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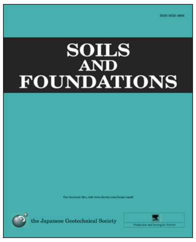

Physical modeling of sheet piles behavior to improve their numerical modeling and design

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Abstract

This paper considers the problem of the determination of the real parameters of the cross-sectional values of sheet piling walls made of U-profile piles (moment of inertia and section modulus) and their drivability with regard to interaction of piles through soil. Among the main factors which influence this are the soil friction in the interlocks and the transmission of longitudinal shear forces in the interlocks of the sheet piles. In the field, the soil–interlock interaction depends mainly on the installation method and the soil properties. The aim of this research was to study the dependencies between the applied forces and the friction in the interlocks by full-scale physical modeling during press-in by taking the pile–pile and interlock–soil interactions into account. The results of the on-site full-scale tests as well as the laboratory physical modeling of U-profile piles in different soil conditions are presented in the paper. Using the data obtained, "force–displacements" diagrams were constructed to assess the influence of soil friction and resistance in the interlocks. The calculation model was improved based on the results to provide a more reliable numerical modeling and design of the "sheet pile–soil media" system. The physical modeling clearly shows the influence of soil behavior on the interlock between sheet piles, especially in the case of saturated sand.

Keywords: Press-in method; Sheet pile; Interlock friction; Full-scale modeling; Press-in equipment

1. Introduction

The evaluation of the flexural stiffness of sheet-pile walls is increasingly important because of necessity to take into account the deformation of the wall for the design at Serviceability Limit States. The stiffness of one pile can be easily calculated based on its geometric shape and the characteristics of the constitutive steel. However, for a sheet-pile wall built up with U shaped sheet-piles, the calculation of the wall stiffness must consider the transfer of shear force between each pile. Indeed, for such walls, the position of the interlock corresponds to the location with maximum shear force.

If the interlock resistance (shear force transmitted from one clutch to the other) is not high enough, a deficit of shear force transmission could develop, resulting in a decrease in the wall stiffness. From the structural viewpoint, we distinguish between walls without shear force transmission in the interlocks and those with shear force transmission (U-profile piles and so called "Jagged Walls", Figs. 1–3).

When determining the cross-sectional values of connected sheet piling, all sheet piles are taken into consideration. U-profile piles and jagged wall-sections, however, may be calculated as a uniform cross-section only if full shear force absorption in the

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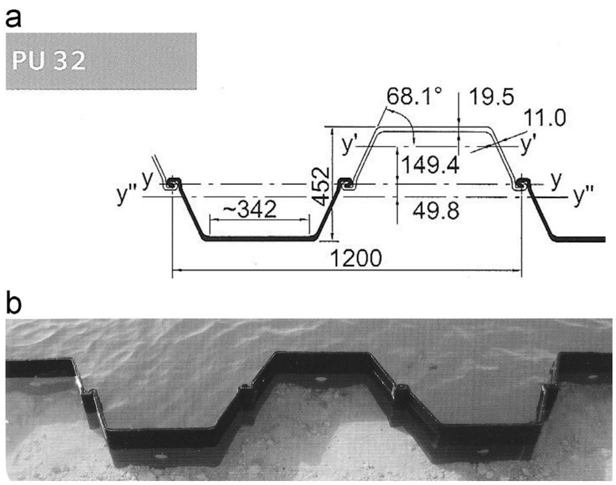

Fig. 1. Sheet pile wall made of PU 32 section: scheme and plan view of driven piles.

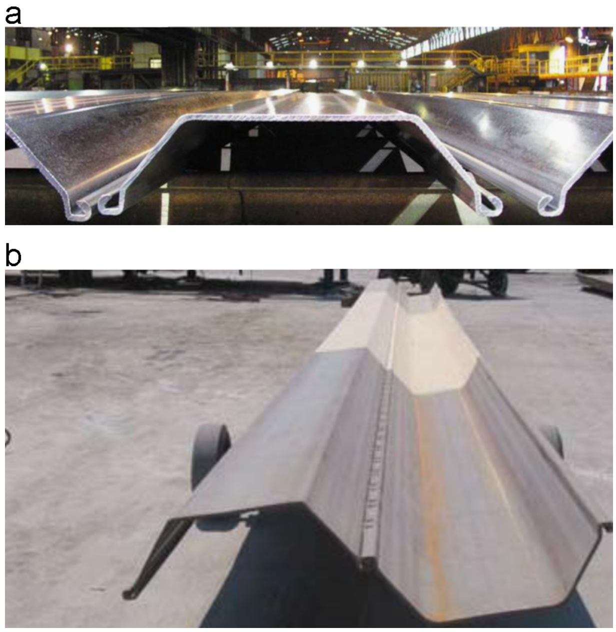

Fig. 2. Rolled U-profile pile. (a) Single. (b) Double, crimped.

Fig. 3. Jagged sheet pile wall.

interlocks is provided. Jagged walls in wave-like form consist of U-shaped or Z-shaped sheet piles in which half the wavelength consists at least of one individual pile. In this case, the uniform cross-section is already achieved by the transmission of shear forces in every second interlock.

In case of two individual piles per half wavelength, 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 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, namely, the degree of displacement.

Above mentioned and other related peculiarities were considered and studied before by number of researchers: Vanden Berghe et al. (2001), Symons et al. (1987), McNulty and Little (1987), Little and Williams (1989), Gajan (2011), Munee et al. (2011) and others.

There are some cases in engineering practice when forces and deformations in the interlocks play a significant role in the behavior of U-section piles and in the formation of the geometric parameters of the real wall section. This happens, for instance, in cases where the significant vertical load caused by crane or other equipment is applied upon the front sheet piling of the quay wall, or when the rear anchor sheet pile wall of the quay is not equipped with a framing beam or a 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 as follows:

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

Correspondingly, in reality, theoretical and effective values of moment of inertia and section modulus may differ by a factor several orders in magnitude. In some cases, the demonstrated difference has been reported to be 1.5–3.5 times.

Regarding gained experience, in the field, the soil–interlock interaction depends mainly on the installation method and the 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 appropriate methods to study the soil–interlock interaction is the press-in method, which involves varying the applied forces at specified intervals, the speed and steps of loading, and the direction of the applied force. It is supposed that the press-in approach provides the most effective results from the point of view of the positive utilization of friction forces.

