Port and Marine Structures Made of Sheet Piling with Staggered Toe

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Abstract: Some new approaches to designing and calculation of maritime structures made of sheet piling with staggered toe are considered and discussed. Obtained results allow determination of piles spacing efficiency in staggered embedment wall. The specificity of interaction of piles in "comb" with the soil foundation regarding transition from continuous to "comb" wall is investigated. Practical application is illustrated by example of calculation.

Key words: Sheet piling quay wall, staggered toe, driving depth.

1. Introduction

In a number of designs it is expedient on the base of economic reasons (especially for fully fixed walls) to provide sheet piles driving below the bottom level not as a continuous wall but with staggered embedment (let say, as a "comb" wall). Sheet piles driven by "comb" method, is one of perspective directions in material consumption reduction of bulkhead quay walls and provides economic design solutions. At the same time, the specificity of the constructive decision causes consideration of a number of questions in the field of designing and calculation of such quay wall. It is necessary to take into account the changes in rigidity of the sheet pile wall along its height (i.e., transition from a continuous wall to "comb" wall), character of "comb" wall-soil interaction, optimal spacing of sheet piles in the "comb" wall.

2. Design Approach and Main Dependencies

The preferable way to describe the stressed-deformed state of the discussed sheet pile wall

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(considerations below relate to reinforced concrete piles) is to use a model of a beam of variable rigidity laying (partially) on elastic-plastic foundation and loaded by soil pressure [1, 2]. The presence of staggered part below the bottom level can be taken into account by proper flexural stiffness of a beam on this part regarding a spacing of piles in the "comb". Elastic properties of the foundation can be reflected by sub-grade soil reaction model (Winkler type) [3-5]. The size of a zone of soil plastic deformations on the contact with a wall can be determined on the basis of comparison between soil reactions obtained by subgrade soil reaction model and Coulomb (or Rankin) theory. Values of soil reaction obtained in the first case cannot exceed values corresponded to the second approach. Corrections of size of the plastic zone can be fulfilled by iterations.

The analysis of rational spacing of the piles in staggered part of the wall, its optimal height and corresponding stresses/deformations' distribution was fulfilled for a sandy soil with following characteristics: unit weight $\gamma = (10 \div 20)$ kN/m^3, internal friction angle $\varphi = 30^o$. The following types of the "comb" were taken for consideration: 1/1, 2/1, 3/1, 1/2, where m/n is

accepted as a relation of full length piles' number to reduced length piles' number per unit of the wall's extent.

In numerical modeling all above-mentioned types of the "comb" wall with a variation of "comb" part height are considered. The optimum ratio of height of "comb" part and wall type is determined regarding allowable level of structure's stresses and deformation. It used a condition that height of staggered part should be maximal, and m/n ratio-minimal.

Structure's calculation was made regarding the mixed stressed state of the soil with use both of linear and nonlinear approximation of lateral soil pressure-wall displacements dependencies considered in works from Refs. [1-3].

Important feature of the "comb" wall designing and calculation is the reduction of the moment of inertia (I) and sectional area (F) values in a staggered embedment zone according to the following dependencies:

• moment of inertia per unit of the wall extent

$$I = I_o \times K \qquad (1)$$

where, I_o—moment of inertia of single sheet pile, K—conventional number of piles in the "comb" per unit of the wall/s extent.

• the sectional area per unit of the wall's extent

$$F = F_o \times K \qquad (2)$$

where, F_o—sectional area of single pile.

Necessary preliminary stage of the "comb" wall design is determination of the rational piles' spacing in the staggered embedment part and development of the reliable approach to define parameters of the soil interacting with piles regarding peculiarities of the piles work in the "comb".

For quay retaining walls made of reinforced concrete piles the following technique can be offered. For a substantiation of criterion of rational spacing of piles in staggered embedment part of the wall it is necessary originally to determine maximal distance between piles L_o. It can be found on the basis of the known suggestion on calculation of bearing capacity of horizontally loaded piles [6]. In a considered case

maximal distance L_o is defined by junction soil back pressure prisms' borders (in a horizontal plane) for the adjacent piles. From geometrical reasons and taking into account concurrence of directions of pressure exerted upon a pile and large main deformations, we can receive:

$$L_o = b \times \Phi(\varphi) \qquad (3)$$

where, b—size of cross-section of a pile,

$$\Phi(\varphi) = \cos\varphi \, \exp(\pi/2 \, tq\varphi) \, / \, [2\sin(\pi/4 - \varphi/2) \cos(\pi/4 + \varphi/2)] \qquad (4)$$

In Eq. (4), φ—internal friction angle for the soil layer corresponding to the location of considered cross-section of a pile. Eq. (3) testifies that maximal distance L_o in the "comb" for homogeneous (in a horizontal plane), soil layer (φ = const) depends only on the sizes of piles cross section. For possible for sandy soils interval of angle φ values 25°-35°, the distance L_o includes four-six width "b" of a pile.

