Some peculiarities of U-shape sheet piles driven into sandy soil

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ABSTRACT

There is a serious engineering/scientific problem to determine real parameters of the flexural stiffness of U-profile sheet piles. Among main factors which influence on this we can mention soil friction in the interlocks and the transmission of longitudinal shear forces in the interlocks. Theoretical and effective values of moment of inertia and section modulus may differ several times (known experiments demonstrated difference 1.5 – 3.5 times). In engineering practice soil-interlock interaction depends, particularly, on installation method. Application of press-in approach provides most effective result from the point of view of friction forces positive utilization. Presented study includes analysis of both in-situ and laboratory experiments based on pressing-in of U-profile steel sheet piles into sandy soil which gave possibility to work out improved numerical model of sheet pile – soil interaction. On the base of obtained results it is possible to conclude that standard values of steel sheet pile wall's flexural stiffness are largely overestimated and therefore lateral displacements are underestimated. In the worst cases effective wall stiffness can be of as small as 32% of the full wall stiffness. Proposed new technological approaches ensure more reliable integrity of adjacent U-profile sheet piles in the wall; improvement of quality and effectiveness of design solutions, and lowering the expenses for the maintenance of retaining sheet pile walls.

Key words: *Sheet piling, Press-in, Physical modelling, Numerical modelling, Retaining wall stiffness*

1. Introduction

From the structural viewpoint, we distinguish between walls without shear force transmission in the interlocks and those with shear force transmission (the so called "Jagged Walls"). When determining the cross-sectional values of connected sheet piling, all sheet piles are taken into consideration. The jagged wall-section however may be calculated as a uniform cross-section only if full shear force absorption in the interlocks is certain. Jagged walls in wave-like form consist of U-shaped sheet piles in which the half the wave length consists at least of one individual pile. In this case, the uniform cross-section is achieved already by transmission of shear forces in every second interlock. In case of two individual piles per half wave length, the interlocks are alternately placed on the wall axis (neutral axis) and outside in the flanges. Here the uniform cross-section is only achieved when all interlocks on the wall axis are linked shear-resistant. The interlocks in the flanges are the threaded locks in construction. The interlocks located on the wall axis can be drawn together in the workshop and prepared accordingly for the transmission of the shear forces, namely:

- by welding the interlocks together
- by crimping the interlocks;

however, only a partial connection can be achieved because the interlocks at the crimping points are displaced by several millimeters to take up the loads. The degree of partial connection depends on the number of crimping points per member, which has a critical influence on the deformation behavior, respectively the degree of displacement.

Above-mentioned peculiarities were considered and studied before by number of researchers (J-F.Vanden Berghe, A.Holeyman, E.Juaristi, A.Schmitt, 2001, Symons I. F. et al., 1987, McNulty T.A. and Little J.A., 1987, Little J.A. and Williams S.G.O., 1989, and others); importance of this problem was reflected also in "Recommendations of the Committee for Waterfront Structures, Harbours and Waterways" (EAU 2004 and further).

There are some cases in engineering practice when forces and deformations in the interlocks play a significant role in U-section piles behavior and in formation of the real wall section's geometrical parameters. For instance, one can meet such cases when significant vertical load caused by crane or other equipment is applied upon front sheet piling of the quay wall, or when rear anchor sheet pile wall of the quay is not equipped with framing beam or concrete cap, etc. So, in such cases there is an engineering/scientific problem to determine real parameters of the flexural stiffness of U-profile sheet piles.

Two extreme cases may be indicated:

- 0% transmission (independent work of each sheet pile in spite of interlock connection) and
- 100% transmission of shear forces in the interlock (i.e. welded interlocks).

Correspondingly in reality, theoretical and effective values of moment of inertia and section modulus may differ several times (e.g. some known experiments demonstrated difference 1.5 – 3.5 times). Regarding gained experience, in reality soil-interlock interaction depends mainly on the installation method and soil properties (it is assumed that the rolling quality of interlocks is good enough and does not influence the longitudinal forces distribution).

One of the most proper methods to study soil-interlock interaction is the press-in method that involves varying the applied forces at specified intervals, speed and steps of loading, direction of the applied force. We suppose that press-in approach provides most effective result from the point of view of friction forces positive utilization (Meshcheryakov, Doubrovsky, Dubrovska. 2018).

The presented study includes analysis of in-situ and laboratory experiments based on press-in of U-profile steel sheet piles which gave possibility, particularly, to work out improved numerical model of sheet pile – soil interaction (Doubrovsky and Meshcheriakov, 2010, 2015). It was aimed to provide reliable numerical modeling and design of the system "sheet pile – soil media". Besides some new technological approaches that may ensure more reliable integrity of adjacent U-profile sheet piles in the wall are worked out and studied (Petrosyan and Doubrovsky, 2017).

