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LIMIT STATES OF SHALLOW BRIDGE FOUNDATIONS WITH SHEET PILING COVERS

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Abstract. This article presents an analytical method which takes into account the beneficial effects of the sheet piling located around the foundation in the calculations of ULS and SLS of shallow foundations. The analytical method proposed by the author was described in detail on the example of a "theoretical bridge" with the assumed geometry and loads as well as with the assumed subsoil and water conditions under the bridge. The stresses in the subsoil under the foundation and the settlement were determined. The author's method was also used to calculate the foundation settlement of an "existing bridge" located in Gdańsk (Poland). In both cases, the results were compared with the results obtained using PLAXIS 3D Advanced 2023.1 and additionally with geodetic measurements for "existing bridge". The author's proposal was based on the EN 1997-1: Eurocode 7 standard applicable in the European Union. It has original elements that are not included in the cited standard. The proposed method is not the only one that could be used to assess the limit states of shallow foundations with sheet piling cover. However, it is based on the applicable regulations, gives similar results to the results obtained with FEM and geodetic measurements.

Keywords: bridge support, deformation of subsoil, displacements of bridge foundation, finite element method, sheet piling foundation cover, shallow bridge foundation, stresses in subsoil under foundation.

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Introduction

In the design of bridges, the influence of the sheet piling cover made around the shallow foundation on the bearing capacity of the subsoil and the displacements of the foundations is often neglected. In such cases, the calculations of the ultimate and serviceability limit states do not take into account the influence of the sheet piling. Analytical methods are widely known, e.g., in European standards for geotechnical design (European Committee for Standardization, 2004, 2007; expanded and upgraded by annexes and appendixes in 2009, 2010 and 2013) along with examples of their use (Frank et al., 2005; Siwowski et al., 2020; Wysokiński et al., 2011), where foundations (without sheet piling) are treated “only as”: spread foundations (shallow foundations) or pile foundations. Designers assume (often without performing appropriate calculations) that sheet piling cover made around shallow foundations limits displacements of both the foundation and the whole structure. Additional, the foundations with sheet piling cover have a high “level of resistance” to the horizontal inertia force caused by earthquakes (Higuchi et al., 2008).

The main aim of this study is to present an analytical method (based on the assumptions of EN 1997-1: Eurocode 7) that takes into account the beneficial effects of the sheet piling cover around the foundation in the calculations of the ultimate and serviceability limit states of shallow foundations.

The cover of shallow foundations by sheet piling is made due to difficult geotechnical conditions (high groundwater level, stratification of soils with various strength), asymmetry of loads, as well as with the purpose to reduce earth pressure (including lateral earth pressure) and to facilitate and accelerate earthworks and foundation works. In practice, foundations with sheet piling cover are most often designed as “classic” shallow foundations without considering the sheet pile cover in the calculations. This is due to the lack of a calculation method, which would give unambiguous and reliable results for the assessment of limit states (ULS and SLS), taking into account the sheet pile cover.

According to Wymysłowski & Kurałowicz (2012, 2014, 2016, 2022), there are three methods to connect *shallow foundation – sheet piling cover:*

A rigid connection occurs when adequate adhesion of concrete to sheet pile steel is ensured. This adhesion is increased by welding reinforcing bars to the sheet piling cover, while keeping the minimum length of load-bearing welded joints and the length of rebars anchorage, depending on their diameters. The shape of the rebars is most often adapted to the wave shape of the sheet piling cover, and their arrangement and location (reinforcement bars) should avoid the sheet pile interlocks (see Figure 1a). In practice, a more frequently used case is joining rebars while maintaining regular reinforcement mesh. In this way, a sufficient connection of the sheet piling cover to the foundation is achieved by using only several rebars welded to the sheet piles. As a result, the scope of costly and labour-intensive welding of a larger number of reinforcing bars to the sheet piling cover around the perimeter of the foundation and at its height is reduced (see Figure 1b).

A joint connection occurs in the case of small loads, e.g., due to crowd of pedestrians. Therefore, welding the rebars to the sheet piles is not necessary (see Figure 1c). However, an appropriate regime should be kept during concreting (proper compaction of the concrete in places of sheet piling waves) and during concrete maturation (protection against excessive shrinkage and detachment of concrete from the sheet piling). This type of connection is ensured by the adhesion of the concrete of the shallow foundation to the steel of the sheet piles and by the frictional resistance occurring at the contact between the sheet piling and the shallow foundation in the event of loss of adhesion of the concrete to the steel.

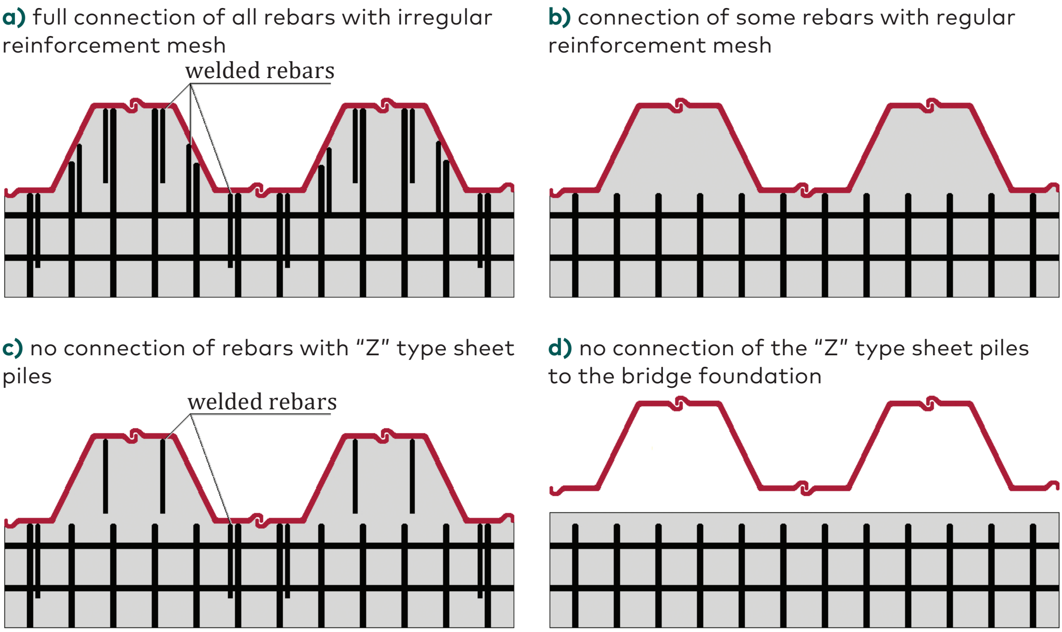

Figure 1. Arrangement of rebars for the scheme connection: "Z" type sheet pile – bridge foundation

A close proximity connection occurs most often when, due to certain circumstances (renovation/reconstruction), the sheet piling cover is made around the pre-existing shallow foundation (Tikanta et al., 2016; Wilmers, 2012). The smaller the distance between the foundation contour and the sheet piling, the greater the impact of the sheet piling cover on the behaviour of the bridge (see Figure 1d).

According to the author, the location of the sheet piling, which also serves as the permanent cover around the foundation of the bridge structure, should be included in the calculations. The most effective type of connection between the sheet piling cover and the foundation is the rigid connection (Wymysłowski & Kurałowicz, 2012, 2014, 2016, 2022).

This article was divided into two main parts. Part No 1 presents the method proposed by the author allowing for the cooperation of the sheet piling cover made around the shallow foundation of the "theoretical bridge" based on the requirements of EN 1997-1: Eurocode 7 when checking the selected ultimate limit state (*ULS – Ultimate Limit State*) and the selected serviceability limit state (*SLS – Serviceability Limit State*). Part No 2 introduces the method of estimating the settlement of the "existing bridge" support foundation based on the method proposed by the author, which is described in detail in Part No 1 (without and with sheet piling cover). For comparative purposes, in both parts of the article, the results of calculations of selected limit states based on the Finite Element Method (FEM) are also presented. The results are compared with those obtained on the basis of theoretical analyses proposed by the author in Part No 1. Additionally, in Part No 2 the settlement values of the "existing bridge" support obtained from the calculations (the author's proposal & FEM) are compared with the real settlements of the same support obtained by geodetic measurements carried out in the field.

1. Part No 1 "Theoretical Bridge" calculations

To demonstrate the computationally beneficial effect of the sheet piling cover for designing the bridge foundation, calculations below were made for two cases: Case No 1 – *shallow foundation of the "theoretical bridge" with sheet piling cover without taking into account the sheet piling* (for simplicity, named "shallow foundation" shown in Figure 2) and Case No 2 – *shallow foundation of the "theoretical bridge" with sheet piling cover including the sheet piling* (for simplicity, named "substitute foundation" shown in Figure 3). In both cases, due to the adopted high level of groundwater, it was necessary to use a sheet piling cover around the foundation. However, only in Case No 2 it was taken into account in the calculations. An additional assumption was to adopt the same settlement value for both foundations of ~50 mm. Adoption of this assumption made it possible to compare the main geometric and strength parameters of two cases of the foundations of the "theoretical bridge". Case No 1 and Case No 2 were the same in terms of bridge use (similar value of settlement), but they differed in terms of the adopted dimensions and the determined bearing capacity of the subsoil under the bridge foundation.

The design of shallow (spread) foundations consists in checking the ultimate limit states (ULS) and serviceability limit states (SLS). The article was limited to checking the ultimate limit state (ULS) of GEO – failure or excessive deformation of the ground based on the DA2 computational approach with a set of coefficients A1+M1+R2 (listed in Table 1) and checking the serviceability limit state (SLS) based on estimating of the foundation settlement *s*.