The present study includes in-situ and laboratory experiments based on the press-in of U-profile steel sheet piles. The results present the possibility, particularly, of improving the numerical model of sheet pile–soil interaction. It was aimed to provide reliable numerical modeling and design of the system "sheet pile–soil media". It is necessary to note the difference between the intervals of loads and pile displacement for the stage of pile installation and for the stage of structure operation. Pile displacements may be limited by a few millimeters or centimeters under more or less stable loading. During installation, the steps of loading as well as pile displacements are significantly larger. As such, full-scale physical modeling is the most suitable method for assessing the behavior of the piles during the installation period.

Concerning the assessment of the operating stage, it is useful to apply precise laboratory tests. In some laboratory and numerical modeling studies (Juaristi, 2001; Gajan, 2011; Doubrovsky, 1999), the interlock–soil interaction for the operation period of the sheet pile wall was evaluated. However, a wider range of soils and pile sections must be considered.

Laboratory tests and the theoretical development were fulfilled in Odessa National Maritime University (The Department of the Sea, River Ports and Waterways). We fulfilled in-situ experiments in cooperation with our colleagues from the Engineering Center Transzvuk (Odessa, Ukraine) with significant experience in press-in applications in civil engineering and modular construction

By studying the dependencies between the applied forces and friction in the interlocks during pressing-in regarding the pile–pile interaction and the soil properties, it was possible to refine the calculation model and to provide a better understanding of the "sheet piling–soil media" behavior.

2. Full scale in situ test

2.1. *Conceptual press-in equipment and technology*

2.1.1. *Modular coordinating piling system*

The basic research for full-scale physical modeling on press-in and extraction equipment was based on the Modular Piling System (Fig. 4). This multifunctional equipment has been developed with the intended purpose of implanting prefabricated construction elements using the press-in method. The piling system is equipped with the original piling machine (wedge-operated clamps) and a modular skidding system (MSS).

The strategic technological advantages of the piling system are its high productivity, precision and quality control (Table 1). The piling system is designed with the modular principle. Modules are identical and interchangeable and can be connected to each other with a wide range of combinations, forming a continuous coordinating grid system, which conforms to the plane of the pile foundation. The modular concept of MSS provides highly precise coordinated movements of the pressing-in equipment. Depending on the features of the project, location of the piles in terms of engineering and geological conditions of the site, pressing construction elements into the ground could be provided with the flow-line and coordinating installation methods. The technology is derived

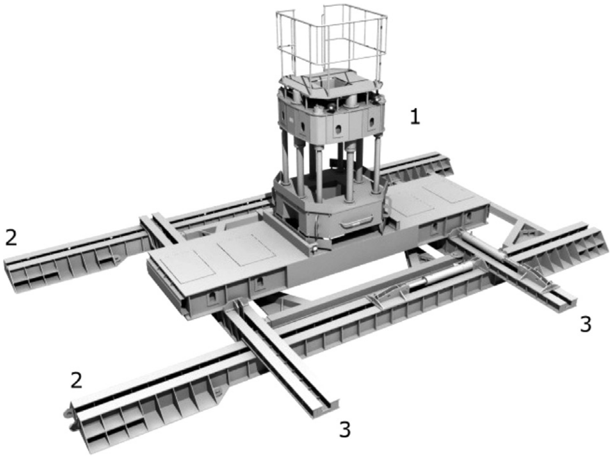

Fig. 4. Modular section of the piling system. (1) press-in piling machine SO-450. (2) Longitudinal guides (skid tracks). (3) Transverse guides (cross slide).

Table 1
Technical specifications of testing stand.

Insertion force	2000 kN (200 t)
Extraction force	1000 kN (100 t)
Positional precision	10 mm
Self-motion	Two-axis controlled

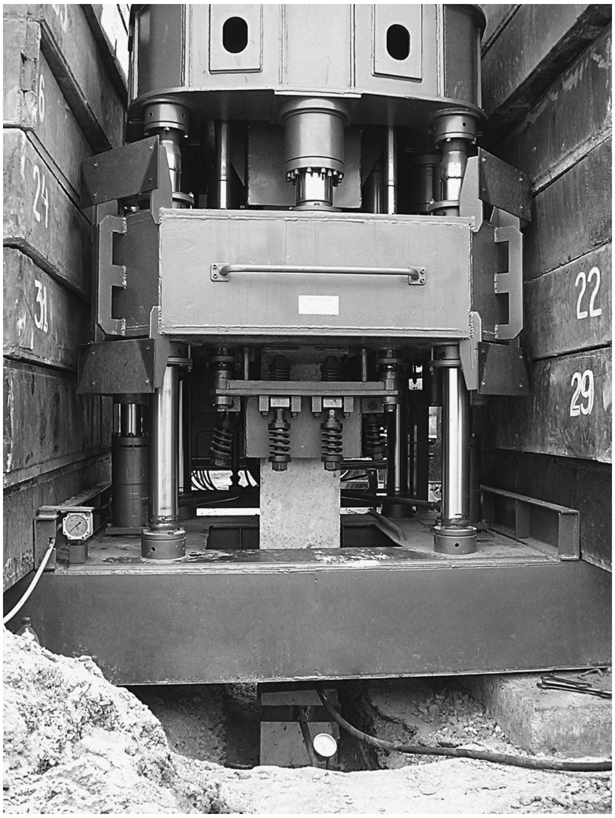

Fig. 5. Press-in piling machine SO-450.

from the superiority of the press-in principle and the conceptual design of the piling equipment.

2.1.2. Press-in piling machine

The hydraulic piling machine, with a side wedge clamping system is intended for the construction of different pile foundations and geotechnical structures using the press-in method. The piling machine is applied for the pressing-in of prefabricated concrete piles, sheet piles and other construction elements with an insertion force up to 2000 kN. Due to the side wedge-clamping system, the inclination of the pile is avoided and there is no limitation to the pile length. The piling machine is also applied as the multifunctional testing stand for the axial testing of piles during installation and after the “set-up” period, excluding the installation of the anchor piles and usage of the conventional heavy testing equipment (Fig. 5). Continuous measurements of the current and final insertion force perform the complete installation monitoring for every pile.