It is necessary to note the difference between intervals of loads and pile displacement for the stage of piles installation and for the stage of structure operation. For the last one, piles displacement may be limited by a few millimeters or centimeters under more or less stable loading. During installation, steps of loading as well as piles displacement are larger significantly. So full-scale physical modeling is the most suitable to assess piles behavior during the installation period. Concerning the assessment of the operating stage it is useful to apply precise laboratory tests.

2. In-situ experiments

At the experimental site, off the coast of Odessa (Black Sea), a series of experiments on the base of hydraulic pressing equipment were conducted (**Fig. 1, 2**). The subject of the investigation was U-section sheet pile with Larsen type interlocks. Two pile elements were used in the experiments to clarify the driving effect. Both pile elements were reshaped by cutting along the interlocks including the interlock and part of the flange with a width of 150 mm. The first pile element was 10 m in length while the second was 5 m in length. The first element was considered as the basic (or fixed) element; the second element was pressing-in along the first one and was considered as mobile (**Fig. 2, 3**).

Longer pile element was embedded by pressing until its refusal. Immobility of this pile element along its axis has been provided by fixing of the pile's head after full pile embedding (it was also checked during installation and withdrawal of the mobile pile element).

The mobile pile element (1) was installed and extracted through the interlock (2) of the fixed element (3), see Fig. 2, 3. Due to a preliminary interlock surface preparation, resistance in the interlocks occurred because of two factors: soil-interlock friction during their relative displacement and soil resistance at the end of the mobile sheet pile.

Figure 1. General view of hydraulic pressing equipment (full-scale testing device)

Figure 2. Driving and extracting the mobile pile element (on the right) through the interlock of the basic pile element (left)

There were two different soil foundation types (Fig.3):

Type 1. Existing soil foundation (depth more than 10 m) – mainly fill-up ground (banked earth) with the following main parameters: unit weight 11.0 kN/m^3, internal friction angle 40 degrees, no cohesion.

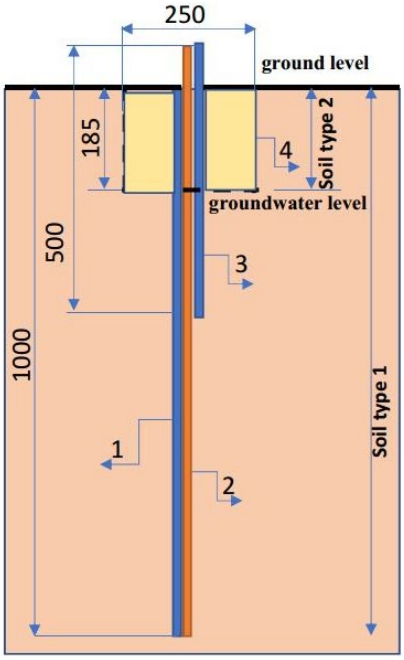


Figure 3. Scheme of the in-situ experiment:
1 – fixed pile (embedded position); 2 – interlock connection; 3 – mobile pile (intermediate position during installation); 4 – sand column

Type 2. Modified type 1 by changing the upper layer (above ground water strata) by fine sand (plan sizes of the sand column (4) were 2500 x 2000 mm; depth 1850 mm as shown in Fig. 3) with the following geotechnical parameters: unit weight 17.6 kN/m^3, internal friction angle 34 degrees. (Note: interlock axis of the basic pile element was located along the vertical axis of this sand column). To prepare such sand column, above mentioned upper layer was moved away manually and dug hole was filled up with sand.

During all tests, the dependence "longitudinal loading – axial displacement" was measured for the considered sheet pile elements.

Applied load was measured by load gauge (dynamometer) with scale factor 0.1 kN; displacements were measured by steel ruler (grating period 1.0 mm).

To provide reliability of the observed data each series of experiments included three similar tests. Stages of each experiment fulfilled:

- Stage 1 - pressing-in of the basic element
- Stage 2 - pressing-in of the mobile element through interlock connection along the basic element
- Stage 3 - extraction of the mobile element through interlock connection.
- Stage 4 - extraction of the basic element.

The second experiment had two options:

Option 1 – sandy soil in the interlocks was of the same density as other filled sand.
Option 2 - soil in the interlocks was of increased density provided by in washing of the sandy pulp (hydraulic filling).

Through the experiments the following parameters were determined (for both types of the foundation soil):

- resistance on the pile surface (friction force)
- resistance under the pile foot (soil reaction while driving)
- resistance in the interlocks (for both directions of relative piles displacement)

Some diagrams relating to the determination of the most interesting parameter – soil resistance in the interlock – are presented in **Fig. 4 and Fig. 5.**