Table 1. Factors used in the calculations in accordance with the DA2 approach

A1			M1			R2	
γ_G	γ_Q	γ_A	$\gamma_{\gamma'}$	$\gamma_{\phi'}$	$\gamma_{c'}$	$\gamma_{R;v}$	$\gamma_{R;h}$
1.35 or 1.0	1.5 or 0	1.0	1.0	1.0	1.0	1.4	1.1

The adoption of the DA2 calculation approach with the appropriate factors (listed in Table 1) means that the analyses were carried out on the design values of the A1 actions (increase of unfavourable permanent loads by 35%, unfavourable variable loads by 50%, accidental loads were omitted). The favourable action of permanent loads (γ_G = 1.0) and the favourable action of variable loads (γ_Q = 0) were also omitted. The DA2 calculation approach also assumes the adoption of characteristic soil parameters M1 (among others: the effective bulk weight of the soil, the effective angle of internal friction of the soil, and the effective cohesion of the soil). The characteristic value of the bearing capacity determined in this way was converted into the design value by applying the R2 factors (reduced for vertical actions by 40% and horizontal ones by 10%).

For the purposes of the calculations, an analysis of selected limit states (ULS and SLS) was performed for the intermediate support of the "theoretical bridge" (pillar). It was assumed that a homogeneous non-cohesive soil in the form of fine sands (FSa) lied under the foundation of the bridge support, completely below the groundwater table. These are the conditions for which the use of sheet piling cover around the foundation is a typical and fully justified design solution (see Figures 2 and 3).

1.1. Assumptions (for calculation purposes) regarding the intermediate support of the "theoretical bridge"

Geometrical data for foundation on the "shallow foundation" – Case No 1 (see Figure 2) and for foundation on the "substitute foundation" – Case No 2 (see Figures 3 and 4) are listed in Table 2.

Table 2. Comparison of calculation data in accordance with the assumed cases

Calculation data	Case No 1	Case No 2
Foundation width	B_a = 7.50 m	B_b = 5.80 m
Foundation length	L_a = 15.00 m	L_b = 15.00 m
Foundation height	h_a = 1.50 m	h_b = 1.50 m
Foundation depth	D_a = 1.50 m	D_b = 1.50 m
Support height	H_a = 4.50 m	H_b = 4.50 m
Angle of inclination of the base of the foundation to the horizontal	α_a = 0.00 deg	α_b = 0.00 deg
Sheet pile height (designed value)		h_{sp} = 421 mm
Sheet pile width (designed value)		b_{sp} = 700 mm
Sheet pile thickness		t_{sp} = 10 mm
Sheet pile length (in cross section)		l_{sp} = 1064 mm
Unit weight of the sheet pile		w_{sp} = 83.50 kg/m
Number of sheet piles along the width of the foundation		$n_{spB} = B_b/b_{sp} = 9$
Number of sheet piles along the length of the foundation		$n_{spL} = L_b/b_{sp} = 22$
Total number of sheet piles around the perimeter of the foundation		$n_{sp} = 2 \cdot (n_{spB} + n_{spL}) = 62$
Perimeter of the sheet piling foundation cover		$C_{sp} = n_{sp} \cdot l_{sp}$ = 65.97 m
Sheet pile length		S_{sp} = 6.00 m

Table 3. List of loads on the intermediate bridge support of the "Theoretical Bridge"

Type of loads based on the standard EN – 1991: Eurocode 1	G_{Fi} / Q_{Fi}, kN	γ_{Fi}
Vertical reaction applied to the bridge bearings, caused by permanent loads: dead weight of the span structure and elements of equipment	22 000.00	1.35
Support weight: (pile cap + columns + "shallow foundation")	5200.00	1.35
Support weight: (pile cap + columns + "substitute foundation")	4300.00	
Vertical reaction applied to the bridge bearings due to live loads: (Load LM1 + LM4)	2800.00	1.50
Horizontal reaction applied to the bridge bearings parallel to the length of the span, caused by braking and friction on the bearings	500.00	1.50
Horizontal reaction applied to the bridge bearings perpendicular to the length of the span due to wind action	300.00	1.50

Loads (from Table 3 listed in Table 5 and Table 6) and soil parameters are listed in Table 4.

Table 4. Soil parameters

Weight density of subsoil	γ = 19.00 kN/m^3
Weight density of water	γ_w = 9.81 kN/m^3
Gravitational acceleration	g = 9.81 m/s^2
Effective weight density of subsoil	$\gamma' = (\gamma - \gamma_w)$ = 9.19 kN/m^3
Groundwater table (level height)	h_{GW} = 0.00 m
Angle of shearing resistance in terms of effective stress	ϕ' = 30.00 deg
Cohesion intercept in terms of effective stress	c' = 0.00 kPa
Structure (concrete) – ground interface friction angle	δ_c = 30.00 deg
Structure (steel) – ground interface friction angle	δ_s = 20.00 deg
Poisson's ratio of subsoil	ν = 0.30
Young's modulus of subsoil (design value)	E_m = 40.00 MPa

1.2. Calculations of the intermediate support of the "theoretical bridge on the shallow foundation"

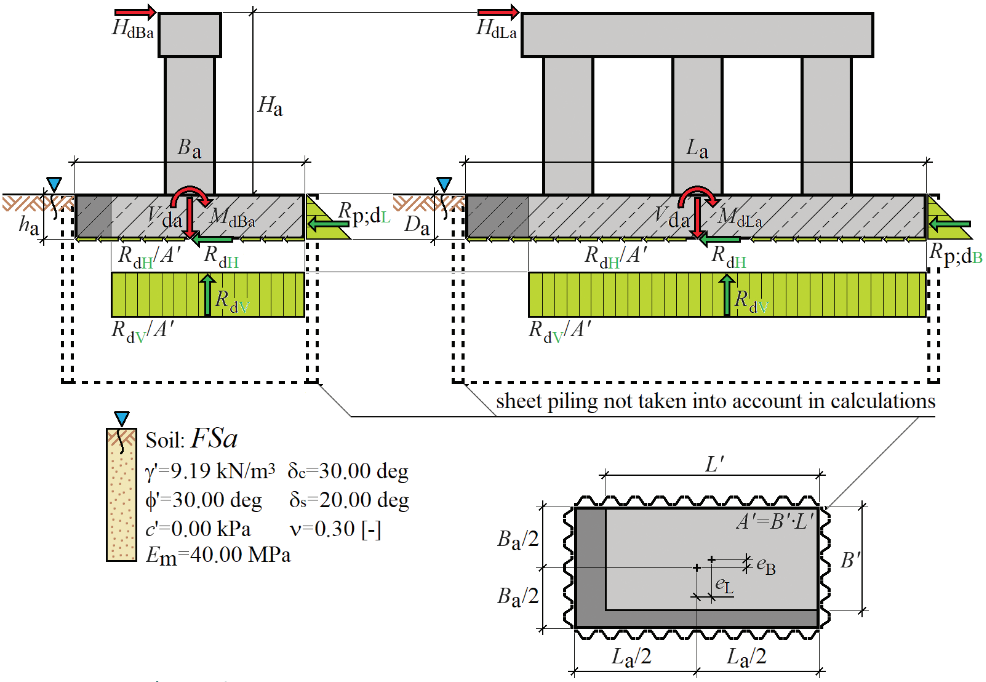

Figure 2. Bridge support of the "theoretical bridge" founded on the "shallow foundation"

Table 5. Forces transferred by the "Shallow Foundation of the Theoretical Bridge" to the subsoil (from Table 3)

Type of forces	Characteristic value	Design value
Horizontal force (B – direction)	H_{kBa} = 500.00 kN	H_{dBa} = 750.00 kN
Horizontal force (L – direction)	H_{kLa} = 300.00 kN	H_{dLa} = 450.00 kN
Bending moment (B – direction)	M_{kBa} = 3000.00 kNm	M_{dBa} = 4500.00 kN
Bending moment (L – direction)	M_{kLa} = 1800.00 kNm	M_{dLa} = 2700.00 kN
Vertical force	V_{ka} = 30 000.00 kN	V_{da} = 40 920.00 kN

1.2.1. Ultimate Limit State (ULS – GEO)

1.2.1.1. Checking the load-bearing capacity of the subsoil under the "shallow foundation of the theoretical bridge"

Subsoil resistance according to EN 1997-1: Eurocode 7 (Annex D) for drained conditions

Determination of the design resistance:

$$R_d = \frac{A'\left(c'N_c b_c s_c i_c + q'N_q b_q s_q i_q + 0.5\gamma' B' N_\gamma b_\gamma s_\gamma i_\gamma\right)}{\gamma_{R;v}} \rightarrow$$

$$R_d = \frac{108.62\left[\left(13.79\times18.4\times1\times1.25\times0.97\right)+\left(0.5\times9.19\times7.3\times20.09\times1\times0.85\times0.96\right)\right]}{1.4} =$$

$$= 66533.63\ \text{kN} \tag{1}$$

$$V_{da} \le R_d \rightarrow 40\,920.00\ \text{kN} < 66\,533.63\ \text{kN} \tag{2}$$

Equation (2) proves, based on the performed calculations, that the requirements of the EN 1997-1: Eurocode 7 standard were assured.

1.2.1.2. Checking the load-bearing capacity of the subsoil for displacement (slip) under the "shallow foundation of the theoretical bridge"

Shear resistance according to EN 1997-1: Eurocode 7 (6.5.3) for drained conditions

Resistance to displacement (slip parallel to the B_a width of the foundation):

$$R_d = \frac{V_d' \tan\delta_k}{\gamma_{R;h}} = \frac{30000 \tan 30}{1.1} = 15745.92\ \text{kN} \tag{3}$$

$$R_{p;d} = \frac{0.5 D_a \sigma_p(z) L_a}{\gamma_{R;h}} = \frac{0.5\times1.5\times9.45\times15}{1.1} = 96.65\ \text{kN} \tag{4}$$

$$H_{\mathrm{dBa}} \le R_{\mathrm{d}} + R_{\mathrm{p;d}} \rightarrow 750.00\ \mathrm{kN} < (15745.92 + 96.65) = 15842.57\ \mathrm{kN} \tag{5}$$

Resistance to displacement (slip parallel to the L_{a} length of the foundation):

$$R_{\mathrm{p;d}} = \frac{0.5 D_{\mathrm{a}} \sigma_{\mathrm{p}}(z) B_{\mathrm{a}}}{\gamma_{\mathrm{R;h}}} = \frac{0.5 \times 1.5 \times 9.45 \times 7.5}{1.1} = 48.32\ \mathrm{kN} \tag{6}$$

$$H_{\mathrm{dLa}} \le R_{\mathrm{d}} + R_{\mathrm{p;d}} \rightarrow 450\ \mathrm{kN} < (15745.92 + 48.32) = 15794.24\ \mathrm{kN} \tag{7}$$

Equations (5) and (7) prove, based on the performed calculations, that the requirements of the EN 1997-1: Eurocode 7 standard were assured.