The use of these developments can help to reduce or eliminate static load tests, leading to consequent financial benefits for the client together with the assurance that all piles are supporting required loads and are going to perform in the manner predicted in the design of the pile foundation. This is achieved by an elaboration of the specific correlation between the computerized installation records (load-displacement behavior, soil parameters) and in situ test results. In terms of its impact capability, the piling machine is completely quiet and vibrations in the ground are at an absolute minimum allowing for the machine to work on certain highly sensitive ground areas, extremely small spaces, and in historical preservation areas, while restoration of the foundations are being done, inside basements, elevator shafts and under the floors of buildings.

2.1.3. Modular skidding system

There is no doubt that over the years skidding is still the most appropriate, the most effective and the safest technology for the moving of heavy structures on the construction site (the total weight of the piling system is more than 200 tones).

For the synchronized two-dimensional skidding motion, the MSS employs the hydraulic push-pull and control system, each with four driving cylinders and with a total capacity of 500 kN. The skidding system is designed according to the modular principle (according to the Modular Size Coordination Standard accepted in building engineering) on the base of the following production modules: M10, M12, M15 (basic, medium and multivariate). The modules are identical and interchangeable, and can be connected to each other using a wide range of combinations (in the lengthwise direction, parallel or transversal), forming a continuous coordinating grid system, which conforms to the plane of the pile foundation.

2.1.4. Flow-line sheet pile installation method

The flow-line installation method (Fig. 6) – moving a machine on the longitudinal coordinates in a fixed module section, is used for setting the location of sheet piles in conditions of maximum proximity to existing buildings (less than 1 m).

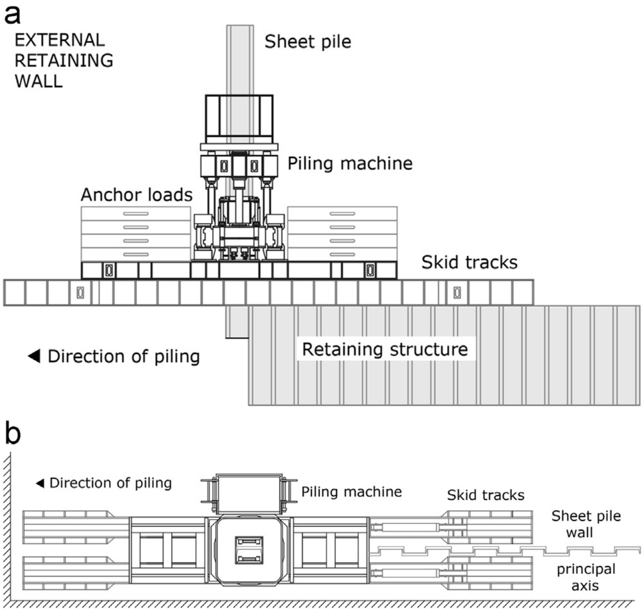

Fig. 6. Installation of sheet pile elements (retaining structure) with a flow-line method. (a) Front view. (b) Plan view.

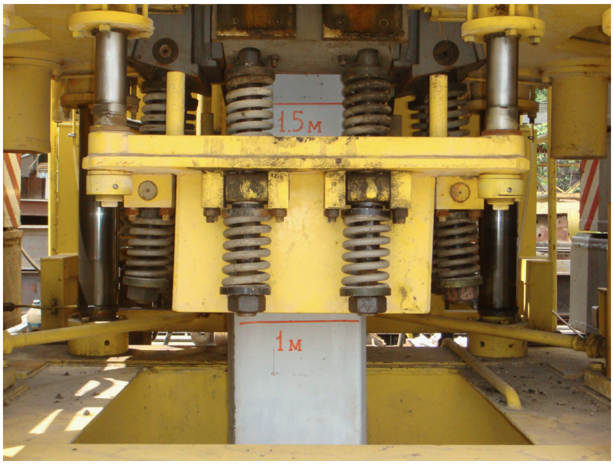

Fig. 7. Pressing-in the basic pile element by hydraulic press-in piling machine SO-450.

2.2. Press-in in-situ experiments

At the experimental site, off the coast of Odessa (Black Sea), a series of experiments on the base of press-in piling equipment were conducted in July 2009 (Figs. 5 and 9). The subject of the investigation was the U-section sheet pile with Larsen type interlocks.

Two pile elements were used in the experiments to clarify the driving effect. Both of the 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 (Fig. 7) was considered as the basic (or fixed) element. The second element (Fig. 8) was pressing-in along the first one and was considered mobile.

Fig. 8. Pressing-in and extracting the mobile pile element (on the right) throw the interlock of the basic pile element (left).

Fig. 9. General view of MSS (full-scale testing device).

The mobile pile element was pressing-in and extracting out through the interlock of the fixed element. Besides the preliminary interlock surface preparation, resistance in the interlocks occurred because of two other factors: the soil-interlock friction during their relative displacement and the soil resistance at the end of the mobile sheet pile (Fig. 9).

There were two different soil foundation types:

Type 1. Existing soil foundation (with a depth of 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°, no cohesion.

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

During all the tests, the dependence “longitudinal loading–axial displacement” was measured to enable the sheet pile elements to be fully considered.

The applied load was measured by a load gauge (dynamometer) with a scale factor of 0.1 kN; and displacements were measured by a steel ruler (grating period 1.0 mm).

Because of the limited time of construction equipment availability, only two experiments were fulfilled by the pressing-in/extracting of the above-mentioned sheet pile elements in different soil conditions (types 1 and 2, as described above).

To ensure the reliability of the observed data, each series of experiments included three similar tests. The stages of each experiment were as follows:

Stage 1 – the pressing-in of the basic element and its fixing in the foundation soil.
Stage 2 – the pressing-in of the mobile element through interlock connection along the basic element at the maximum possible depth.
Stage 3 – the extraction of the mobile element through interlock connection.
Stage 4 – the extraction of the basic element.

The second experiment had two options:

Option 1 – the sandy soil in the interlocks was of the same density as other filled sand.
Option 2 – the soil in the interlocks was of increased density, provided by the in washing of the sandy pulp (hydraulic filling). Through the experiments the following parameters were determined:

1. The components of the soil resistance to sheet pile driving and extraction for the foundation soil – type 1:
   - Resistance on the pile surface (the friction force);
   - Resistance under the pile foot (the soil reaction while pressing-in);
   - Resistance in the interlocks (for both directions of relative piles displacement).
2. The same parameters for the foundation soil of type 2 (option 1).
3. The same parameters for the foundation soil of type 2 (option 2).