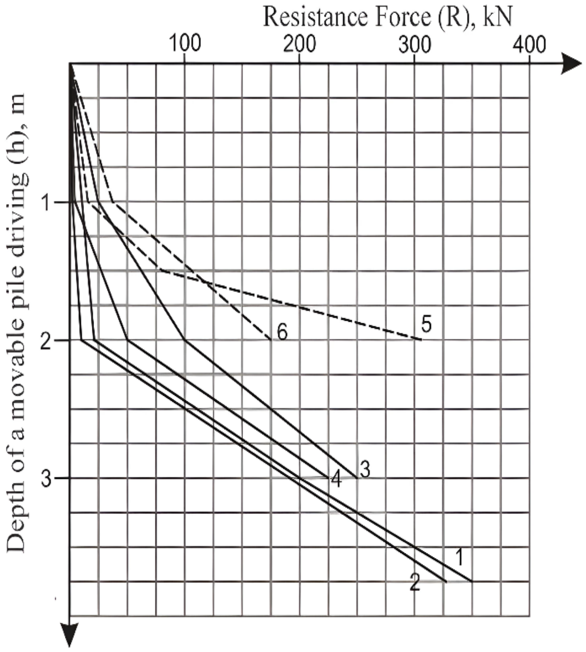


Figure 4. Resistance forces (R) to the depth of a movable pile element pressing in the different soil conditions:
1 – total resistance in the first experiment
3 – the same in the second experiment (option 1)
5 - the same in the second experiment (option 2)
2 – resistance force due to friction in the interlock in the first experiment
4 - the same in the second experiment (option 1)
6 - the same in the second experiment (option 2)

Generally speaking resistance force **R** in the interlock was determined as difference between total resistance for single pile driving just into soil and total resistance to pile driving through interlock connection. Its intensity ***r*** was determined as linear force along the interlock. At the first stage of pressing-in (R≤50 kN) obtained curves are linear; for larger forces (up to 400 kN) these are non-linear (and can be described by curve chart of the second order).

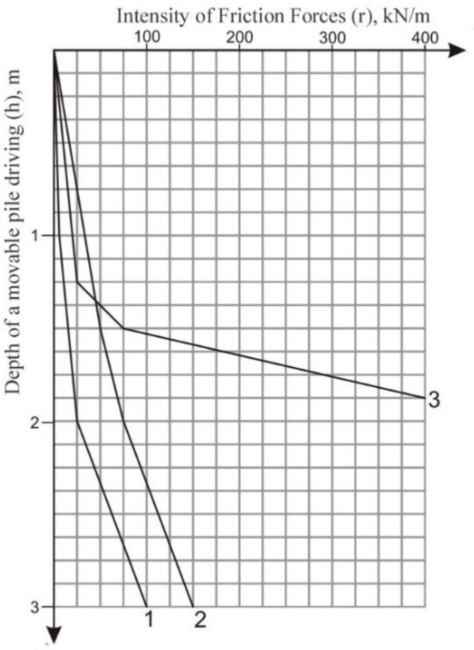


Figure 5. Intensity of friction forces (r) in the interlock of a mobile pile driving in different soil conditions:
1 - for the first experiment; 2, 3 - for the second experiment (options 1 and 2 correspondingly)

More detailed analysis was based on the following. Total resistance forces for installation of fixed R11 and mobile R21 pile elements were determined by direct measurement. Resistance force due to friction in the interlock $R21_t$ was calculated as $R21_t = R21 - R11$. The base resistance at the considered depth $R11_s = R21 - R22$, where R22 – resultant shaft friction and interlock friction resistance (it was determined by direct measurement during mobile pile withdrawal); we assumed that friction forces are the same for pressing and for extracting the pile and that base reactions are the same for fixed and for mobile piles at the considered depth. The shaft resistance of the fixed pile $R11_{fi}$ was calculated as $R11_{fi} = R11 - R11_s$.

As our research was focused on interlocks behavior, tested sheet piles were reshaped by cutting along the interlocks (see above). So, sufficient part of the pile resistance was provided by friction in interlocks.

Some of the basic findings are as follows:

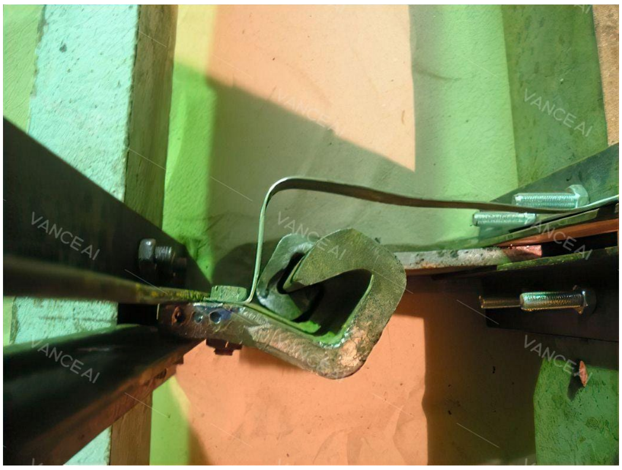
- friction forces in the interlock connections play significant role in the "pile - soil" interaction, reaching 60-90% of total soil resistance to a pile driving; the contribution of friction forces to the total value of resistance increases according to the driving depth of the sheet pile);
- resulting friction force in the interlock and its nonlinear intensity increase as more mobile pile is driven along the interlock connection; character of this nonlinearity may be described by hyperbolic function;
- replacement of the upper strata of initial foundation soil (above ground water) by fine sand provokes an essential increase of soil resistance to pile driving along the interlock mainly due to contribution of friction forces. Such increase may reach 2.5 to 5 times, as shown on the Fig. 4, if to compare graphs 1, 2 either with graphs 3, 4 or with graphs 5, 6.
- additional compressing of the fine sand in the interlock of the basic pile element (by in-washing of the sandy pulp) before driving of the mobile pile element causes a sharp increase of soil resistance to pile penetration.