1.2.2. Serviceability Limit State (SLS – settlement *s*) under the “shallow foundation of the theoretical bridge”

The total foundation settlement E_{da} on non-cohesive soil was estimated using the theory of elasticity according to EN 1997-1: Eurocode 7 (Annex F):

$$E_{\mathrm{da}} = s_{\mathrm{a}} = \frac{p_{\mathrm{a}} B_{\mathrm{a}} f_{\mathrm{a}}}{E_{\mathrm{m}}} = \frac{241.78 \times 7.50 \times 1.11}{40000.00} \approx 50\ \mathrm{mm} \tag{8}$$

$$C_{\mathrm{d}} = 50\ \mathrm{mm}\ \text{– based on EN 1997–1: Eurocode 7 (Annex H)} \tag{9}$$

$$E_{\mathrm{da}} \le C_{\mathrm{d}} \rightarrow 50\ \mathrm{mm} \le 50\ \mathrm{mm} \tag{10}$$

Equation (10) proves, based on the performed calculations, that the requirements of the EN 1997-1: Eurocode 7 standard were assured.

1.3. Calculation of the intermediate support of the “theoretical bridge on a substitute foundation”

Assumptions about the “substitute foundation” (see Figure 3):

1. The “substitute foundation” consists of: an isolated footing or a wall footing, a sheet piling made along the outline of the foundation, and cover-filling soil inside of the sheet piling. The height of the cover-filing soil body extends from the foundation level of the isolated footing or the wall footing to the lower level of the sheet piles.
2. The “shallow foundation” – sheet piling joint is a rigid connection.
3. The cover-filling soil is treated as a dead load.
4. The sheet piling cover (from the outside) is loaded by the rest pressure of the subsoil lying around the “substitute foundation”.

5. As a result of the action of vertical loads and rest pressure of the subsoil: the sheet piling cover is loaded by friction forces. The location of these forces is limited only to the outer surface of the sheet piling cover. The cover-filling soil inside the sheet piling moves and deforms with the entire "substitute foundation" and does not create friction forces on the inner surface of the sheet piling cover.

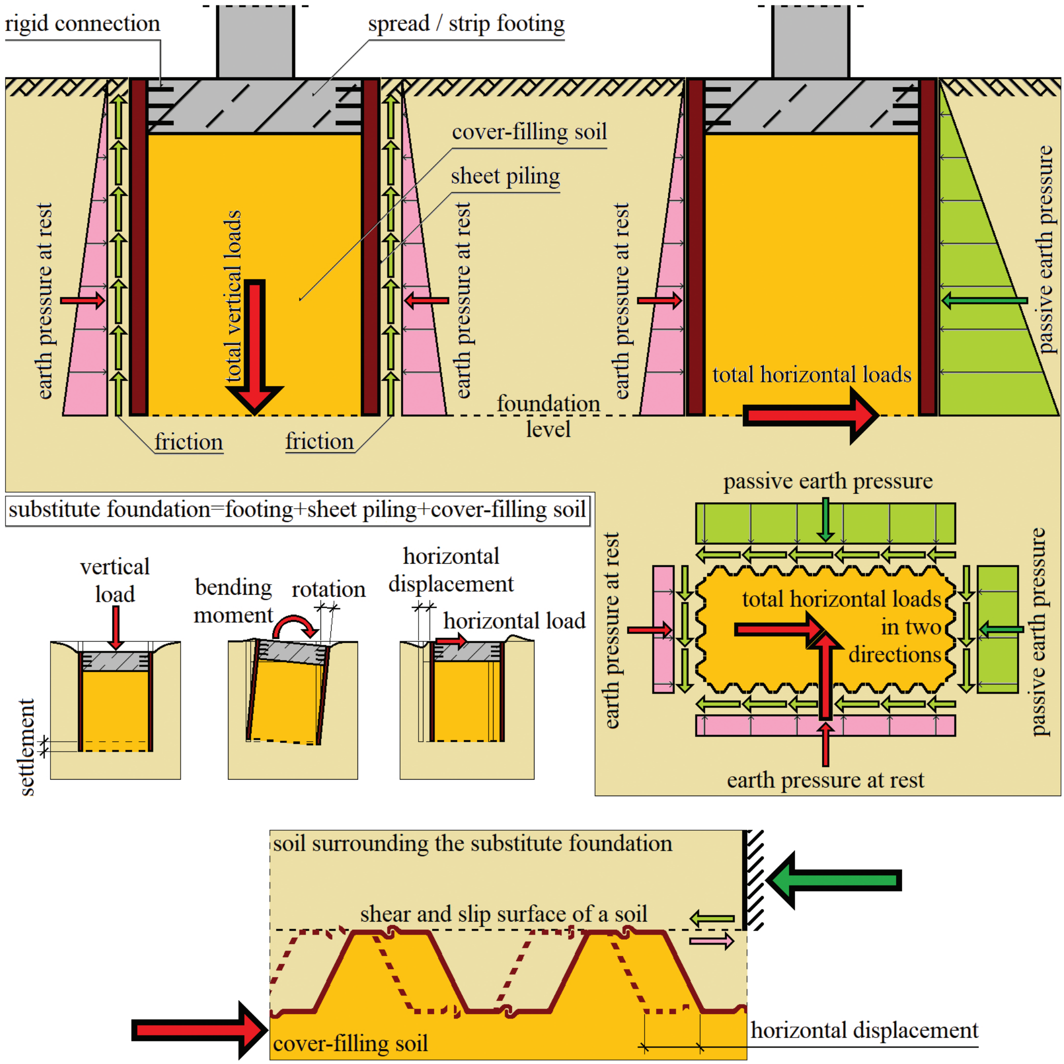

Figure 3. Principle of operation of the "substitute foundation"

6. As a result of the action of horizontal loads and rest pressure of the subsoil: the sheet piling cover is loaded by friction forces and passive soil pressure. The location of these forces is limited only to the outer surface of the sheet piling cover. The soil shear surface, for each side of the "substitute foundation", passes in the place of the convex curvature of the sheet piling wave.
7. The foundation level of the "substitute foundation" is located in the lower level of the sheet piling cover. This has a direct impact on ensuring the appropriate ULS and SLS limit states.

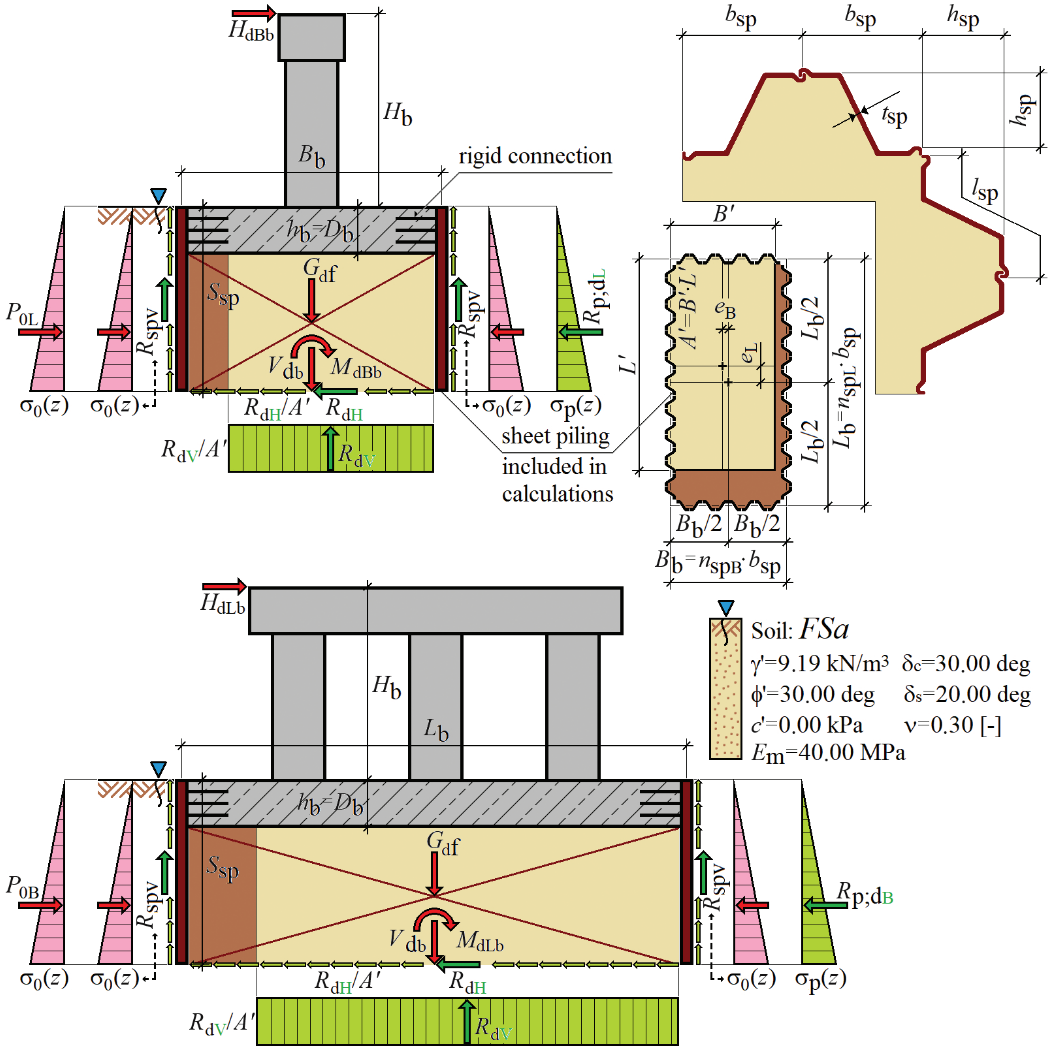

Figure 4. Support of the "theoretical bridge" placed on the "substitute foundation" – subsoil resistances in a vertical view