Some diagrams relating to the determination of the most interesting parameter – soil resistance in the interlock – are presented in Figs. 10 and 11.

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

2.3. Main findings

Some of the basic findings are as follows:

- friction forces in the interlock connections of the sheet piles play a significant role in the interaction of the elements “pile–

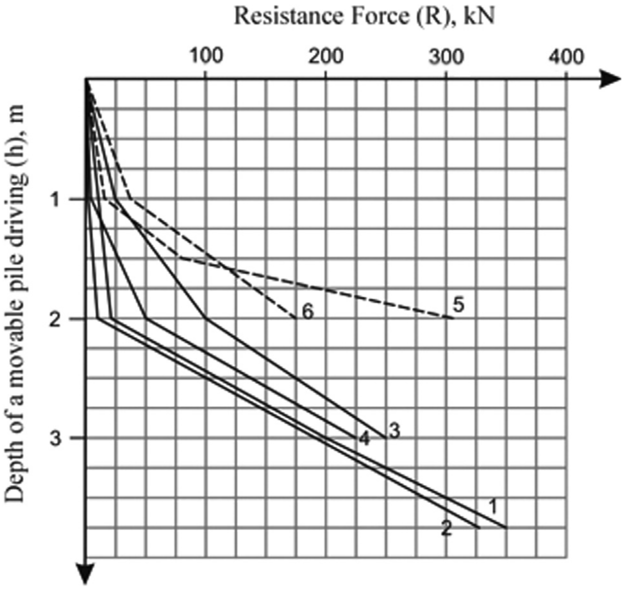

Fig. 10. Resistance forces (*R*) to the depth of a movable pile element pressing in the different soil conditions: (1) total resistance in the first experiment. (2) Resistance force due to friction in the interlock (1exp). (3) The same in the second experiment (option 1). (4) The same in the second experiment (option 2). (5) The same in the second experiment (option 1). (6) The same in the second experiment (option 2).

soil”, reaching 60–90% of total soil resistance to pressing-in a pile; the contribution of friction forces to the total value of resistance increases according to the driving depth of the sheet pile (the indicated interval was determined for the pile elements and soil types used in the experiments);

- the resulting friction force in the interlock and its nonlinear intensity increase as more mobile pile is driven along the interlock connection; the character of this nonlinearity may be described by hyperbolic function;
- the replacement of the upper strata of the initial foundation soil (above ground water) by fine sand provokes an essential increase in the soil resistance to pile driving along the interlock (2.5–5 times as large), mainly due to the contribution of friction forces;
- any additional compressing of the fine sand in the interlock of the basic pile element (by in-washing of the sandy pulp) before the pressing-in 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”) from the end of 2009 to the beginning of 2010. Interlocks of the same sheet piles as in situ testing as well as the same soils were applied in order 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 in the laboratory. Sheet pile elements were pressed-in by jack, and then the applied force was measured by load gauge (dynamometer) with a scale factor 0.1 kN; displacements were measured by indicating the gauge (scale factor 0.01 mm) and by steel ruler (grating period 1.0 mm).

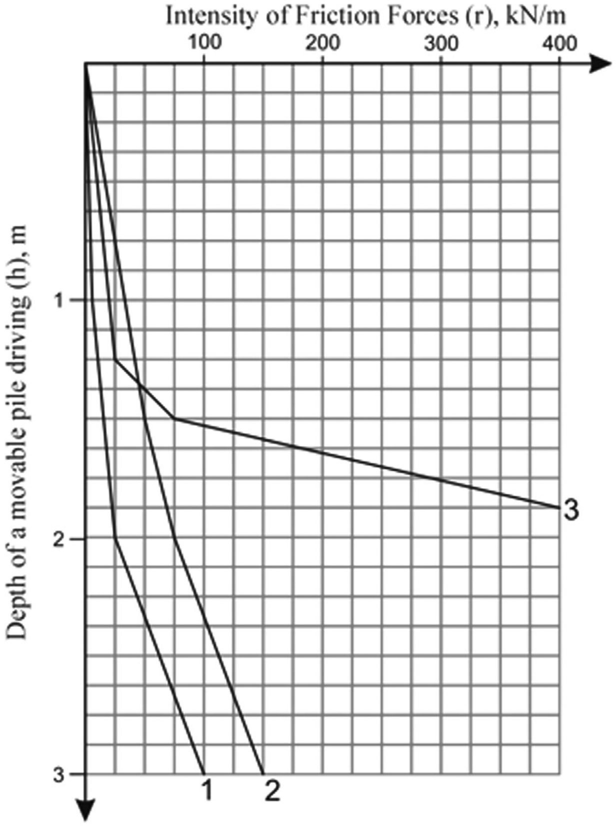

Fig. 11. Intensity of friction forces (*r*) in the interlock of a mobile pile driving in different soil conditions: (1) for the first experiment. (2) For the second experiment (option 1). (3) For the second experiment (option 2).

Two types of experiments were carried out. The first one relates to the horizontal location of sheet piles elements covered by sandy soil (correspondingly piled elements with interlocks were moved horizontally) (Figs. 12–14).

This experiment was considered a preliminary one in order to compare the interlocks interaction with and without the soil inside them. The results obtained relate to the pile–pile interaction (no soil in the interlocks, just steel/steel friction on contacting interlock surfaces) and to sandy soil application (soil type 2, option 1) as illustrated by Fig. 15.

Relations of “resistance force–pile displacement” for the first series (no soil in the interlocks) show stable resistance values after some increase during the initial period of mobile interlock displacements (Table 2).

Dependencies “resistance force–pile displacement” for the case of sandy soil in interlocks are qualitatively similar to the curves described by the in situ testing results.

A comparison of two curves (Fig. 15) demonstrates an essential influence of the presence of soil inside interlocks while the friction forces develop. Thus, for the conditions taken into consideration (comparatively small displacements of the sheet pile elements at intervals of 100–500 mm), the presence of soil in the interlocks stipulated an approximate 10 fold increase in the resistance force

Fig. 12. General view of testing device during laboratory experiment (first series – horizontal location).