3. Large scale laboratory test

Laboratory studies were arranged in the Research Laboratory of the Odessa National Maritime University (Department "Sea, River Ports and Waterways"). Interlocks of the same sheet piles as in situ testing as well as the same soils were applied to model similar elements of interaction. One element was fixed and another one was mobile along the pile axis. Both movements of interlock and resistance forces were measured at laboratory testing. Sheet pile elements were pressed-in by jack; applied force was measured by load gauge (dynamometer) with scale factor 0.1 kN; displacements were measured by indicating gage (scale factor 0.01 mm) and by steel ruler (grating period 1.0 mm).

Experimental facilities and equipment for this main testing stand are presented in **Fig. 6**. Relations of "force - displacement" (one of the fulfilled series) are presented in **Fig. 7**.

Tests were provided for two schemes of support of the fixed sheet pile element: underside of the fixed element was supported by bottom of the soil box (similarity to the end-bearing pile) and underside of the fixed element was located in the soil (similarity to the friction pile). These two schemes allow by comparison to assess influence of real boundary conditions at the pile end as well as to study the effect of soil compaction in the interlock in case of opened and closed pile end conditions.



(a) Plan view

b) Front view

Figure 6. Laboratory modeling of pile-pile friction with sandy soil in interlocks

Examination of obtained relations gave possibility to conclude the following. If fixed element works as end-bearing pile, it is more difficult to press-in mobile element via interlock of fixed element in comparison with case when fixed element works as friction pile. Thus, for both series of laboratory experiments [for the same external pressing force in the interval 4 to 20 kN], relative displacements of mobile element along the interlock of fixed element in case of “end-bearing pile” occurred to be 40% larger than in case of “friction pile”.

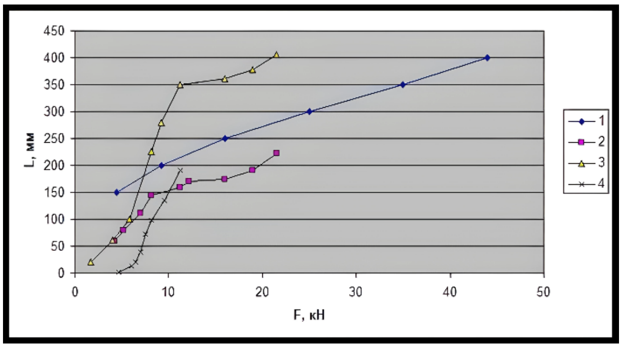


Figure 7. Dependence between displacements of mobile sheet pile element and driving force:

1 - displacements of mobile sheet pile element in case when fixed element works as end-bearing pile;

2 – relative displacements of mobile sheet pile element;

3 – absolute displacements of mobile sheet pile element (jointly with fixed element);

4 - absolute displacements of fixed sheet pile element (jointly with mobile element).

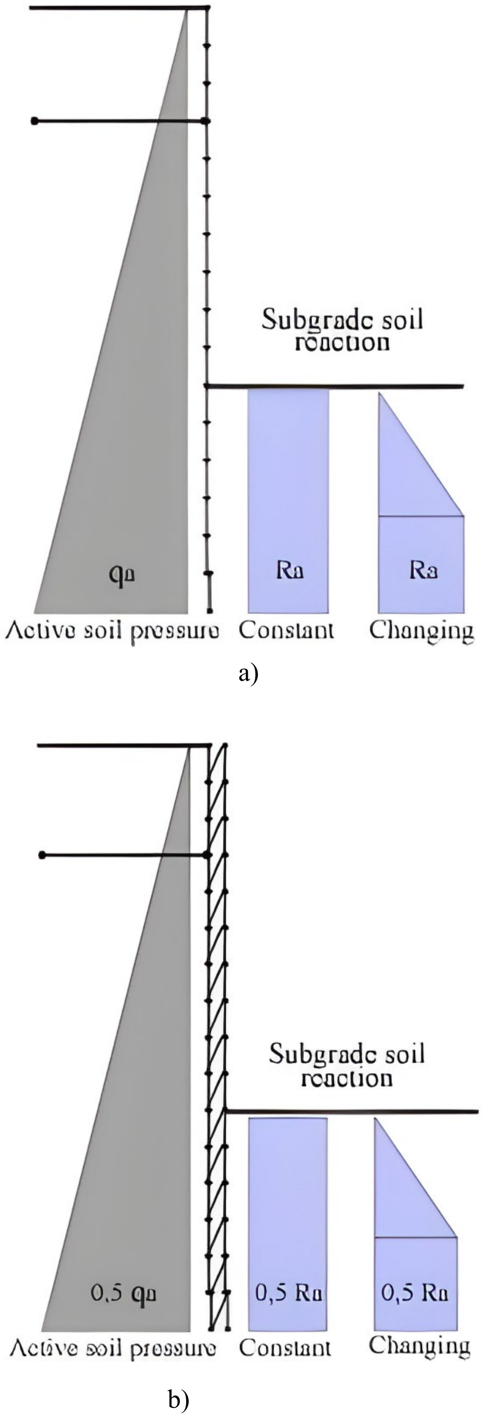
To reach the same relative displacements [in the interval 100 to 275 mm] of the mobile element along the fixed element (the last worked as end-bearing pile), we had to apply to mobile element up to 3 times larger force than in case of fixed element worked as friction pile.

