/m^4
1. Solid loam	26.2/17.5	23.2/20.2	18.2/18.0	6000
2. Soft plastic loam	15.0/14.0	17.0/16.0	18.8/18.7	2800
3. Stiff plastic clay	33.0/32.0	18.0/17.0	18.6/18.6	4680
4. Semi-stiff clay	36.0/36.0	19.0/18.0	18.7/18.0	5720

In the calculation using the strength 5 steps of reducing the pressing boundary was necessary followed by determining it at the level of 9.0 m from the planned surface and 7.3 m from the lower end of the tubular welded pile. In the calculation using the displacemetns the pressing boundary was obtained on the planned surface at the first stage of the calculation.

The results of the calculation are presented in Fig. 8c: digrams of contact pressures, moments (horizontal displacements) according to the results of the calculations of the first (second) group. The horizontal displacements (32 mm) of the upper end of the wall of the tubular welded pile was no more than 0.01 of the height of the overground part.

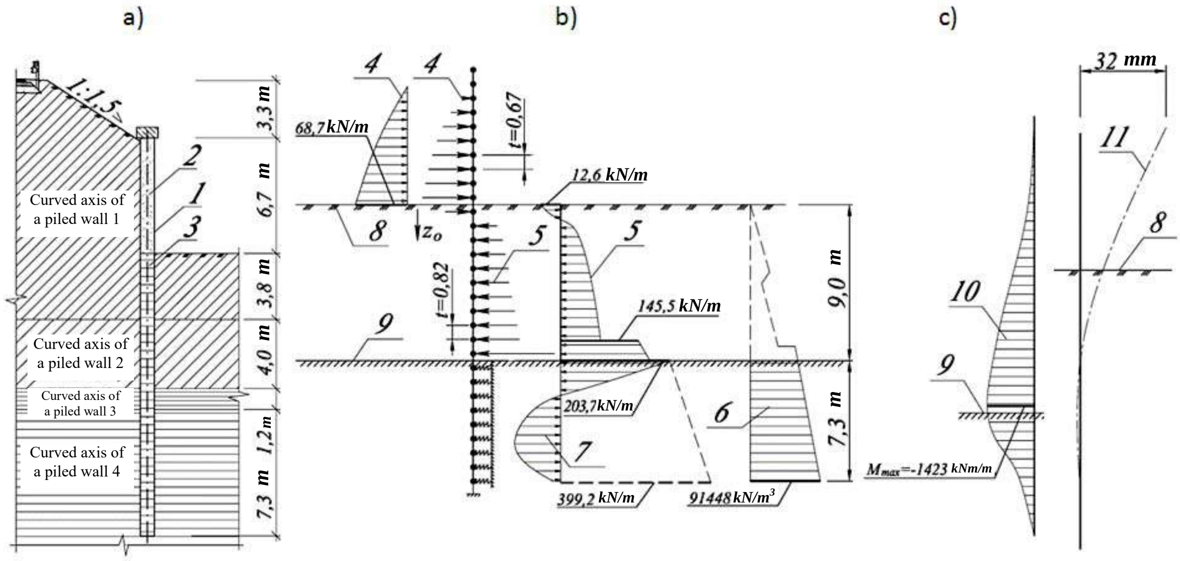

Fig. 8. Scheme and results of the calculation of a road supporting wall:
a) section of the wall of a tubular welded pile, butt and base;
b) calculation scheme for calculation (final) position of the level of the start of a tubular welded pile;
c) results of the calculation of;
1 — a structure of the tubular welded pile; 2 — filling of a sand-cement mix; 3 — soil nuclear;
4 — diagram of distribution of the active pressure and node forces F_{ai} in the overground part of the supporting wall;
5 — linear load P_{determ} and its replacement with the node forces $F_{determi}$;
6 — diagrams of the coefficient of the subbase $C_z = Kz_O$; 7 — contact pressure $p_z = C_z\, y_z$;
8 — planning surface; 9 — pressing boundary;
10 —diagrams of the bending moments M; 11 — curved axis of a piled wall

Conclusions

Based on the known solutions of the theory of soil mechanics, the engineering method of calculating one-sided tubular piled systems as part of a road supporting structure (bridge abutments, soil enveloping, etc.) including the description of loads, engineering schematization of a force impact with the soil environment, a set of tests using the limit states. The obtained solutions and their algorithmization can be applied to other types of bending piled supporting walls.

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