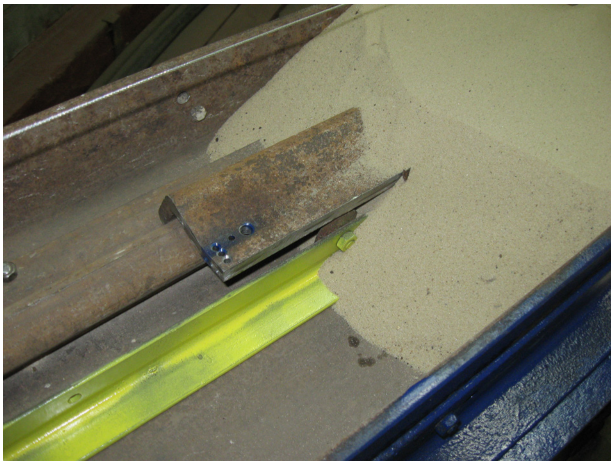

Fig. 13. Laboratory modeling of pile–pile friction with sandy soil in interlocks (first series – horizontal location). (a) Forces. (b) Displacement.

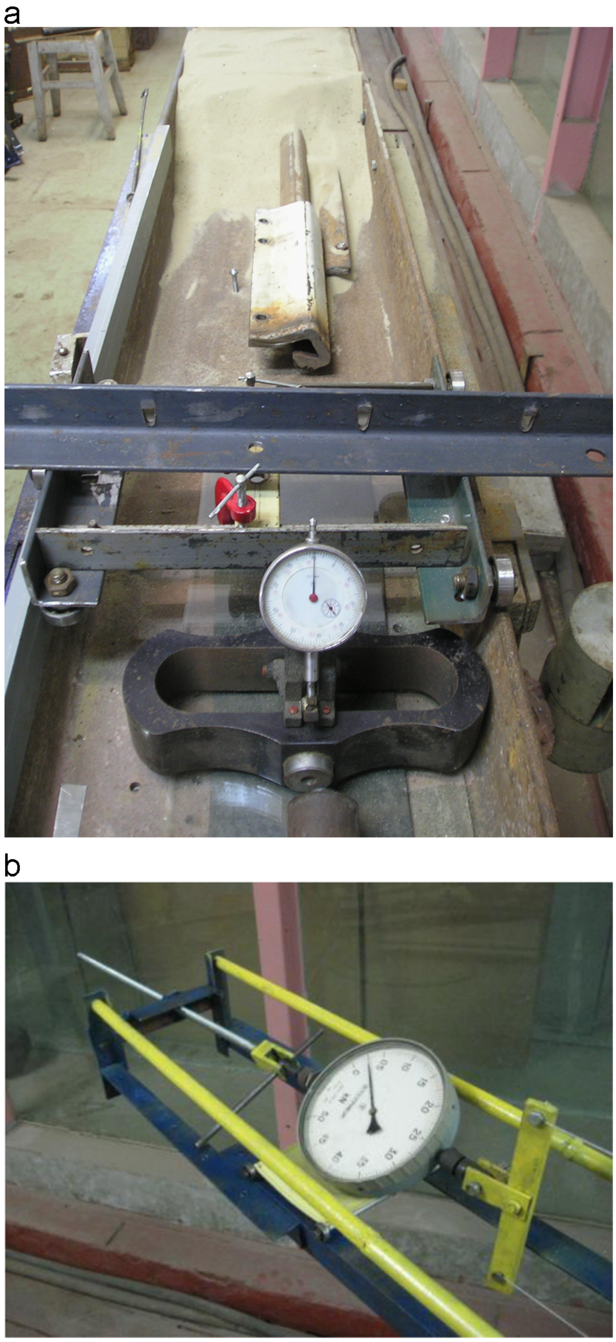

Fig. 14. Forces and displacements measurement. First series – horizontal location. (a) Forces. (b) Displacement.

for the mobile element (in comparison with steel–steel friction without sand in interlock).

The second type of experiment relates to the vertical alignment of sheet pile elements and corresponds to the actual situation on the construction site. Corresponding experimental facilities and equipment for this main testing stand are presented in Figs. 16 and 17.

The testing stand presented in Fig. 17 consists of a soil box (2) with glass walls (3). The soil box is filled with sand, and sheet piles elements (1) are pressed-in the sand through the interlock connection.

Tests were provided for two schemes of support for the fixed sheet pile element: the underside of the fixed element was supported by the bottom of the soil box (similar to the end-bearing pile) and the underside of the fixed element was located in the soil (similar to the friction pile). By comparing these two schemes, it is possible to assess the influence of the 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.

The relations of “force–displacement” obtained for the second type of experiments (two different series) are presented in Figs. 18 and 19. The following conclusions were made based on these relationships:

If a fixed element functions as the end-bearing pile, it is more difficult to press-in a mobile element via interlock of the fixed element than when the fixed element is functions as the friction pile. Thus, for both series of laboratory experiments [for the same external pressing force at intervals of 4–20 kN], the relative displacements of the mobile element along the interlock of the fixed element in case of the “end-bearing pile” was 40% larger than that of the “friction pile”. To reach the same relative displacements [at intervals of 100–275 mm] of the mobile element along the fixed element (the last worked as

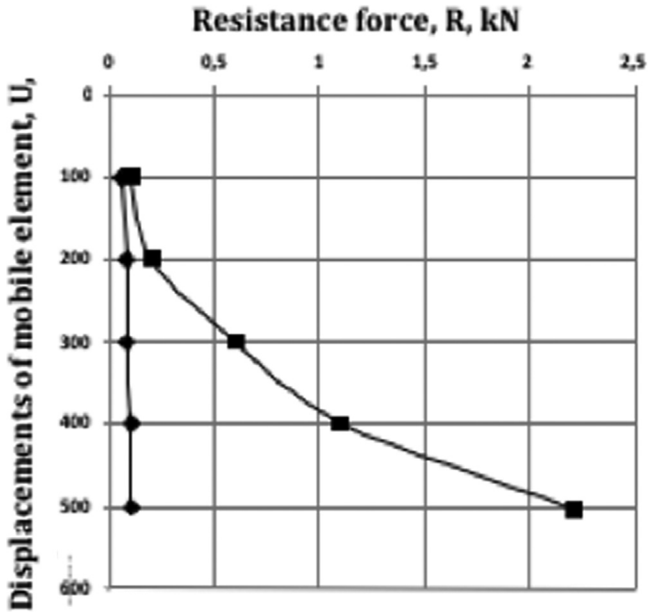

Fig. 15. Resistance force (*R*) as function of displacement (*U*) of mobile piled element along the fixed one without (curve 1) and with (curve 2) sandy soil in interlocks.