Criterion of piles spacing efficiency in staggered embedment wall can be considered as the following ratio:

$$A_j = \Sigma F_{ci}/F_{ri} \qquad (5)$$

where, ΣF_{ci}—total area of cross sections of piles, placed within the limits of the length L_o, F_{ri}—area of the soil foundation involved in soil back pressure (reaction) in addition to a soil back pressure wedge, which corresponds to the work of the first (basic) pile, i.e., pile from which the distance L_o is measured.

Obviously, the less A_j, the worked out design of "comb" wall is more effective.

Let's address now to the following important problem and consider the specificity of interaction of piles in "comb" with the soil foundation regarding transition from continuous to "comb" wall.

As retaining wall is considered as a beam, which is on elastic-plastic foundation, the specificity of interaction of elements of system "structure-soil media" can be reflected by the appropriate correction of the elastic characteristics of soil media (modulus of deformation, coefficient of sub-grade reaction and so on). In Ref. [6, 7] the dependence allowing to calculate

coefficient of sub-grade reaction for soil interacting with a laterally loaded pile on depth z from a surface of the bottom was derived:

$$k_z = 2p_z / [\eta \, b \, \sin^2\psi \, \exp(2\theta \, tq\varphi)] \qquad (6)$$

where, p_z—soil reaction (back pressure) on contact with a pile on depth z, η—critical shear angle determined by formula:

$$\eta = 4 \, a_0 \, \sigma_1 \, tq\varphi \, \lambda_0/(1 - \lambda_0^2) \qquad (7)$$

$$\psi = \pi/4 + \varphi/2 \qquad (8)$$

where, a_o—coefficient of compressibility, σ_1—greater normal stress, λ_0—coefficient of soil lateral pressure for the state at rest.

Coefficient of compressibility a_o can be determined on the base of consolidation tests, and then the value of the modulus of deformation can be calculated as:

$$E = (1 - e_o)/a_o, \qquad (9)$$

where e_o—void ratio.

As shown in Ref. [1], the dependence for calculation of the modulus of deformation can be presented generally as:

$$E_z = d_o \times (I/\delta - I_o/\delta_o)/ f(I\delta_o/I_o\delta) \qquad (10)$$

where, $d_o = (1 + e_o)/c_m$,

f—the function describing the stressed state of the soil (for the majority types of the soil this function is close to logarithmic or power one),

c_m—coefficient characterizing consolidation curve (for cohesive soils $c_m = c_e$, c_e—coefficient of compression, for sandy soils $c_m = c_\kappa/(1 + e_o)$, c_κ—compressive deformation corresponding to initial pressure),

I and I_0—current and initial values of the first invariant of the stresses tensor at the considered point,

$\delta = 1 + (r_o - 1) \mu/(1 - \mu)$—characteristic of dimension of process of formation of the stresses state of soil media,

r_o—dimension of the stressed state.

It is obvious, that in the back pressure zone of the soil in front of the wall the stresses in the soil can vary their values in an interval from pressure in the state of rest up to passive pressure. In case of horizontal surface of the bottom and homogeneous soil in back pressure zone:

$$I_0 = \sigma_{zo} + \sigma_{xo} + \sigma_{yo} = \gamma z \, (1 + 2\lambda_o) \qquad (11)$$

$$I = \sigma_z + \sigma_x + \sigma_y = \gamma z \, (1 + 2\lambda_p) \qquad (12)$$

where λ_p—coefficient of soil passive pressure.

As the soil in front of the continuous wall works in conditions of one-dimensional compression, in this case:

$$r_o = 1, \delta = 1 \qquad (13)$$

soil in front of the "comb" wall has an opportunity of lateral displacements, i. e.,

$$r_o = 2, \delta = 1/(1 - \mu). \qquad (14)$$

By substituting Eqs. (11) and (12) in Eq. (10) and regarding Eqs. (13) and (14) it is possible to obtain dependence for definition of the modulus of deformation for a continuous part of the wall as:

$$E_c = (1 + e_o)/c_m \times 2 \, \gamma z(\lambda_p - \lambda_o)/f[1 + 2\lambda_p/1 + 2\lambda_o] \qquad (15)$$

and for staggered embedment part of the wall:

$$E_r = (1 + e_o)/c_m \times \gamma z \times [(1 + 2\lambda_p) \, (1 - \mu) - (1 + 2\lambda_o)]/ f[(1 + 2\lambda_p) \, (1 - \mu) /1 + 2\lambda_o] \qquad (16)$$

Taking into account some following relations:

• between the modulus of deformation and coefficient of compression in Eq. (9),

• between critical angle of shear and coefficient of compression in Eq. (7),

• between coefficient of subgrade reaction and angle of shear in Eq. (6).