Table 6. Forces transferred by the "Substitute Foundation of the Theoretical Bridge" to the subsoil (from Table 3)

Type of forces	Characteristic value	Design value
Horizontal force (B – direction)	H_{kBb} = 500.00 kN	H_{dBb} = 750.00 kN
Horizontal force (L – direction)	H_{kLb} = 300.00 kN	H_{dLb} = 450.00 kN
Bending moment (B – direction)	M_{kBb} = 5250.00 kNm	M_{dBb} = 7875.00 kN
Bending moment (L – direction)	M_{kLb} = 3150.00 kNm	M_{dLb} = 4725.00 kN
Vertical force including: $^{(1)}$weight of the "substitute foundation"	V_{kb} = 32 132.82 kN	V_{db} = 43 799.31 kN

$$^{(1)}G_{\mathrm{df}} = \left[w_{\mathrm{sp}}\,S_{\mathrm{sp}}\,n_{\mathrm{sp}}\,g + C_{\mathrm{sp}}\left(S_{\mathrm{sp}} - h_{\mathrm{b}}\right)\gamma'\right]\gamma_{\mathrm{G}} \rightarrow$$

$$^{(1)}G_{\mathrm{df}} = \left[83.5\times 6\times 62\times 9.81 + 65.97\times\left(6-1.5\right)\times 9.19\right]\times 1.35 = \\ = {}^{(1)}4094.31\ \mathrm{kN} \tag{11}$$

($^{(1)}$by Michał Wymysłowski shown in Figure 4)

1.3.1. Ultimate Limit State (ULS – GEO)

1.3.1.1. Checking the load-bearing capacity of the subsoil under the "substitute foundation of the theoretical bridge"

Subsoil resistance according to EN 1997-1: Eurocode 7 (Annex D) for drained conditions.

R_{d} – resistance determined by analogy for the "shallow foundation", taking into account the geometry of the "substitute foundation" shown in Figure 4.

$^{(2)}R_{\mathrm{spv}}$ – resistance caused by the vertical friction forces of the "substitute foundation" of the bridge in the subsoil.

($^{(2)}$by Michał Wymysłowski shown in Figure 4)

$$R_{\mathrm{d}} = \frac{A'\left(c'N_{\mathrm{c}}b_{\mathrm{c}}\,s_{\mathrm{c}}\,i_{\mathrm{c}} + q'N_{\mathrm{q}}b_{\mathrm{q}}s_{\mathrm{q}}i_{\mathrm{q}} + 0.5\gamma' B' N_{\gamma}b_{\gamma}s_{\gamma}i_{\gamma}\right)}{\gamma_{\mathrm{R;v}}} \rightarrow$$

$$R_{\mathrm{d}} = \frac{81.03\left(55.14\times 18.4\times 1\times 1.18\times 0.97 + 0.5\times 9.19\times 5.48\times 20.09\times 1\times 0.89\times 0.96\right)}{1.4} = \\ = 92230.09\ \mathrm{kN} \tag{12}$$

$$^{(2)}R_{\mathrm{spv}} = \frac{0.5 S_{\mathrm{sp}}\sigma_0\left(z\right)C_{\mathrm{sp}}\tan\delta_{\mathrm{s}}}{\gamma_{\mathrm{R;v}}} = \frac{0.5\times 6\times 57\times 65.97\tan 20}{1.4} = \\ = {}^{(2)}2932.79\ \mathrm{kN} \tag{13}$$

$$V_{db} \le R_d + {}^{(2)}R_{spv} \rightarrow$$

$$43799.31 \text{ kN} < \left(92230.09 + {}^{(2)}2932.79\right) = 95162.88 \text{ kN} \tag{14}$$

Equation (14) proves, based on the performed calculations, that the requirements of the EN 1997-1: Eurocode 7 standard were assured.

1.3.1.2. Checking the load-bearing capacity of the subsoil for displacement (slip) under the "substitute foundation of the theoretical bridge"

Shear resistance according to EN 1997-1: Eurocode 7 (6.5.3) for drained conditions

R_d – resistance determined by analogy for the "shallow foundation", taking into account the geometry of the "substitute foundation" shown in Figure 4.

$R_{p;d}$ – resistance determined by analogy for the "shallow foundation", taking into account the geometry of the "substitute foundation" shown in Figure 4.

${}^{(3)}R_{sph}$ – resistance caused by the horizontal friction forces of the bridge "substitute foundation" in the subsoil.

${}^{(4)}P_{0L}$; ${}^{(4)}P_{0B}$ – rest pressure of the soil acting on the "substitute foundation" of the bridge with the orientation and direction consistent with the horizontal force parallel to the length of proper side of the "substitute foundation" (properly: ${}^{(4)}P_{0L} || H_{dBb}$ and ${}^{(4)}P_{0B} || H_{dLb}$).

(${}^{(3\,;\,4)}$by Michał Wymysłowski shown in Figures 4 and 5)

Resistance to displacement (slip parallel to the B_b width of the foundation):

$$R_d = \frac{V_d' \tan\delta_k}{\gamma_{R;h}} = \frac{32132.82 \tan 30}{1.1} = 16865.36 \text{ kN} \tag{15}$$

$$R_{p;d} = \frac{0.5 S_{sp} \sigma_p (z) L_b}{\gamma_{R;h}} = \frac{0.5 \times 6 \times 37.8 \times 15}{1.1} = 1546.36 \text{ kN} \tag{16}$$

$${}^{(3)}R_{sph} = \frac{0.5 S_{sp} \sigma_0 (z) 2 B_b \tan \frac{\varphi' + \delta_s}{2}}{\gamma_{R;h}} =$$

$$= \frac{0.5 \times 6 \times 57 \times 2 \times 5.8 \tan \frac{30 + 20}{2}}{1.1} = {}^{(3)}840.88 \text{ kN} \tag{17}$$

$${}^{(4)}P_{0L} = \frac{0.5 S_{sp} \sigma_0 (z) L_b}{\gamma_{R;h}} = \frac{0.5 \times 6 \times 57 \times 15}{1.1} = {}^{(4)}2331.82 \text{ kN} \tag{18}$$

$$H_{\mathrm{dBb}} \le R_{\mathrm{d}} + R_{\mathrm{p;d}} + {}^{(3)}R_{\mathrm{sph}} - {}^{(4)}P_{0\mathrm{L}} \rightarrow$$
$$750.00\ \mathrm{kN} < \left(16865.36 + 1546.36 + {}^{(3)}840.88 - {}^{(4)}2331.82\right) =$$
$$= 16920.78\ \mathrm{kN} \tag{19}$$

Resistance to displacement (slip parallel to the L_b length of the foundation):

$$R_{\mathrm{p;d}} = \frac{0.5 S_{\mathrm{sp}} \sigma_{\mathrm{p}}(z) B_{\mathrm{b}}}{\gamma_{\mathrm{R;h}}} = \frac{0.5 \times 6 \times 37.8 \times 5.8}{1.1} = 597.93\ \mathrm{kN} \tag{20}$$

$$^{(3)}R_{\mathrm{sph}} = \frac{S_{\mathrm{sp}} \sigma_0(z) L_{\mathrm{b}} \tan \frac{\varphi' + \delta_{\mathrm{s}}}{2}}{\gamma_{\mathrm{R;h}}} =$$
$$= \frac{6 \times 57 \times 15 \tan \frac{30 + 20}{2}}{1.1} = {}^{(3)}2174.69\ \mathrm{kN} \tag{21}$$

$$^{(4)}P_{0\mathrm{B}} = \frac{0.5 S_{\mathrm{sp}} \sigma_0(z) B_{\mathrm{b}}}{\gamma_{\mathrm{R;h}}} = \frac{0.5 \times 6 \times 57 \times 5.8}{1.1} = {}^{(4)}901.64\ \mathrm{kN} \tag{22}$$

$$H_{\mathrm{dLb}} \le R_{\mathrm{d}} + R_{\mathrm{p;d}} + {}^{(3)}R_{\mathrm{sph}} - {}^{(4)}P_{0\mathrm{B}} \rightarrow$$
$$450\ \mathrm{kN} < \left(16865.36 + 597.93 + {}^{(3)}2174.69 - {}^{(4)}901.64\right) =$$
$$= 18736.34\ \mathrm{kN} \tag{23}$$

Equations (19) and (23) prove, based on the performed calculations, that the requirements of the EN 1997-1: Eurocode 7 standard were assured.

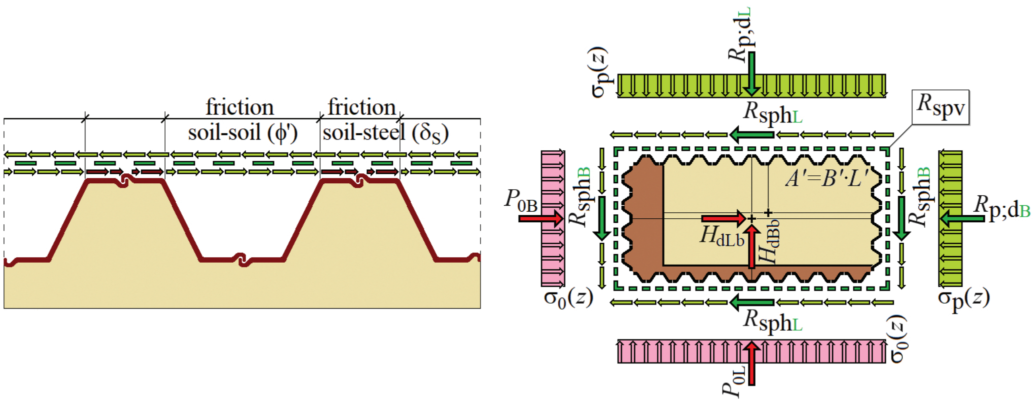

Figure 5. Support of the "theoretical bridge" placed on the "substitute foundation" – soil resistances in the horizontal view

1.3.2. Serviceability Limit State (SLS – settlement *s*) under the "substitute foundation of the theoretical bridge"

The total foundation settlement E_{db} on non-cohesive soil was estimated using the theory of elasticity according to EN 1997-1: Eurocode 7 (Annex F):

p_b – pressure on the soil, distributed linearly under the "substitute foundation" of the bridge reduced by [(2)]the characteristic resistance force due to the vertical friction of the "substitute foundation" of the bridge in the subsoil (explained in 1.3.1.1).

$$E_{db} = s_b = \frac{p_b B_b f_b}{E_m} = \frac{289.96 \times 5.8 \times 1.20}{40000.00} \approx 50\,\text{mm} \tag{24}$$

$$C_d = 50\,\text{mm} - \text{based on EN 1997–1: Eurocode 7 (Annex H)} \tag{25}$$

$$E_{db} \leq C_d \rightarrow 50\,\text{mm} \leq 50\,\text{mm} \tag{26}$$

Equation (26) proves, based on the performed calculations, that the requirements of the EN 1997-1: Eurocode 7 standard were assured.