The above-mentioned effect may be explained by development in the interlock (while fixed piled element works as end-bearing pile) of zone of compacted soil between ends of fixed and mobile elements. As both pressing force and relative displacement of mobile element along interlock are increasing, soil’s density inside interlock rises. Correspondingly, resistance of the system to driving of mobile element goes up.

The measured parameters allow for comparatively small intervals (in comparison with the above considered in-situ tests) of applied pressing force to determine mutual displacements of sheet pile elements. Similarity of “resistance force – pile displacement” diagrams both in laboratory and in full scale modeling confirms possibility to use experimental diagrams for creation of numerical model of the system “sheet piling – soil media” in the wide range of loads and displacements to describe peculiarities of friction force influence on interlocks behavior.

4. Numerical modelling

To take into account real conditions corresponding to the friction in the interlocks, consideration and comparison of two schemes are proposed (**Fig. 8**).



a)

b)

Figure 8. Schemes for numerical modeling:

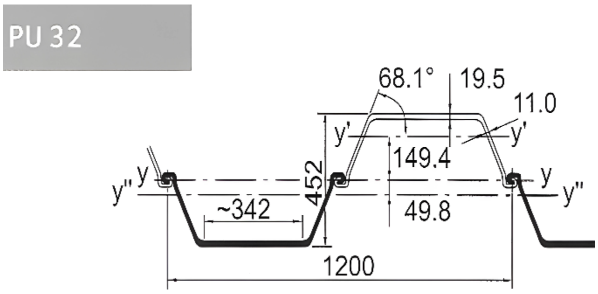
a – traditional scheme; b – proposed scheme;

q_a – intensity of active soil pressure upon the wall at the sheet piling’s foot level; Ra – intensity of soil reaction at the sheet piling’s foot level.

The first scheme considers normal sheet pile wall made of single U-piles **(Fig. 8, a).** Two cases are considered for this traditional scheme:

(1) Running (or linear) wall flexural stiffness corresponds to free interlocks (each sheet pile behaves independently, friction in the interlocks is absent). Stiffness of the wall (per 1 m of its length) is equal to the corresponding stiffness of single piles **(Fig. 9, a)**. For instance, for PU 32 piles **(Fig. 10)** moment of inertia is as follows: 2×10950 cm^4/1.2m = 18250 cm^4/m (25% of maximum possible value). Distance between two rows is reasonable to assume equal to the distance between neutral axis y'-y' of the considered rows. For instance, for PU 32 piles this distance b = 2×149.4 = 298.8 mm (see **Fig. 9**).

a) Single sheet pile



(b) Double sheet pile (crimped)

Figure 9. Rolled U-profile piles

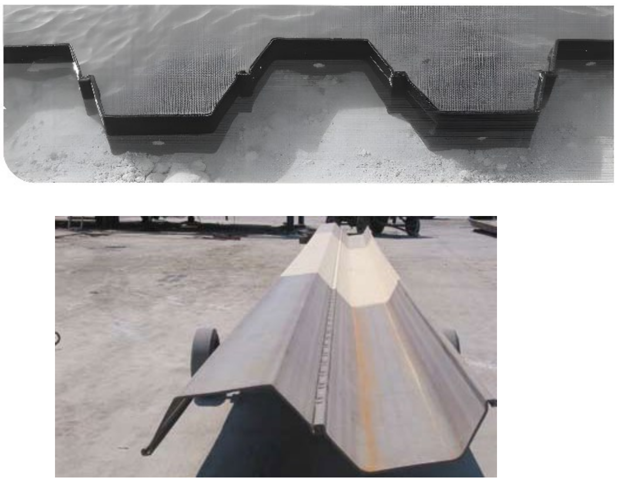


Figure 10. Sheet pile wall made of PU 32 section

(2) Wall flexural stiffness corresponds to fixed interlocks (each sheet pile works together with adjacent piles, friction in the interlocks is full), stiffness of the wall (per 1 m of its length) is equal to the corresponding value indicated by manufacturer **(Fig.9, b).** For instance, for PU 32 piles moment of inertia is 72320 cm^4/m (100% of maximum possible value).