Table 2
Press-in piling machine – specifications.

Nom. press-in force	2000 kN
Max. press-in force	2300 kN
Pressing-in speed	1.5–3.5 m/min
Max. cross–section of the pile	500 mm
Power consumption	60 kW t
Machine weight	14 t
Dimensions, m	6 × 1.6 × 3.05
Distance from nearby object	0.9 m
Noise level	85 dB

end-bearing pile), the force we had to apply was up to 3 times larger in the case of a mobile element than when a fixed element was functioning as the friction pile.

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

The relationship between the "pressing force–displacement along interlock" for the considered system "sheet pile elements–soil media" are non-linear. In case of the end-bearing pile scheme (for the fixed element), this dependency at the initial stage of loading [press-in force is up to 10 kN] may be described by parabolic function. For larger external force, the considered function is similar to the linear one. In the case of the friction pile scheme (for the fixed element), we indicated three intervals of mobile element displacement along the fixed one. The first and the third intervals correspond to the pressing of the mobile element along the motionless fixed element. The first interval occurs at the beginning of the press-in process when the mobile element cannot move against the fixed element because of insufficient friction forces in the interlock. The third interval occurs at the final stage of pressing-in when the element is fixed by the experimenter to avoid contact with the bottom of the soil box.

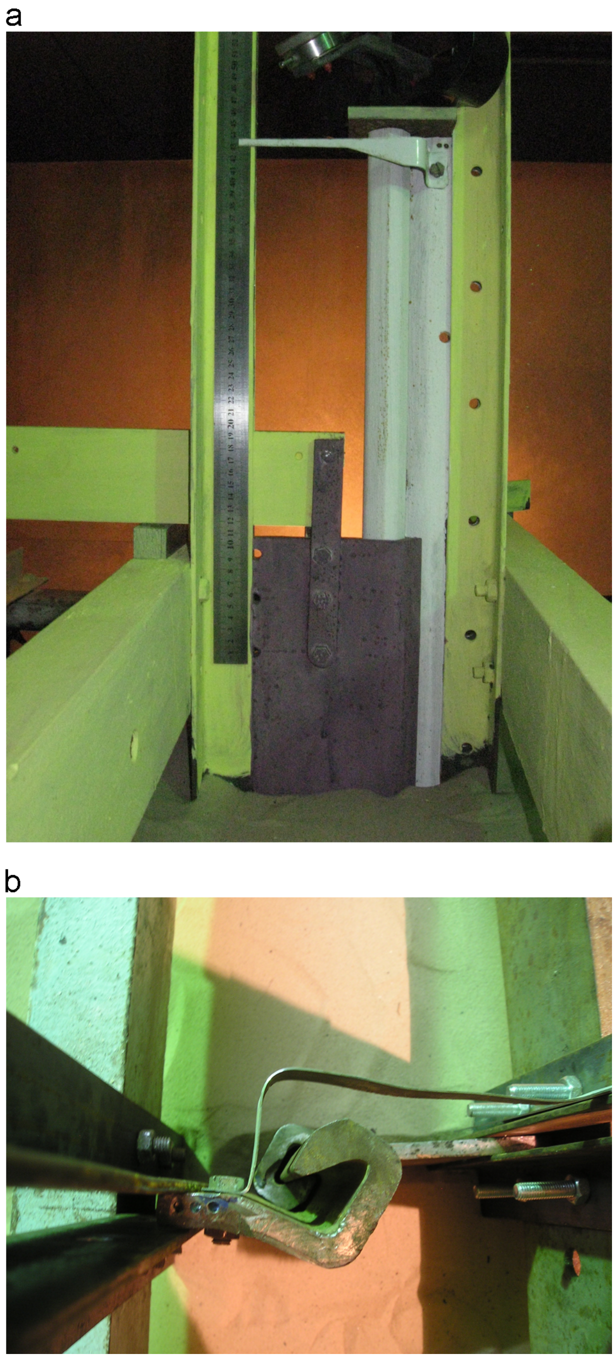

Fig.16. Laboratory modeling of pile–pile friction with sandy soil in interlocks (second series – vertical pile alignment). (a) Front view. (b) Plan view.

The second (intermediate) interval corresponds to the joint movement of both sheet pile elements. Thus, applied pressing force is transferred (due to the development of friction forces) through the mobile element to the fixed in the soil element, and this element is involved in joint movement.

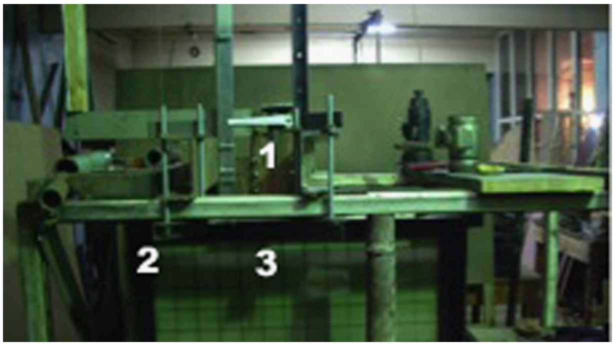

Fig. 17. Laboratory modeling of pile–pile friction: 1 – sheet piles elements; 2 – soil box; 3 – glass walls (second series – vertical pile alignment.).

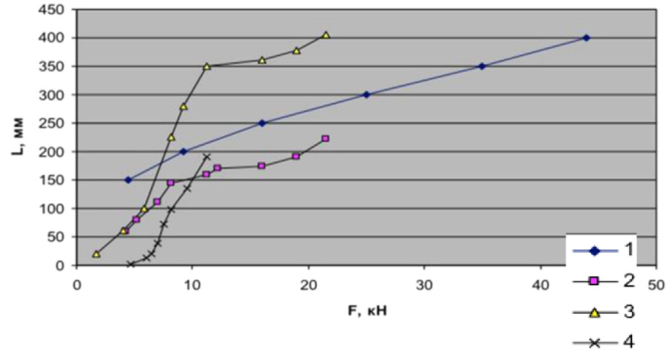

Fig. 18. Dependence between displacements of mobile sheet pile element and press-in force (the first series). (1) Displacements of mobile sheet pile element in case. When fixed element works as end-bearing pile. (2) Relative displacements of mobile sheet pile element. (3) Absolute displacements of mobile sheet pile element (jointly with fixed element). (4) Absolute displacements of fixed sheet pile element (jointly with mobile element).