1.4. Calculations using the Finite Element Method (FEM)

For numerical calculations, to determine theoretical displacements from the available geotechnical software, the computer program called PLAXIS 3D Advanced 2023.1 was selected. It was used for a scientific analysis of engineering structures and geotechnical issues showing a non-linear reaction of the subsoil medium.

To describe the numerical subsoil under the foundations, the Coulomb-Mohr (MC) plastic model for conditions with drainage was adopted in all cases. The Coulomb-Mohr model required defining the following parameters: the stiffness parameters – effective Young's modulus and effective Poisson's ratio; the strength parameters – effective cohesion, effective friction angle, dilatancy angle (PLAXIS 3D 2023.1–Reference Manual 3D, 2023).

The Linear Elastic model (LE) for concrete was used to model the foundations of supports cooperating with the subsoil. The necessary parameters to define them were – effective Young's modulus and effective Poisson's ratio (PLAXIS 3D 2023.1–Reference Manual 3D, 2023).

The shell elements (plates) were used to model the steel sheet piling foundation cover as structural objects used to model thin two-dimensional structures in the ground with a significant flexural rigidity (bending stiffness) (PLAXIS 3D 2023.1–Reference Manual 3D, 2023).

The interface elements (contact surface, contact elements) were used at the contact point between the sheet piling foundation cover and the surrounding soil. For real soil-structure interaction, the interface is weaker and more flexible than the surrounding soil (PLAXIS 3D 2023.1–Reference Manual 3D, 2023). Therefore, in the case of interface elements, a factor was used to reduce their strength and stiffness: 0.667 for non-cohesive soils and 0.5 for cohesive soils.

Settlements under the "shallow and substitute foundation of the theoretical bridge" were determined using the Finite Element Method (see Figures 6 and 7).

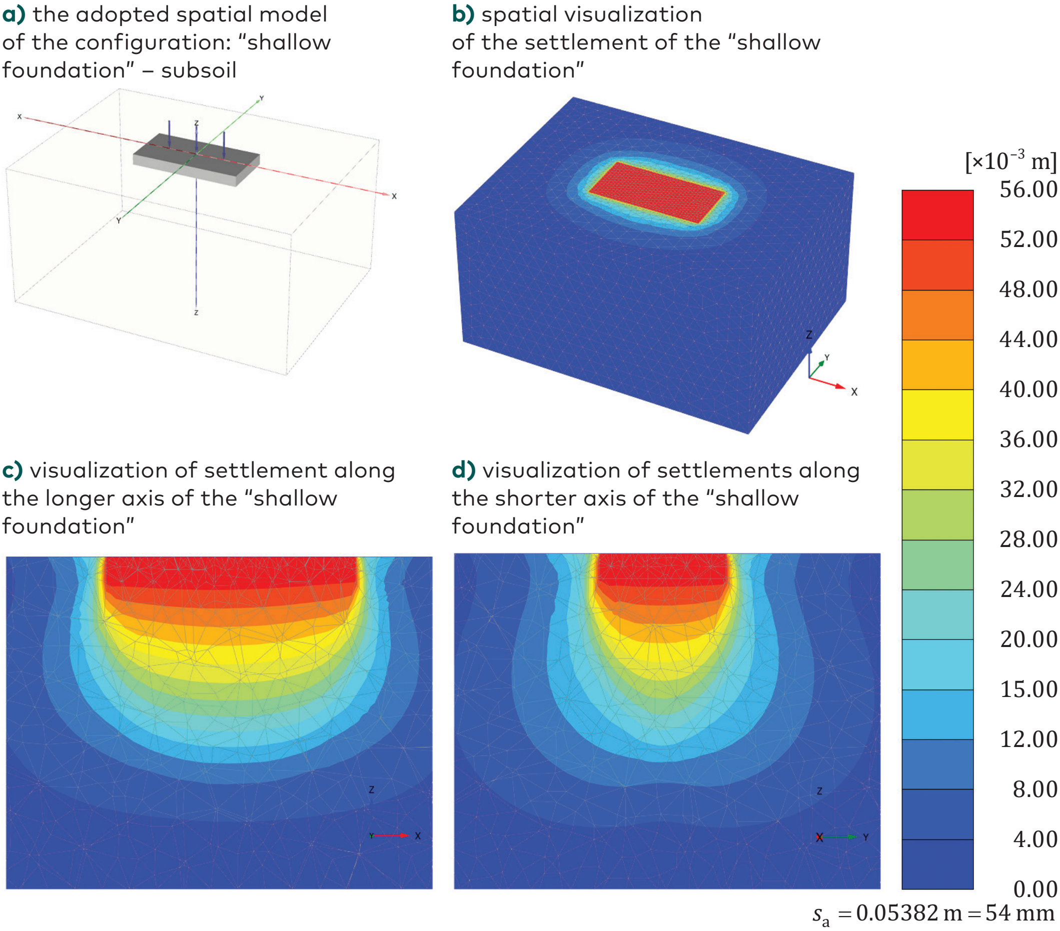

Figure 6. Settlement of the "shallow foundation of the theoretical bridge" determined using the PLAXIS 3D Advanced 2023.1 computer program

a) the adopted spatial model of the configuration: "substitute foundation" – subsoil

b) spatial visualization of the settlement of the "substitute foundation"

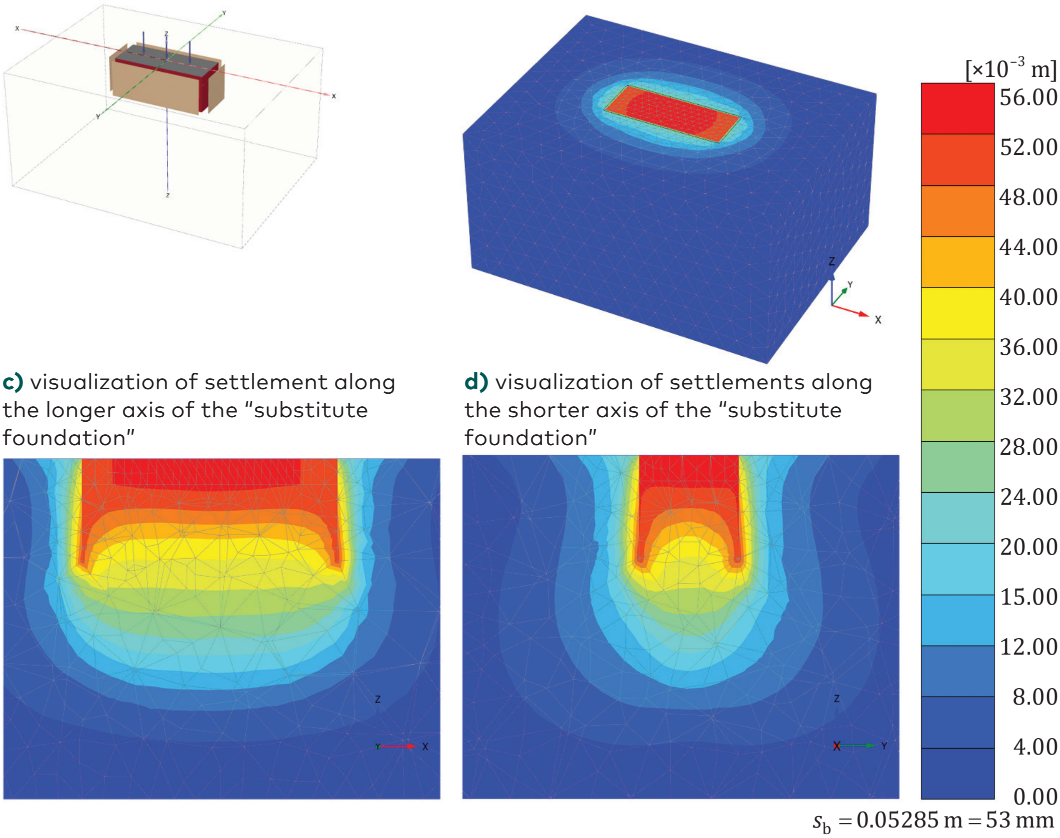

Figure 7. Settlement of the "substitute foundation of the theoretical bridge" determined using the PLAXIS 3D Advanced 2023.1 computer program

1.5. Comparison of "shallow and substitute foundations"

In Table 7, two variants of foundations of the "theoretical bridge" were compared. The purpose of the comparison was to show the differences between selected characteristic parameters of the "substitute foundation" in relation to the "shallow foundation". The fourth column, titled "Difference", shows the benefits related to the reduction of the consumption of basic building materials, as well as the increase in the load-bearing capacity of the foundation of the "theoretical bridge".