New proposed calculation scheme considers conventional 'double' sheet pile wall made of two rows of single U-piles connected by system of special connecting bar elements **(Fig. 8, b).** To provide compatibility of design approaches flexural stiffness of each row corresponds to the case in **Fig. 8**, a, i.e. to minimum value of moment of inertia. Besides, each row is loaded by a half of active lateral soil pressure exerted upon the wall [i.e. 0.5 qa], as well as soil resistance at the right side of each row is equal to a half of soil subgrade reaction [i.e. 0.5 Ra] used at the traditional scheme.

Also, a half of anchor tie stiffness is used to support each row at the corresponding nodes. Stiffness parameters of the connecting elements can be determined by the following way. Their flexural stiffness (EI) has not to affect the values and distribution of displacements, forces and moments in comparison with the normal wall (EI has to be around zero). Thus, their stiffness in case of axial tension or compression (EF, F – sectional area) has to provide the same values and distribution of displacements, forces and moments in comparison with the normal wall in known cases.

These principles give a possibility to calibrate stiffness parameters of the connecting elements. From comparison with the case in **Fig. 9,a** we can obtain minimum values of (EF) corresponding to 25% of maximum wall stiffness. From comparison with the case in **Fig. 9, b** we can obtain maximum values of (EF) corresponding to 100% of maximum wall stiffness. At last, from experimental data (for instance, obtained in our in-situ and laboratory tests or in other above-mentioned researches), it is possible to use real values of stiffness parameters of the connecting elements. Due to this we can put in initial data for conventional 'double' wall calculation values of (EF) corresponding to real friction in interlock regarding a specific kind of soil.

Parameters of stress-strain state of such conventional 'double' wall with realistic stiffness of connecting elements (for example, maximum wall displacement in horizontal direction as well as maximum bending moment or anchor reaction, etc.) can be used in the analysis of normal wall by the following way.

Regarding above mentioned parameters of stress-strain state of conventional 'double' wall, the flexural stiffness of the normal wall can be corrected to provide the same values of these parameters. So, the intermediate values of flexural stiffness between two extreme cases (25% to 100%) can be obtained by using real values and distribution of interlock shear forces.

In applied software (FEM, structural elements are modeled by bars), only linear law for elastic stage of the bar loading could be used. In the case of high level of axial forces in some connecting elements (when these forces exceed the maximum possible level determined in experiments) iteration approach can be implemented. At each iteration above mentioned elements can be deleted and instead of them a maximum allowable force can be applied.

On the base of fulfilled calculations and obtained results (Doubrovsky and Meshcheriakov, 2010, 2015) it is possible to conclude: standard values of steel sheet pile wall's flexural stiffness in case of single U-piles (PU 32 sections) are largely overestimated and therefore lateral displacements are underestimated (we assume that at the same soil conditions and under the same loads less rigid element is more deformable). In the worst cases effective wall stiffness can be of as little as 32% of the full wall stiffness.

Our calculations based on schemes presented in **Fig. 8** and on described initial data shown that account of real anchor system's pliability (in comparison with case of fixed point of wall anchoring) gives about 10% correction of reduction factors for considered cases. Also, account of changes in subgrade soil reaction values with depth (in comparison with case of its constant values) gives about 7 to 8% correction of reduction factors for considered cases.

5. Some technological modifications

In connection with the above, some improved engineering and technological solutions were worked out (Petrosyan and Doubrovsky, 2017). They are aimed at the creation of reliable and efficient construction of sheet pile wall made of U-shape steel sheet piles with interlock connections located at the zone of the neutral axis of the wall.

5.1. Use of special connection elements

The retaining wall is provided on the inside and outside with tiers of rigid straps distributed in longitudinal and vertical directions, which connect flanges of two or more piles. In this case, the straps connect only those piles that are located on the one side of the neutral axis of the construction, while the positions of the strip tiers height wise correspond to the zones of sheet piles maximum deflections. The role of the straps consists in the prevention of mutual longitudinal displacement of adjacent piles. In such a case, the possibility of sheet piles slipping in interlock connections (irrespectively to the force of friction in the connection) is excluded. Due to this approach, a rigid connection of sheet piles is ensured, which improves the efficiency and reliability of the construction in service (calculated and real values of both moment of inertia and section modulus are the same).

Fig. 11 shows the horizontal cross-section of the berthing structure construction at the level of one of the tiers of rigid straps; **Fig. 12** shows the vertical cross-section and a fragment of the construction facade.