The measured parameters allow for comparatively small intervals (in comparison with the above considered in-situ tests) of the applied pressing force to determine the mutual displacement of sheet pile elements. Good agreement was found between the “resistance force–pile displacement” results in both the laboratory tests and in the full scale modeling, thus confirming the appropriateness of using experimental diagrams for the creation of a numerical model of the system “sheet piling–soil media” for a wide range of loads and displacements to describe the peculiarities of the friction force influence on interlocks behavior.

4. Numerical modeling

4.1. Approach description

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

The first scheme considers a normal sheet pile wall made of single U-piles (Fig. 20). Two cases are considered for this scheme:

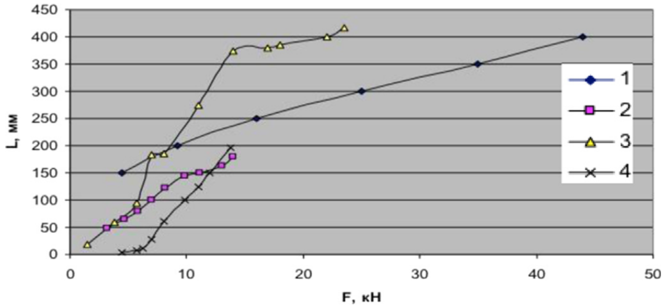

Fig. 19. Dependence between displacements of mobile sheet pile element and press-in force (the second series). (1) Displacements of mobile sheet pile element in case. when fixed element works as end-bearing pile. (2) Relative displacements of mobile sheet pile element. (3) Absolute displacements of mobile sheet pile element (jointly with fixed element). (4) Absolute displacements of fixed sheet pile element (jointly with mobile element).

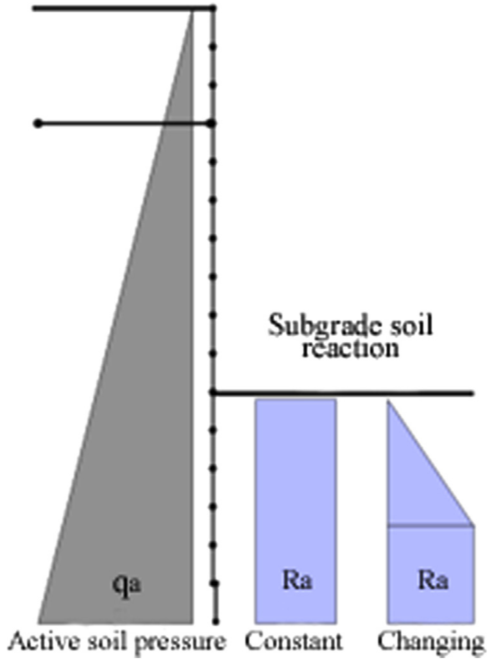

Fig. 20. The first scheme for numerical modeling. qa – intensity of active soil pressure upon the wall at the sheet piling's foot level; Ra – intensity of bottom soil reaction at the sheet piling's foot level.

(1) Running (or linear) wall flexural stiffness corresponds to free interlocks (each sheet pile behaves independently, friction in the interlocks is absent), the stiffness of the wall (per 1 m of its length) is equal to the corresponding stiffness of single piles. For instance, for PU 32 piles moment of inertia is as follows: $2 \times 10{,}950\ \text{cm}^4/1.2\ \text{m} = 18{,}250\ \text{cm}^4/\text{m}$ (25% of maximum possible value). The distance between the two rows is such that it can be assumed equal to the distance between the neutral axis y'–y' (see Fig. 1a) of the considered rows. For instance, for PU 32 piles this distance $b = 2 \times 149.4 = 298.8$ mm (or $+/-0.3$ m).

(2) The flexural stiffness of the wall corresponds to the fixed interlocks (each sheet pile works together with adjacent piles, the friction in the interlocks is full), the stiffness of the wall (per 1 m of its length) is equal to the

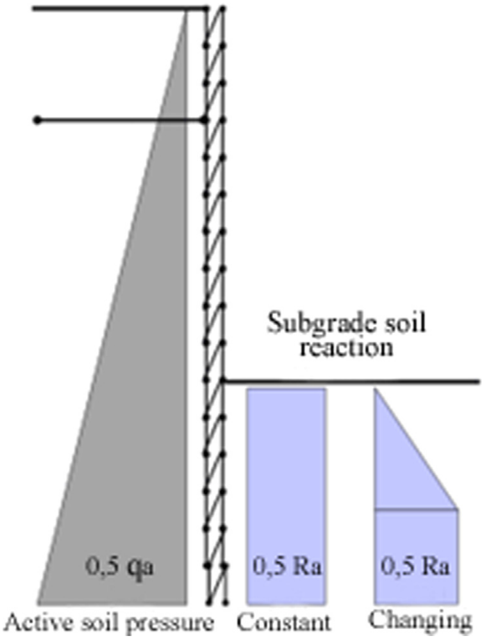

Fig. 21. The second scheme for numerical modeling.

corresponding value indicated by the manufacturer. For instance, for PU 32 piles, the moment of inertia is 72,320 cm^4/m (100% of the maximum possible value).

The second scheme considers the conventional 'double' sheet pile wall made of two rows of single U-piles connected by a system of special connecting bar elements (Fig. 21). The flexural stiffness of each row corresponds to a.m. case (a), i.e. to the minimum value of moment of inertia. Each row is loaded by half the active lateral soil pressure exerted upon the wall [i.e. 0.5 qa] according to the first scheme, and the soil resistance at the right side of each row is equal to a half of the soil subgrade reaction [i.e. 0.5 Ra] used in the first scheme.

Also half of the anchor tie stiffness is used to support each row at the corresponding nodes. The stiffness parameters of the connecting elements can be determined by the following way.

The flexural stiffness of the piles (EI) must not affect the values and distribution of displacements, forces and moments as much as the normal wall (EI has to be around zero). Thus, their stiffness in the case of axial tension or compression (EF, F – sectional area) must provide the same values and distribution of displacements, forces and moments as the normal wall in known cases, (a and b).