It is possible to conclude that the influence of conditions of soil/continuous wall interaction and soil/"comb" wall interaction on value of coefficient of sub-grade reaction is similar to influence of the specified factors on value of the modulus of deformation. Thus, the given dependencies allow at retaining "comb" sheet pile wall design to take into account the specificity of interaction of soil with a staggered embedment part of the wall and to reflect quantitatively this specificity at determination of values of the modulus of deformation and coefficient of sub-grade soil reaction.

It represents a practical interest to study change of the elastic characteristics of soil media depending on piles spacing in staggered embedment wall. From

geometrical reasons volume of the deformed soil is equal:

$$v_z = r_k^2 \, \eta \, \cos^2\varphi/2 = L_o^2 \, \eta \, \cos^2\varphi/[8 \cos^2(\pi/4 - \varphi/2)] \quad (17)$$

hence, coefficient of subgrade soil reaction:

$$k_z = \sigma_z b/v_z \ = 8\sigma_z b \cos^2(\pi/4 - \varphi/2)/[L_o^2 \, \eta \, \cos^2\varphi] \quad (18)$$

In case of the soil for which the logarithmic approximation of compression curve is valid, the dependence:

$$\eta = 4c_e\lambda_o\tan\varphi/(1-\lambda_o^2) \times \ln((1 + \lambda_p)/(1 + \lambda_o)) \quad (19)$$

is applicable as shown in Ref. [2]. Substituting Eq. (19) to Eq. (18) and making some transformations, it is possible to receive convenience for the further analysis expression:

$$\alpha_z = k_z/\sigma_z = D(\varphi) \, b/[c_e \, L_o^2] \quad (20)$$

where

$$D(\varphi) = 4 \cos^2(\pi/4 - \varphi/2) (1 - \lambda_o^2) / [\lambda_o\sin2\varphi \ln((1 + \lambda_p)/(1 + \lambda_o))] \quad (21)$$

It is necessary also to stipulate the proper limitations of applicability of considered above formulas. Obviously that use of formulas for coefficient of sub-grade soil reaction (derived on the base of consideration of soil foundation bearing capacity in planes, which are normal to the longitudinal axis of piles) is expedient if values of this coefficient do not exceed corresponding values from the traditional law describing changes of this coefficient with the depth. It means that soil back reaction (in case of soil lateral deformations between piles in "comb" wall) can be realized, when there are no soil displacements in a vertical plane (no soil bulging at the surface of the bottom). Other limitation of this model applicability (as, however, for any elastic model) is the level of stresses in the soil, otherwise it is necessary to take into account appearance of zones of plastic deformations and to use the mixed problem approach.

3. Example of Proposed Design Method Application

Let's consider for example the quay wall made of reinforced concrete piles (section 450 × 450 mm^2) (Fig. 1). Numerical modeling was based on the following main input data: bottom depth—6.50 m, wall height above bottom level—9.0 m, wall driving depth—5.0 m, anchor tie rod is fixed to the wall at the one meter distance from the wall top, the height of the staggered embedment part—4 m, the type of the "comb" wall m/n = 1/2.
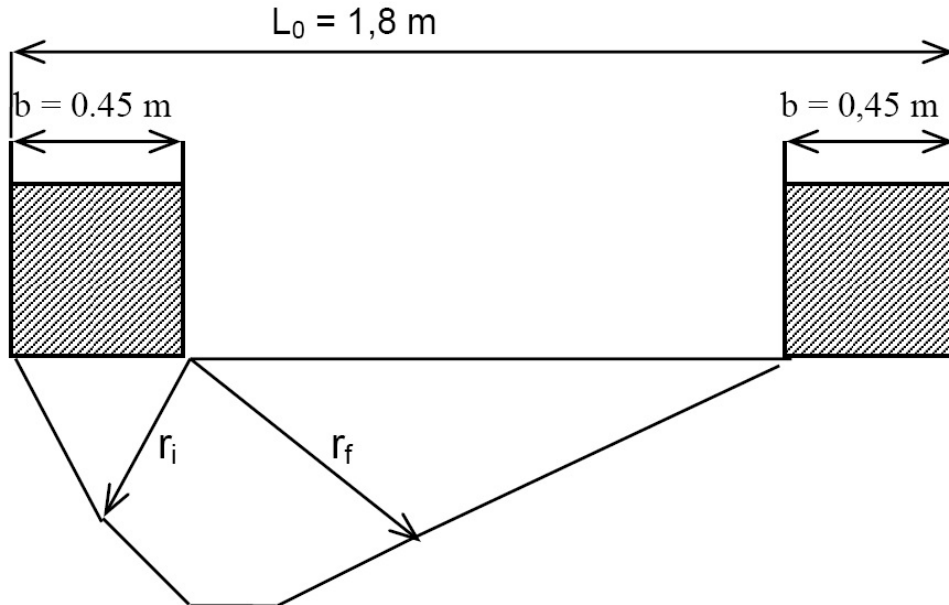