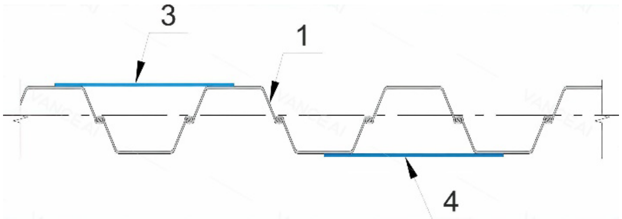


Figure 11. Fragment of the sheet pile wall with connection elements

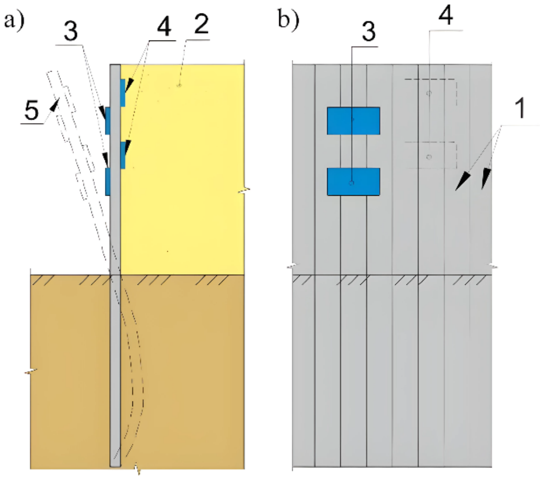


Figure 12. Sheet pile wall with connection elements

The sheet pile retaining wall includes steel U-shape sheet piles 1, driven in soil by the “interlock” method (the locks of sheet piles are located on the neutral axis of the wall) with backfill material 2 behind. Rigid straps (for example, of steel sheet) 3 and 4 are welded to the pile flanges on both sides in the form of tiers along the whole construction. Possible deformations of the sheet pile wall under the influence of the backfill soil active pressure are shown in dotted lines (position 5 on **Fig. 12, a).**

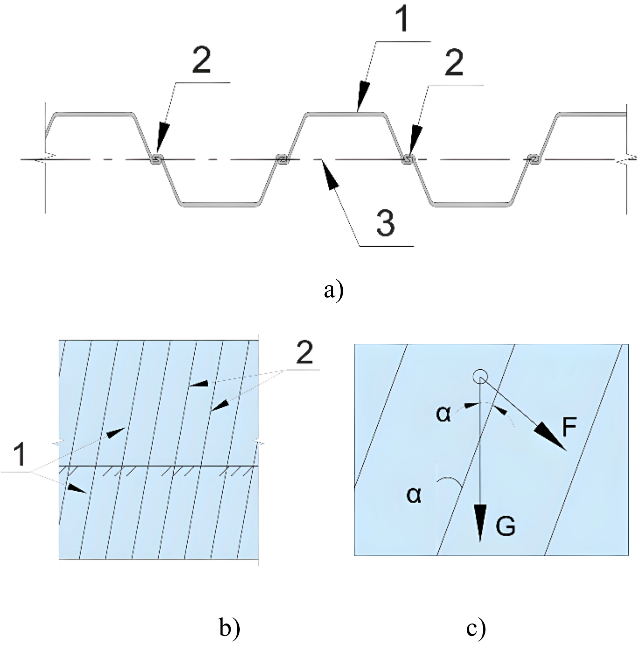
The sheet piling 1 being considered works as follows: under the influence of the backfill soil active pressure the front wall bends as a cantilevered beam driven in the soil at the lower end; as the result of the effect of the backfill active pressure 2, wall 1 will bend and its elastic axis will take position 5. At that, due to the rigidity of the straps, the adjacent piles will not slide in relation to each other in interlocking connections, ensuring thereby maximal (in conformity to manufacturers’ catalogues) values of characteristics of rigidity and geometry of cross sections of the berthing structure.

By varying the sizes of the straps and, consequently, the total length of the welding seam that fixes the plates by their perimeters to the piles flanges, and thus ensuring the connection of the mutual piles, it becomes possible to regulate the degree of free movement of the piles relative sliding in the interlock connections up to its complete elimination. In this way, the effectiveness of the straps welded to the sheet piles flanges can be essentially higher than that of the lap weld, which is made directly in the interlock connection of adjacent piles (because the length of the lap weld is limited by the corresponding length of the interlock connection of the mutual piles). For example, in the piles of European production of the type PU, the length of the lap weld around the perimeter of one strap according to the solution suggested can be 3-4 times as longer than the length of the lap weld in interlock connection at the level of the strap.

5.2. Inclined sheet piles installation

In conformity with the solution suggested, the sheet piles in vertical plane intersect the neutral axis of the wall and the interlock connections of the piles are installed with a rake relative to the vertical. This allows ensuring a growth of friction force in the pile’s interlocks, which prevents mutual displacement of sheet piles in the connections and increases the degree of the construction work as a continuous structure, as well as its rigidity, reliability and effectiveness. The solution of the task is ensured by the fact that each next pile of the sheet pile wall is placed over the interlock connection with the previous pile.