These principles make it possible to calibrate the stiffness parameters of the connecting elements. From a comparison with the a.m. case (a) we can obtain minimum values of (EF) corresponding to 25% of maximum wall stiffness. A comparison with a.m. case indicates that (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 research), it is possible to use the 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 the real friction in the interlock for a specific kind of soil.

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

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

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

Of course, the use of more advanced software (elastic-plastic model of bars behavior) provides an opportunity to avoid this iteration process.

4.2. Conditions of numerical modeling

The described approach is implemented in the numerical analysis of a sheet pile wall made of single PU 32 piles. The sheet pile elements studied in our experiments were the same as those investigated by Juaristi (1998) and Vanden Berghe et al. (2001). From these known experimental data, the real values of (EF) can be derived using the correlation between interlock shear force distributions and the connecting elements located in the considered conventional 'double' wall.

For instance, for sandy soil used in the a.m. experiment, the conventional interlock stiffness (per 1 m of interlock in vertical direction) can be obtained as (EF) $z_{\exp}=125$ MN. When the distance along the Z axis between nodes determined at the beginning and the end of the connecting elements in the 'double' wall is equal to 1 m, the values of (EF) for these elements can be obtained as (EF)=(EF) $z_{\exp}/\cos\alpha$, where the α is the angle between the axis Z and the axis of the connecting element. Regarding the number of interlocks related to 1 m of the considered wall for PU 32 piles, we can obtain: (EF)= $125\times 2/(1.2\times 0.3)=69.444$ MN. If the same connecting elements as those for the Young's modulus for steel as used ($E=200{,}000$ MN/m^2), the sectional area of such element, F, is 0.00347 m^2 (for a conventional diameter of about 6 cm).

Calculations were fulfilled using an FEM approximation (a 1-D problem for bar type elements). Two static systems were considered in the analysis: the propped wall and the cantilever wall. In the first case, we considered a wall length of 21 m and the size was according to the PU 32 section, with an excavation depth of 13 m, a strut depth of 3 m, and soil parameters for sandy soil.

In the second case, we considered that the wall length was 13 m and the size was according to the PU 32 section, with an excavation depth of 6.25 m and soil parameters for sandy soil.

Several additional cases were also considered for the purpose of analyzing some of the peculiarities of the investigated structures.

To study the influence of the pliability of the anchor system, a case with a fixed point of anchorage (zero displacement) was considered.

To take a more realistic (and usually used in design practice) distribution of the subgrade soil reaction into account, a case with values that changed with depth was studied.

Further we will use the following indications of the considered cases:

U32-25: normal scheme with wall stiffness corresponding to free interlocks (25% of full maximum stiffness)

U32-100: normal scheme with wall stiffness corresponding to fixed interlocks (100% of full maximum stiffness)

U32-X: conventional ‘double-wall’ scheme with the stiffness of the connecting elements corresponding to the experimental data for gray sand

U32-NN: normal scheme with wall stiffness corresponding to the stress–strain state of the wall obtained in case U32-X (for instance, U32-35 corresponds to a wall with 35% of full maximum stiffness)

4.3. Main results

Main results of the numerical modeling for considered cases are shown in Table 3.

On the base of the obtained results, it is possible to conclude that the standard values of the flexural stiffness of the steel sheet pile wall in the case of single U-piles is largely overestimated, and therefore the lateral displacements are underestimated. In the worst cases, the effective wall stiffness can be as little as 32% of the full wall stiffness.

By taking into account the real pliability of the anchor system (in comparison with the case with the fixed point of wall anchoring), there was a correction of about 10% of reduction factors for the considered cases.

By taking the changes in subgrade soil reaction values with depth into account (in comparison with using constant values), there was a correction of about 7–8% of the reduction factors for the considered cases.

Table 3
Results of numerical modeling U-sheet pile wall.

Sub-table 3a static system U32-25	Parameters of stress–strain state for considered cases of 1 m of the wall		
	U (Mm)	*M* (kN m)	*R* (kN)
Case 1: (a)	87	302	141
(b)	119	359	153
Case 2: (a)	86	319	130
(b)	117	360	142
Case 3: (a)	81	171	
(b)	130	199	

Sub-table 3b static system U32-100	Parameters of stress–strain state for considered cases of 1 m of the wall		
	U (Mm)	*M* (kN m)	*R* (kN)
Case 1: (a)	23	356	152
(b)	34	443	169
Case 2: (a)	22	361	141
(b)	33	447	158
Case 3: (a)	25	172	
(b)	47	227	

Sub-table 3c static system U32-X	Parameters of stress–strain state for considered cases of 1 m of the wall		
	U (mm)	*M* (kN m)	*R* (kN)
Case 1: (a)	64	246	155
(b)	90	302	171
Case 2: (a)	43	202	
(b)	77	100	
Case 3: (a)	63	128	
(b)	103	157	

Sub-table 3d static system U32-NN	Parameters of stress–strain state for considered cases of 1 m of the wall			
	U (mm)	*M* (kN m)	*R* (kN)	*N* (%)
Case 1: (a)	63	309	144	35
(b)	88	374	155	37
Case 2: (a)	44	323		38
(b)	76	391		40
Case 3: (a)	64	173		32
(b)	103	204		34

Notes: the following cases are considered in Table 3: case 1 – anchored wall (real pliability); case 2 – anchored wall (fixed point of anchoring); case 3 – cantilever wall: (a) constant values of subgrade soil reaction; (b) changing with depth values of subgrade soil reaction. Abbreviations: *U* – maximal horizontal displacement, *M* – maximal bending moment, *R* – anchor force.

5. Summary and conclusions

The full-scale experiments and laboratory testing provided new information about the development of the friction forces in the interlocks of the U profile sheet pile implanted by the press-in method. The applied experimental techniques made it possible to determine all the main components of soil resistance in sheet pile driving, and to consider 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 models describing soil–sheet pile interaction and, correspondingly, to refine design approaches in retaining walls and quay wall constructions. These dependencies may be applied to the stage of pile installation and also to operation period of the piled structures.

An improved calculation model for the design of sheet pile walls was developed and applied to concrete structures. The results obtained demonstrate new possibilities to clarify the real stiffness parameters of sheet piles regarding the development of friction forces during press-in and during the stage of structure operation.

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