Table 7. Comparison of the characteristic parameters (two variants) of the foundations of the "Theoretical Bridge"

Type of compared parameter	The "shallow foundation" of the bridge in sheet piling cover (without taking into account the sheet piling cover in the calculation)	The "substitute foundation" of the bridge in sheet piling cover (taking into account the sheet piling cover in the calculation)	Difference
The length of the shorter side of the foundation	B_a = 7.50 m	B_b = 5.80 m	23% less
The length of the longer side of the foundation	L_a = 15.00 m	L_b = 15.00 m	no difference
Foundation height	h_a = 1.50 m	h_b = 1.50 m	no difference
Foundation area ($A = B{\cdot}L$)	A_a = 112.50 m^2	A_b = 87.00 m^2	23% less
Foundation volume ($V = B{\cdot}L{\cdot}h$)	V_a = 168.75 m^3	V_b = 130.50 m^3	23% less
Weight of reinforced concrete used (concrete = 2500 kg/m^3)	w_a = 422 tons	w_b = 326 tons	23% less
Weight of steel used (sheet piling = 83.50 kg/m)	w_s = 33 tons	w_s = 31 tons	6% less
Vertical bearing capacity of the foundation	66 533.63 kN	95 162.88 kN	43% more
Foundation horizontal bearing capacity (on direction B)	15 842.57 kN	16 920.78 kN	7% more
Foundation horizontal bearing capacity (on direction L)	15 794.24 kN	18 736.34 kN	19% more
Settlement based on EN 1997–1: Eurocode 7	~50 mm	~50 mm	no difference
Settlement based on PLAXIS 3D Advanced 2023.1	~54 mm	~53 mm	< 2% less no difference

2. Part No 2 – Estimation of settlement of the foundation of the "existing bridge" support

2.1. Description of the problem and the adopted assumptions

In northern Poland, in the city of Gdańsk (until 2022), there were 254 bridge structures and 37 tunnels with underground passages, not counting other engineering structures, such as culverts, retaining structures, acoustic screens and observation towers, maintained by the Gdańsk Roads and Greenery Management authority. Bridges and tunnels made a total of 291 structures. The sheet piling was used as a cover for foundations in 39 bridge and tunnel structures, which made up slightly more than 13% of these structures in the city as a whole. This, considered as a kind of indicator proving that the sheet piling in bridge engineering, used to cover or strengthen foundations, may apply to large percent of the total number of bridge structures, for cities and areas with a ground similar to the soil conditions in the Gdańsk region. The numbers quoted above do not apply to bridge structures operated by the General Directorate for National Roads and Motorways and companies associated with the Polish State Railways, also located in Gdańsk. However, it is likely that this percentage (13% in Gdańsk) could be higher due to these exclusions. Summing up the above, it can be concluded that using of sheet piling to cover (protect) the foundations of bridges is not marginal and should not be underestimated.

After analysing the archival designs of the above-mentioned bridge structures, it was found that:

– The use of a sheet piling, permanently left in the subsoil as a foundation cover, did not depend on the type of structure (bridge, viaduct, overpass, footbridge, tunnel) or on the static scheme (simply supported structures, hyperstatic structures, frame structures);
– The application of the sheet piling cover was not affected by the live loads (useful load capacity). Sheet piling, permanently connected to the foundation, was used for all permissible live load classes;
– In Gdańsk, sheet piling, permanently connected to the foundation, was a structural element that had been used in bridge construction at least since the first half of the twentieth century (Archives of Gdańsk Roads and Greenery Management authority).

The next part presents the analysis of the Serviceability Limit State (SLS – settlement s) on the example of the chosen (existing) bridge in Gdańsk (see Figure 5). The calculations were based on the assumptions presented in Part No 1, namely for:

"Shallow foundation" without taking into account the sheet piling cover in the calculations:

- Using the guidance in EN 1997–1: Eurocode 7;
- Using the Finite Element Method (FEM).

"Substitute foundation" taking into account the sheet piling cover in the calculations:

- Using the guidelines contained in EN 1997–1: Eurocode 7 and the author's proposal to take into account (1)the weight of the "substitute foundation" and (2)the vertical friction resistance of the sheet piling cover in the place of contact of the "substitute foundation" with the subsoil;
- Using the Finite Element Method (FEM).

The results of the calculations were compared with geodetic measurements of the settlement of the bridge support.

Description of the chosen existing bridge:

The bridge is a monolithic single-span reinforced concrete frame structure with rigid nodes (described in Table 8), founded on a "shallow foundation" with a sheet piling cover (rigid connection with the foundation). It was built along Stroma Street over the Radunia Canal in the southern area of the city of Gdańsk, called the "Święty Wojciech" district. The bridge was designed in August 2007 in accordance with Polish Standards: "PN–85/S–10030. Bridge objects. Loads" published in 1987 and "PN–91/S–10042. Bridge objects. Concrete, reinforced concrete and prestressed structures. Design" published in 1991. Construction works in site were completed in September 2009 (Mieszczuk & Jumas, 2009; GR&GM Archive).

Table 8. Geometric data

Theoretical length of the span	L_t = 12.10 m
Vertical clearance of the bridge	H_o = 3.25 m
Horizontal clearance of the bridge	B_o = 11.00 m
Bridge span thickness	h_k = 0.53 m
Width of the road on the bridge	6.00 m
Width of the sidewalks on the bridge	2 × 2.00 m
Thickness of the abutment bodies	0.80 m
Thickness of the subbase concrete	1.20 m

Due to lying of a layer of load-bearing soil at the depth of about 2.00 m below the existing bottom of the Radunia Canal and due to the buoyancy of water in the excavation, it was assumed that the foundation should have been made of vibrated sheet piling (AZ 17-700) on a subbase concrete with a thickness of 1.20 m. After the foundation works were made, the sheet piles were cut from the side of the Radunia Canal at the level of the designed bottom, while behind the abutments, only two sheet piles were cut, so that there was no stagnation of water in the ground. Compared to the original construction design, the course of the sheet piling of the chamber under the bridge abutment on the right side of the canal was changed from *the close proximity connection* to *the rigid connection*. During the construction works, the location of the sheet piling was corrected by 1.50 m (the width of the foundation was reduced from 4.10 m to 2.60 m) in order to avoid collisions with the existing telecommunication cables. Additional foundation reinforcement was

Figure 8. View from the north side of the bridge along Stroma Street over the Radunia Canal in Gdańsk (June 2023)

applied (providing *the rigid connection*) and welded to the sheet piling cover at 0.35 m spaces. Then the foundation was concreted over the entire area of the steel sheet piling chamber (see Figures 8 and 9).

Characteristics of the subsoil under the foundations of the chosen existing bridge:

The subsoil of the embankment slopes from the side of the Radunia Canal to the bottom level is made of embankment soils, poorly cohesive clay sands and fine sands contaminated by clay (with an admixture of

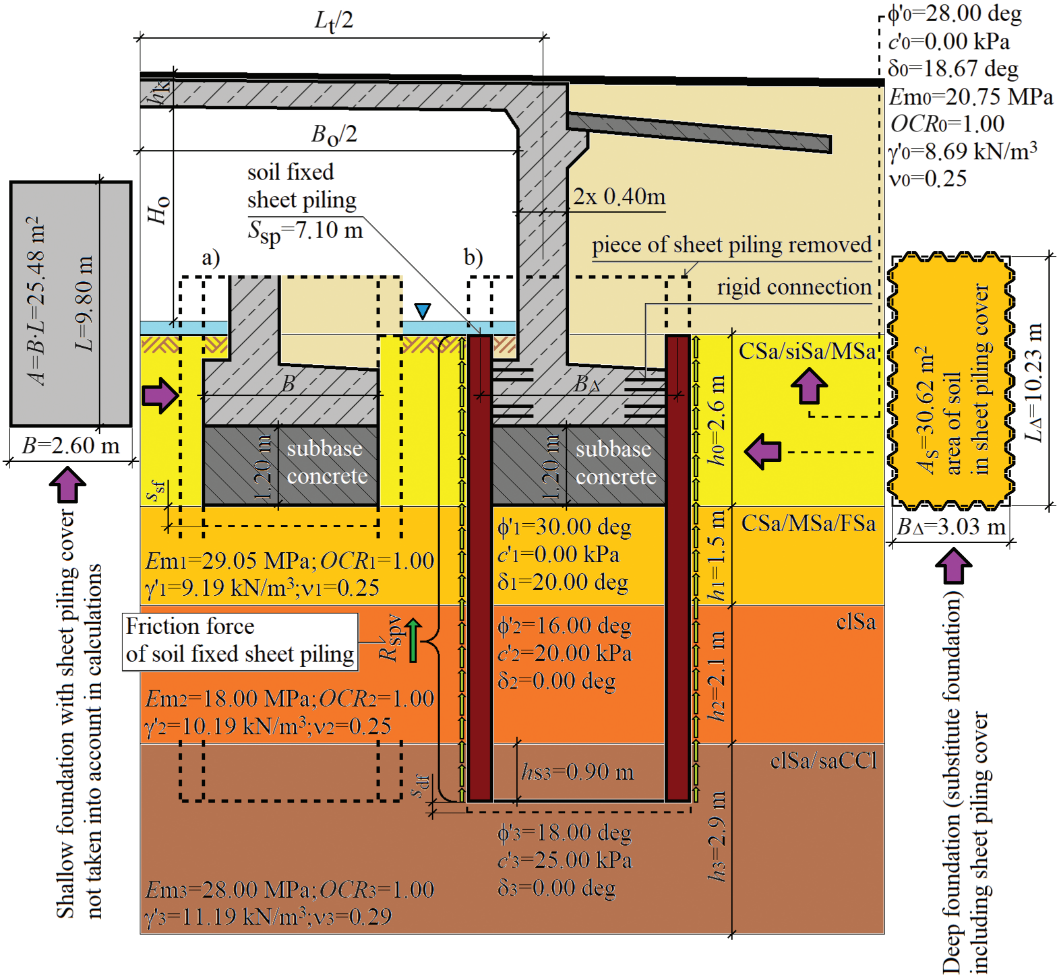

Figure 9. Longitudinal section of the bridge along Stroma Street over the Radunia Canal in Gdańsk – (a) "shallow foundation" in the sheet piling cover without taking into account the sheet piling cover, (b) "substitute foundation" in the sheet piling cover taking into account the sheet piling cover

clay sands). The bottom of the Radunia Canal to the ordinate of about 5.00 m below sea level (about 2.00 m below the water table of ground water) build embankments from sandy soils, often with an admixture of organic parts with silt inserts. Below, there are sandy soils created as various-grained sands and gravel sands. The subsoil to the depth of the soundings of about 10.00 m below ground level is made of sandy loams and loamy sands (see Figure 9). The groundwater table occurs in the near-surface layer of sandy soils and is directly related to the water level in the Radunia Canal. The second level of the groundwater table occurs in sandy soils at the elevation of about 2.00 m below sea level. Due to the lithology and special geotechnical parameters, all soils present in the tested subsoil were divided into individual geotechnical layers. The subsoil described above was included in simple ground conditions and in the second geotechnical category. The soil frost depth for this area is h_z = 1.00 m below a terrain level.