Fig. 1 Reinforced concrete piles of the "comb" wall.
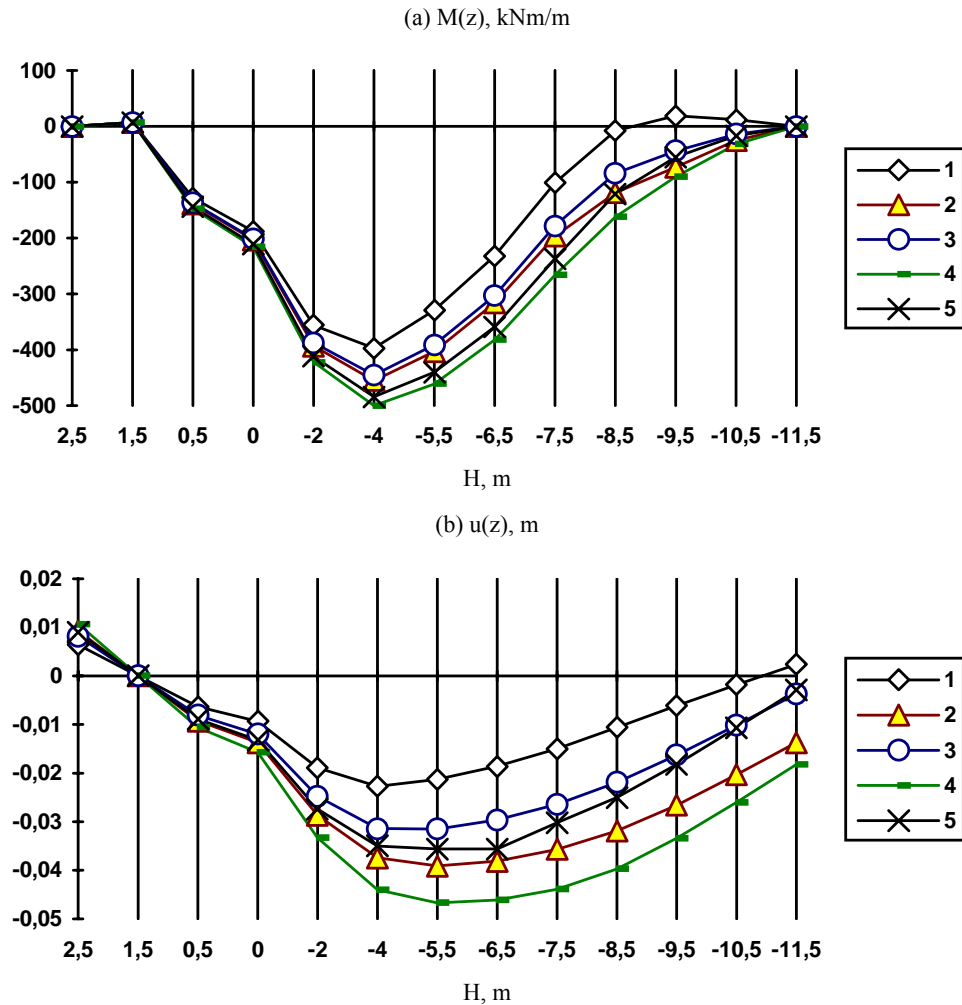
(a) M(z), kNm/m

(b) u(z), m

Fig. 2   Distribution of moments and deformations: (a) bending moment, (b) displacements, 1—zero series (traditional approach regardless of dependence between lateral soil pressure and wall displacement), 2—the first linear series' approximation, 3—the second linear series' approximation, 4—the first nonlinear series' approximation, 5—the second nonlinear series' approximation.

Preliminarily it is necessary to determine the maximal distance between piles L_o, so according to Eq. (3) $L_o = 2.1$ m. By correction to the value divisible by pile's width b = 0.45 m, we can finally obtain $L_o = 1.8$ m ($L_o/b = 4$).

Using Eqs. (20) and (21), it is possible to determine coefficient of sub-grade soil reaction:

$$k_z = \sigma_z \times 111 \ (kN/m^3)$$

Applying this dependence we can obtain the distribution of moments and deformations as shown in Fig. 2.

4. Conclusions

Approaches allowing to design and to calculate quay

walls made of sheet piling with staggered toe are developed. Due to obtained solutions designers can determine optimal geometrical parameters of the "comb" wall and its piles location. In general these solutions may be applied to all types of sheet pile walls (both steel sheet piling and reinforced concrete piles).

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