Such positioning of the sheet piles in the berth wall allows transferring a part of the weight of the overlying pile to its interlock connection with the lower pile and thus increasing the friction force in the interlock, which prevents mutual displacement of the sheet piles in the interlocks. **Fig. 13,a** shows a plan of the sheet pile wall construction; **Fig. 13,b** - longitudinal cross-section of the construction; **Fig. 13,c** - the scheme of the effect of the overlying sheet pile on its interlock connection with the underlying pile.



a)

b) c)

Figure. 13. Inclined sheet pile wall:
a - fragment of the plan view; b - fragment of the longitudinal cross-section (facade plane); c - scheme of the effect of overlying pile on the interlock connection with the underlying pile.

The construction **(Fig. 13,a,b)** includes steel sheet piles 1, which are located in the foundation soil with piles interlock connections 2 located on the neutral axis 3, the piles being positioned with a tilt relative to the vertical.

The effective force of overlying pile on the interlock connection with the underlying one is determined by the formula according to **Fig. 13,c** :

$$F = G \cdot \sin\alpha \qquad (1)$$

where:

G—the resultant gravity of the overlying pile;

α—angle of the piles tilt to the vertical.

The force *F*, normal to the axis of the interlock connection, increases the frictional force, which appears at relative displacement of adjacent piles in the interlock connection and prevents sliding of one pile relative to the other in the interlock connection.

Corresponding friction force increment in the interlock connection *Δf*, stipulated by the effect of the force *F*, will be equal to:

$$\Delta f = F \cdot k_t \qquad (2)$$

where,

k_t—co-efficient of friction in the interlock connection of the sheet piles, to be determined experimentally for concrete soils, in which the sheet pile wall is being built and maintained.

From the point of view of quantitative evaluation of the influence of the force *F* on the friction force increment in the interlock connection of sheet piles, the following is worth marking. Theoretically, maximal value of this force with fixed weight of sheet pile *G* according to Eq. (1) corresponds to angle $\alpha = 90°$, i.e., to horizontal position of the sheet piles.

Obviously, such position of sheet piles certainly disagrees with the constructive idea of the considered berthing structure (sheet piling wall).

Technical parameters of the equipment and mechanisms for driving of sheet piles during construction, reconstruction, repair or strengthening the structures being considered present a real limitation of angle *α*. The question is, for example, of drop hammer (diesel, hydraulic), pressing mechanisms (static, hydraulic) or vibro-hammers (electric, hydraulic), which can be either fixed to the heads of the piles being driven, or move on guide mast. In the last case, the angle of rake of the ram guides can make 4-5° to both sides.

At the value of resultant gravity of the overlying pile of standard (for European production) type $G = 30$ kN and the coefficient of friction $k_t = 0.65$, the use of Eqs. (1) and (2) allows determining friction force increment in the interlock connection of adjacent piles as $\Delta f = 2.67$ kN.

Regarding k_t value we can refer to the recommendations related to friction for contact "steel-steel": https://hypertextbook.com/facts/2005/steel.shtml#:~:text=The%20coefficient%20of%20static%20friction,involves%20many%20processes%20and%20stages.

Also, if to consider friction for contact "steel-sand" and assuming that k_t=tan(fi), we may obtain k_t =tan(33^0)= 0,65.

6. Concluding remarks

The fulfilled full-scale experiments and laboratory testing provided new information about development of the friction forces in the interlocks of U profile sheet pile installed by press-in method. The applied experimental techniques allowed the determination of all the main components of soil resistance to sheet pile driving as well as the influence of soil types and soil densities.

The obtained new dependences "interlock friction force - displacement" and/or "intensity of interlock friction force - displacement" may be useful to improve calculation model describing soil – sheet pile interaction and, correspondingly to refine design approaches in retaining walls and quay walls construction. These dependencies may be applied either for the stage of piles installation and for the piled structures operation period.

Improved calculation model to design sheet pile walls was proposed out and applied to concrete structures. Obtained results demonstrated new possibilities to clarify real stiffness parameters of sheet piles regarding development of friction forces during press-in and at the stage of structure operation.

The elaboration of the engineering and technological solutions proposed in this article has been attempted based on quite simple and non-expensive approaches, namely:

- The provision of pairs or groups of piles having the same orientation relative to the neutral axis of the sheet pile wall with the uniting rigid straps;
- The provision for the tilt of sheet piles relative to the vertical in the longitudinal direction of the berthing structure.

The solutions offered ensure:

- more reliable integrity of adjacent sheet piles in the construction of a berthing structure;
- approach of actual values of sheet piling walls geometrical characteristics (inertia moment, section modulus) to their values in the catalogues offered by the manufacturers of steel rolled sheet piles;
- improvement of quality and effectiveness of design solutions;

- lowering the expenses for the maintenance of retaining sheet pile walls.

One of the remaining solutions is to confirm the validity of the proposed approached in this article

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