2.2. Estimation of bridge settlements on the "shallow foundation" (s_{sf}) according to EN 1997-1: Eurocode 7 (Annex F)

Below there are calculations (Tables 9 and 10) of settlements (Equation (28)) of the bridge foundation (see Figure 9a) built using the sheet piling cover without considering the beneficial effect of the sheet piling cover ("shallow foundation").

Table 9. Permanent loads (V_{k0}) transferred to the subsoil through the bridge foundation

Type of loads	A_{ej}, m^2	L_{ej} "or" H_{ej}, m	γ_{mj}, kN/m^3	$G_{eFj} = A_{ej}L_{ej}\gamma_{mj}$, kN
Road surfaces	0.60	8.00	23.00	111.14
Sidewalk slab	0.96	8.00	25.00	191.20
Span slab	3.92	5.40	25.00	529.02
Bridge cornices	0.35	6.45	25.00	56.44
Bridge support	3.59	9.80	25.00	879.55
Foundation	30.62	0.95	25.00	727.23
Subbase concrete	30.62	1.20	24.00	881.86
Approaching slab	1.00	6.40	25.00	80.00
Soil on the foundation	16.29	3.30	19.00	510.69
Soil on the approaching slab	1.29	6.40	19.00	157.05
Soil under the sidewalk slab	1.79	3.40	19.00	115.94

$$V_{k0} = \sum G_{\mathrm{eFj}} = 4240.11\ \mathrm{kN} \tag{27}$$

Table 10. Settlement (s_{sfi}) of Individual Layers (i) of Stratified Soil

Type of soil	i, –	$p_{(i-1)}$, kPa	B, m	f_i, –	E_{mi}, MPa	$s_{sfi} = p_{(i-1)} B f_i/E_{mi}$, mm
CSa/siSa/MSa	0	–	–	–	20.75	–
CSa/MSa/FSa	1	166.41		0.28	29.05	4
clSa	2	180.19	2.60	0.58	18.00	15
clSa//saCCl	3	201.59		0.84	28.00	16

$$s_{sf} = \sum s_{sfi} = \sum \frac{p_{(i-1)} B F_i}{E_{mi}} = 4 + 15 + 16 \approx 35 \text{ mm} \tag{28}$$

Equation (28) proves, based on the performed calculations, that the requirements of the EN 1997-1: Eurocode 7 standard were assured.

2.3. Estimation of bridge settlements on the "substitute foundation" (s_{df}) according to EN 1997-1: Eurocode 7 (Annex F)

Below there are calculations of settlements (Equation (33)) of the bridge foundation (see Figure 9b) built using the sheet piling cover taking into account the beneficial effect of the sheet piling cover ("substitute foundation").

The weight of the whole "substitute foundation" of the bridge is:

$$\begin{aligned} {}^{(1)}G_{kf} &= \sum A_s h_{si} \gamma_{si} + w_{sp} S_{sp} n_{sp} g = \\ &= 30.63(1.5 \times 9.19 + 2.1 \times 10.19 + 0.9 \times 11.19) + 73.1 \times 7.1 \times 36 \times 9.81 = \\ &= 1385.72 + 183.29 = 1569.01 \text{ kN} \end{aligned} \tag{29}$$

The total force of friction between the sheet piling cover of the "substitute foundation" and the subsoil is:

$$\begin{aligned} &{}^{(2)}R_{spv} = \sum V_{fi} = \sum \left[0.5\left(\tau_{0i}\left(z_{i\min}\right) + \tau_{0i}\left(z_{i\max}\right)\right) h_i C_{sp} \right] = \\ &= 0.5\left[(0 + 8.09) \times 2.6 + (8.75 + 13.94) \times 1.5 + (20 + 20) \times 2.1 + (25 + 25) \times 0.9\right] \times 31.81 = \\ &= 334.75 + 541.42 + 1336.03 + 715.73 = {}^{(2)}2927.93 \text{ kN} \end{aligned} \tag{30}$$

The characteristic vertical force transmitted by the "substitute foundation" to the stratified subsoil is:

$$\begin{aligned} V_{k\Delta} &= V_{k0} + {}^{(1)}G_{kf} - {}^{(2)}R_{spv} = \\ &= 4240.11 + {}^{(1)}1569.01 - {}^{(2)}2927.93 = 2881.19 \text{ kN} \end{aligned} \tag{31}$$

The pressure on the stratified soil layer, distributed linearly under the base of the “substitute foundation”, is:

$$\sum p_{\Delta} = \frac{V_{\mathrm{k}\Delta}}{A_{\mathrm{s}}} = \frac{2881.19}{30.62} = 94.10\ \mathrm{kPa} \tag{32}$$

The settlement of the bridge on the “substitute foundation” in the stratified subsoil is:

$$s_{\mathrm{df}} = \sum \frac{p_{\Delta} B_{\Delta} f}{E_{\mathrm{m}}} = \frac{94.1 \times 3.03 \times 1.33}{28000} \approx 14\ \mathrm{mm} \tag{33}$$

Equation (33) proves, based on the performed calculations, that the requirements of the EN 1997-1: Eurocode 7 standard were assured.

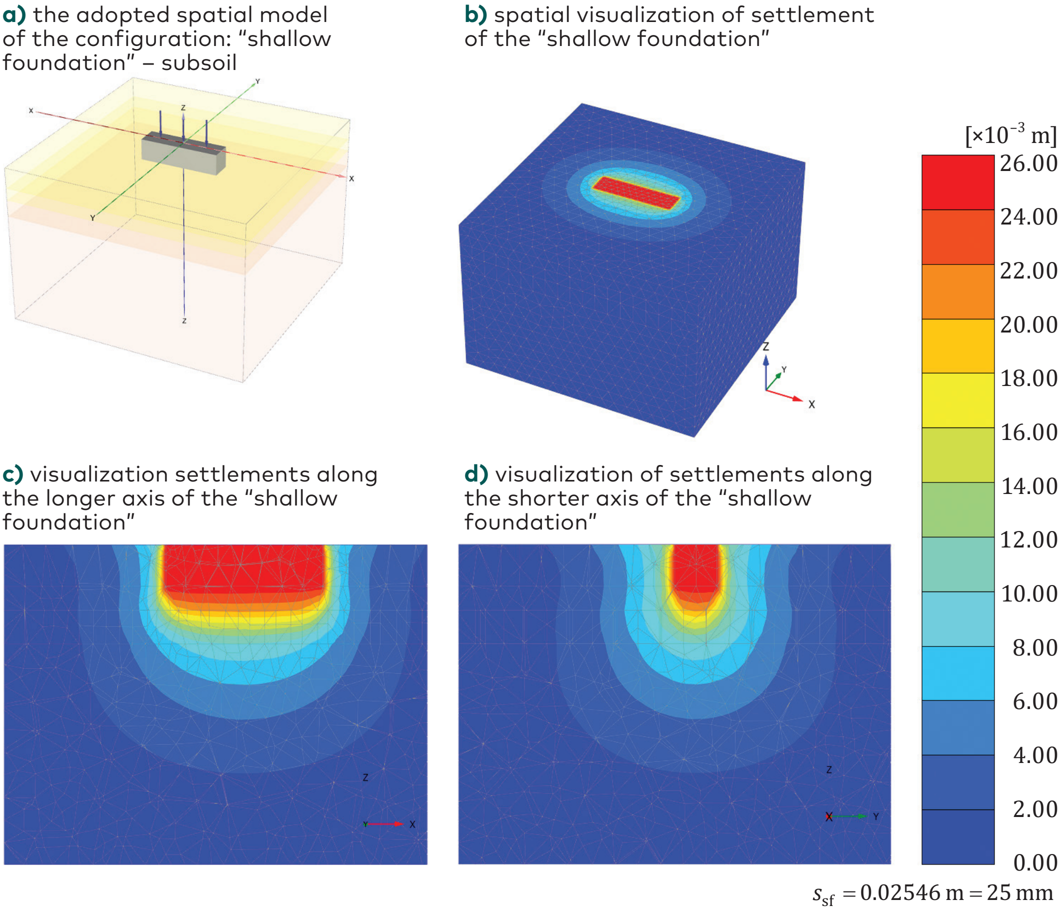

Figure 10. Settlement of the real foundation (without taking into account the sheet piling cover) of the “existing bridge” determined using the PLAXIS 3D Advanced 2023.1 computer program

2.4. Estimation of bridge settlement on the "shallow foundation" (s_{sf}) and on the "substitute foundation" (s_{df}) based on computer calculations using the Finite Element Method (FEM)

Theoretical assumptions regarding numerical analyses and the software used were described in Section 1.4. Below there are the results of calculations of the bridge settlement on the "shallow foundation" (s_{sf} shown in Figure 10) – without considering the influence of the sheet piling cover and the calculation of the bridge settlement on the "substitute foundation" (s_{df} shown in Figure 11) – taking into account the influence of the sheet piling cover.

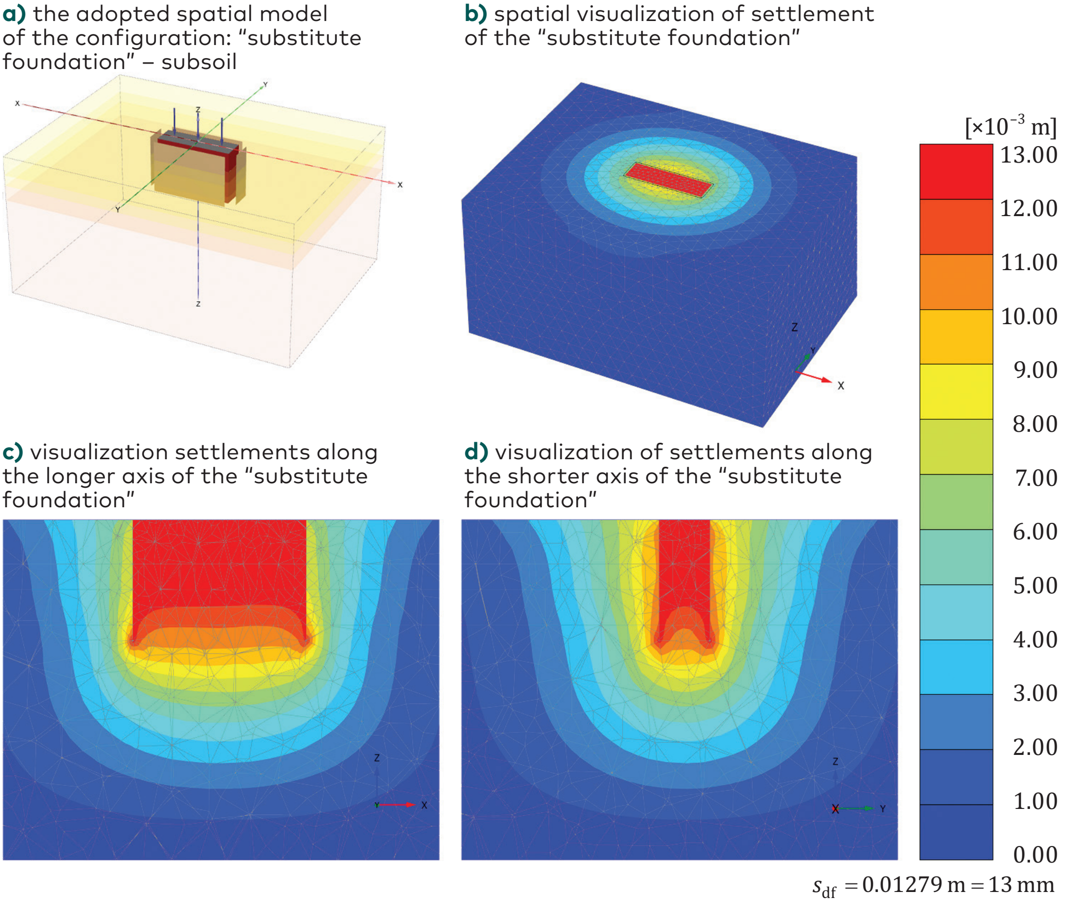

Figure 11. Settlement of the real foundation (taking into account the sheet piling cover) of the "existing bridge" determined using the PLAXIS 3D Advanced 2023.1 computer program

2.5. Determination of bridge settlements based on geodetic measurements using the precise levelling method

The as-built geodetic measurement was carried out in September 2009. The control measurement was made in October 2021. Archival ordinates (measured in September 2009) were taken from the as-built documentation (archives of the Gdańsk Roads and Greenery Management authority). The control measurement (October 2021) was carried out in cooperation with DIAZ company from Gdańsk using the precise levelling method (see Table 11 and Figure 12).

Table 11. Actual (real) settlement of the "Existing Bridge" supports

Measuring points	Real settlement after 12 years of bridge exploitation. The difference in the height of the points between the as-built measurement and the control measurement
1M	0.1 mm – no settlement
2M	22.6 mm
3M	8.6 mm
4M	0.5 mm – no settlement

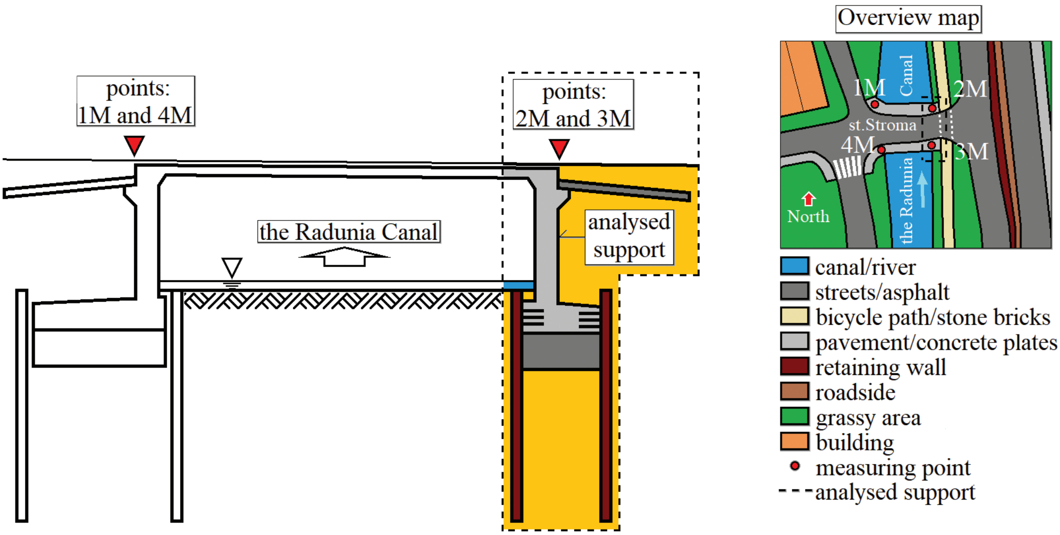

Figure 12. Checkpoints (geodetic points) on the bridge along Stroma Street over the Radunia Canal in Gdańsk

$$s_m = \frac{22.6 + 8.6}{2} = 15.6\ \text{mm} \approx 16\ \text{mm} \tag{34}$$

The average settlement of the bridge support stayed on the "substitute foundation" (real foundation) in the sheet piling cover (rigid connection with the foundation) is presented in Equation (34).

2.6. Comparison of the "shallow and substitute foundations"

Table 12 shows the beneficial effect of including the sheet piling cover while determining the settlement of the bridge "substitute foundation". In the described case (depending on the adopted calculation method), the reduction of settlements, taking into account the sheet piling cover, is about 50%. The design settlements estimated for the actual foundation according to EN 1997-1: Eurocode 7 (Annex F) and using PLAXIS 3D Advanced 2023.1 were close to each other and simultaneously the difference between them and the real settlements determined and based on geodetic measurements was inconsiderable.

Table 12. Comparison of settlements of the analysed variants of the foundation of the supports of the chosen "Existing Bridge"

Settlement of the bridge on the "shallow foundation" (s_{sf}) – without taking into account the sheet piling cover, determined in accordance with EN 1997-1: Eurocode 7 (Annex F)	35 mm
Settlement of the bridge on the "shallow foundation" (s_{sf}) – without taking into account the sheet piling cover determined by the Finite Element Method using PLAXIS 3D Advanced 2023.1	25 mm
Settlement of the bridge on the "substitute foundation" (s_{df}) – taking into account the sheet piling cover determined in accordance with EN 1997-1: Eurocode 7 (Annex F)	14 mm
Settlement of the bridge on the "substitute foundation" (s_{df}) – taking into account sheet piling cover determined by the Finite Element Method using PLAXIS 3D Advanced 2023.1	13 mm
Settlement of the bridge on the real foundation (s_m) – with sheet piling cover based on geodetic measurements using the precise levelling method	16 mm

Conclusions

Based on the literature review, the analysis of the obtained calculation results and geodetic measurements, the following conclusions were formulated:

1. If the investor or designer decides to leave the sheet piling rigidly connected to the foundation as a permanent structural element (cover), the author proposes to include it in cooperation and take it into account for the design calculations. The cover made of the sheet piling rigidly connected to the foundation reduces the vertical displacements (settlement) of the foundation and increases the bearing capacity of the subsoil under the foundation.
2. The main advantages of the proposed method are the following:
   - The calculation algorithm is uncomplicated and can be used without necessity to have advanced computer software;
   - The presented analytical method is based on the assumptions (commonly known) of the EN 1997-1: Eurocode 7 standard;
   - The bridge designers can use the described method for the calculations of the Ultimate and Serviceability Limit States of shallow (typical) foundations, taking into account the sheet piling cover;
   - The proposed method can be used to obtain reliable computational results, which were confirmed by numerical calculations using the Finite Element Method (FEM) and geodetic measurements.

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NOTATIONS

b_q , b_c , b_γ – factors for the inclination of the foundation base;

f – settlement coefficient for a soil layer under the substitute foundation – based on the theory of elasticity;

f_a, f_b – settlement coefficient (*a* – shallow foundation, *b* – substitute foundation) – based on the theory of elasticity;

f_i – settlement coefficient for *i*-layer of a stratified soil – based on the theory of elasticity;

h_i – height of *i*-layer of a stratified soil;

h_{si} – height of a soil layer inside a sheet piling cover;

i – layer number of a stratified soil;

i_q , i_c , i_γ – inclination factors of the load;

j – permanent load (action) number;

N_q , N_c , N_γ – bearing capacity soil factors;

p_a, p_b – bearing pressure, linearly distributed under the base of the foundation (*a* – shallow foundation, *b* – substitute foundation);

p_i – bearing pressure for *i*-layer of a stratified soil, linearly distributed under the base of the foundation;

q' – (design) effective overburden pressure at the level of the foundation base;

s_a, s_b – settlement (*a* – shallow foundation, *b* – substitute foundation);
s_q, s_c, s_γ – shape factors of the foundation base;
V_d' – design value of the effective vertical action or component of the total action acting normal to the foundation base;
V_{fi} – characteristic vertical friction force of *i*-layer of a stratified soil on a sheet piling of the substitute foundation;
$z_{i\min}$, $z_{i\max}$ – maximum and minimum depth of *i*-layer around the substitute foundation for a stratified soil under a terrain level.
Σ – mathematical sum symbol;
$\sigma_p(z)$ – total stress normal to the wall at depth *z* (passive limit state);
$\sigma_0(z)$ – total stress normal to the wall at depth *z* (at rest);
$\tau_{0i}(z_{i\min})$, $\tau_{0i}(z_{i\max})$ – stress tangential to a sheet piling at depth $z_{i\min}$ and $z_{i\max}$ for *i*-layer around the substitute foundation for a stratified soil.

Abbreviations
clSa – clayey sand;
CSa – coarse sand;
FSa – fine sand;
MSa – medium sand;
OCR – over-consolidation ratio;
OCR_i – over-consolidation ratio for *i*-layer of a stratified soil inside a sheet piling cover;
saCCl – sandy cobble clay;
siSa – silty sand.