Design experience of Wisla water collector

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Within the framework of the Wisla project, a water collector will be built in the estuary of the of the Vistula river in Warsaw, Poland, using a micro-tunnel boring machine. The installation and recovery of the boring machine requires construction of access and exit sheet-piling shafts. In many cases in France we provide for the construction of shafts for micro-tunneling using diaphragm wall's regarding rigidity and final structure.

The scope of the following publication is to present the design assumptions adopted for the performance on an independent control calculation of the exit sheet-piling shaft. The execu-

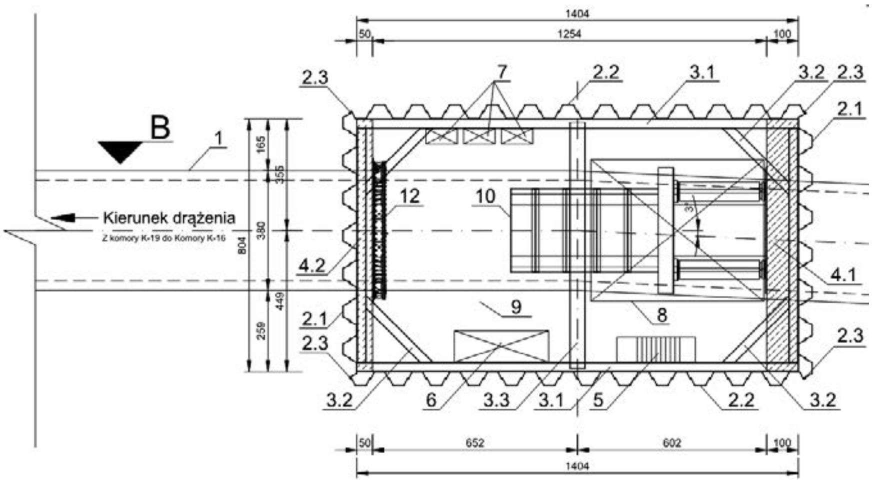

Fig. 1. Plan view of the shaft K-19 retaining structure

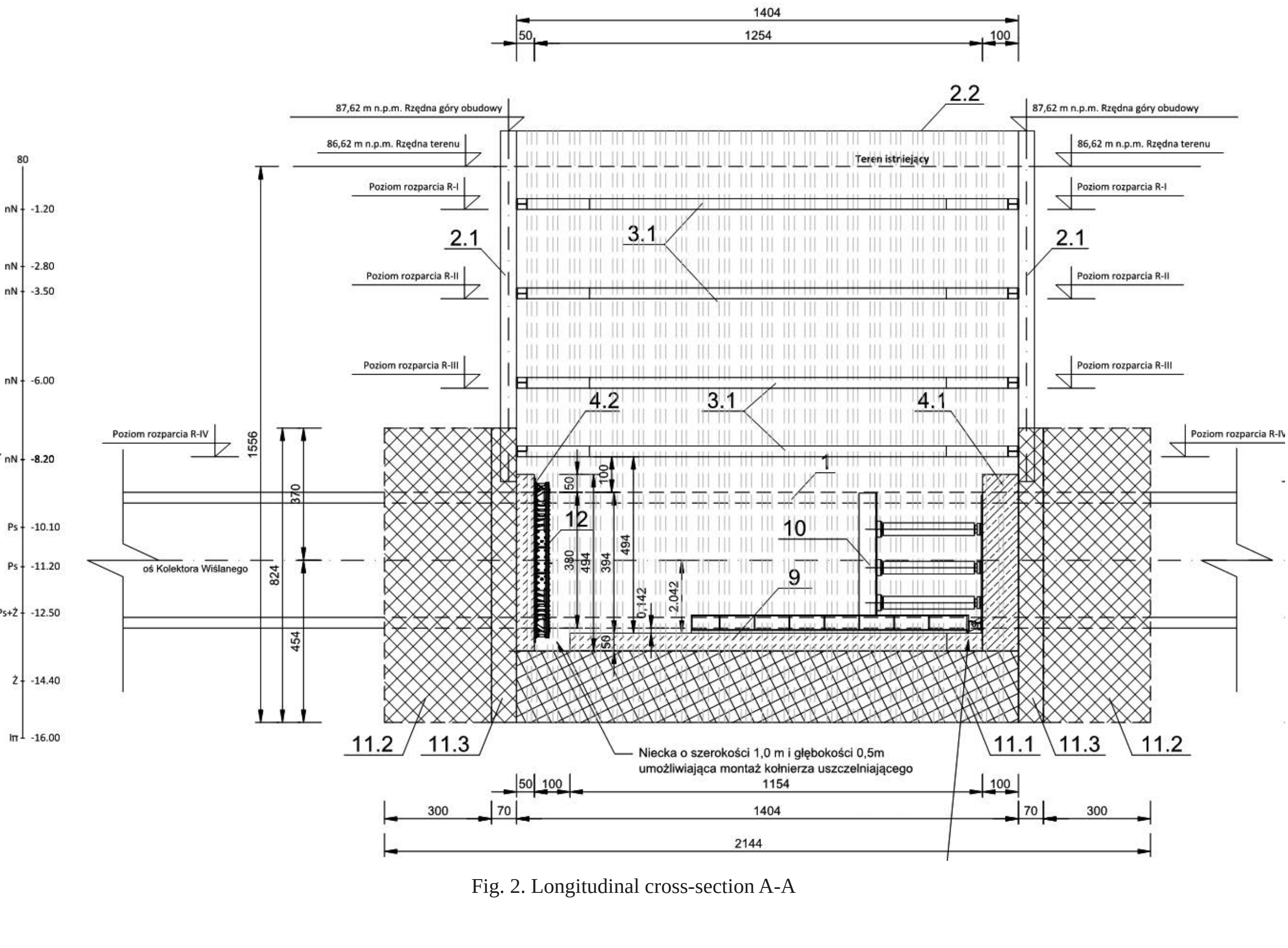

Fig. 2. Longitudinal cross-section A-A

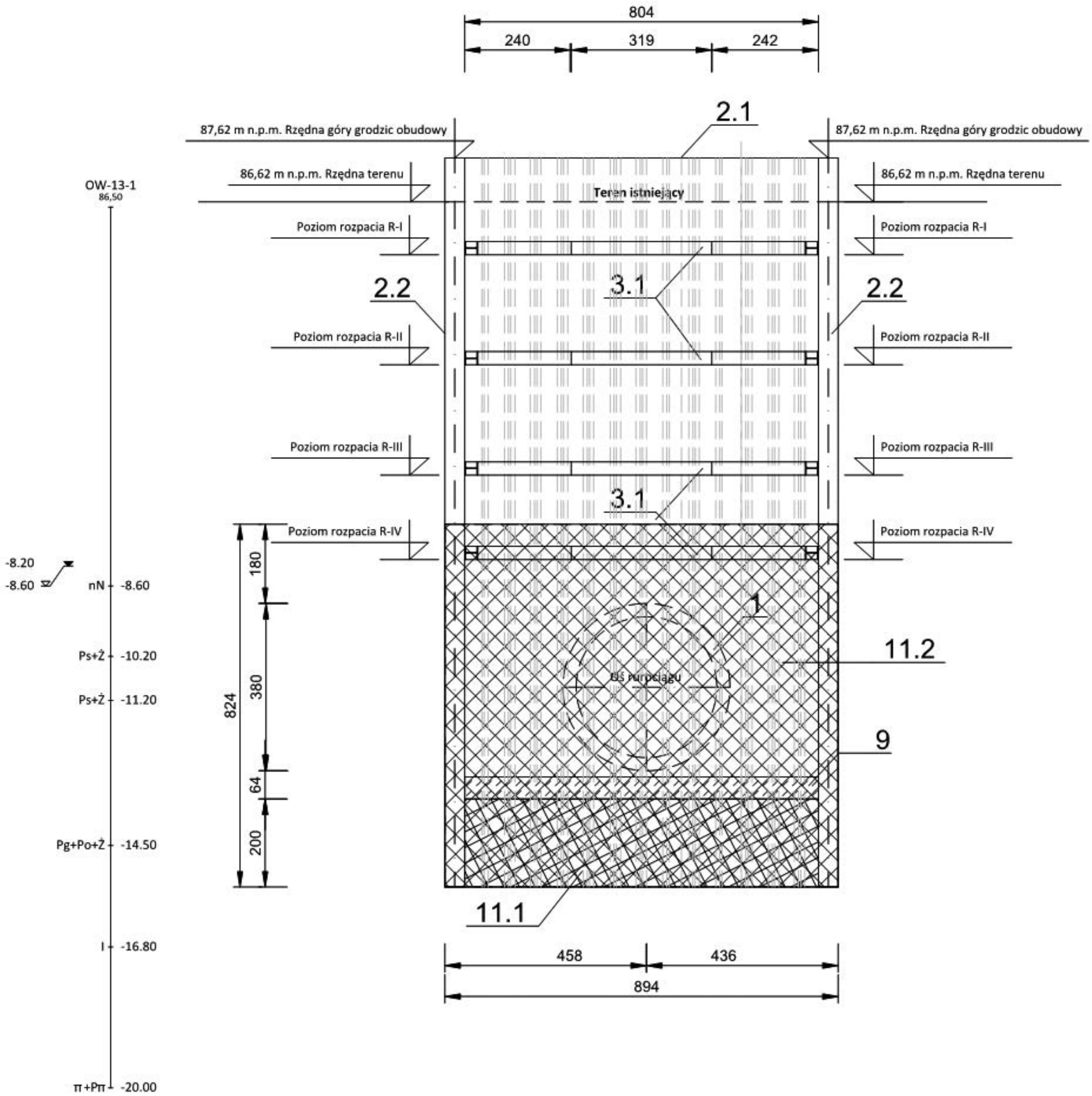

Fig. 3. Transversal cross-section B-B

tion project was carried out by ARCADIS Polska on behalf of BUDIMEX. The objective of the counter calculation was carried out with the aim of optimization by relying on the French expertise described in the recommendations of the association “Travaux sans tranchée”.

As part of the ARCADIS water collector project, six access or exit shafts will be constructed. The micro-tunnel will be performed starting from shaft K-19 towards shaft K-16 and then from shaft K-19 in direction of shaft K- 21.

The shafts will be supported by rectangular box retaining structures made of sheet-piling and reinforced with metal frames and bracing. The base of the sheet-piling will be anchored in a low permeability clay soil layer. Water infiltration into the shafts will be limited by the placement of a jet grouting layer below the base of the shaft and along the lower portions of the entrance and exit faces.

A plan view and cross-sections of the K-19 as the example the sheet-piling retaining structure are presented in the following figures 1, 2, 3.

At the entrance and exit faces of the box structure, the base depth of the sheet-piling will be adjusted in order to not interfere with the passage of the micro-tunneling machine.

GEOMETRY OF THE SHAFT RETAINING STRUCTURE

Water infiltration into the shafts will be minimized by the placement of a jet grouting layer beneath the excavation base and along the lower part of the lateral faces of the shaft. In addition, along the lateral faces of the retaining structure where the depth of the sheet-piling is reduced to avoid the footprint of the water collector, the box structure will be extended by a layer thin layer of jet grouting (see figure 4).

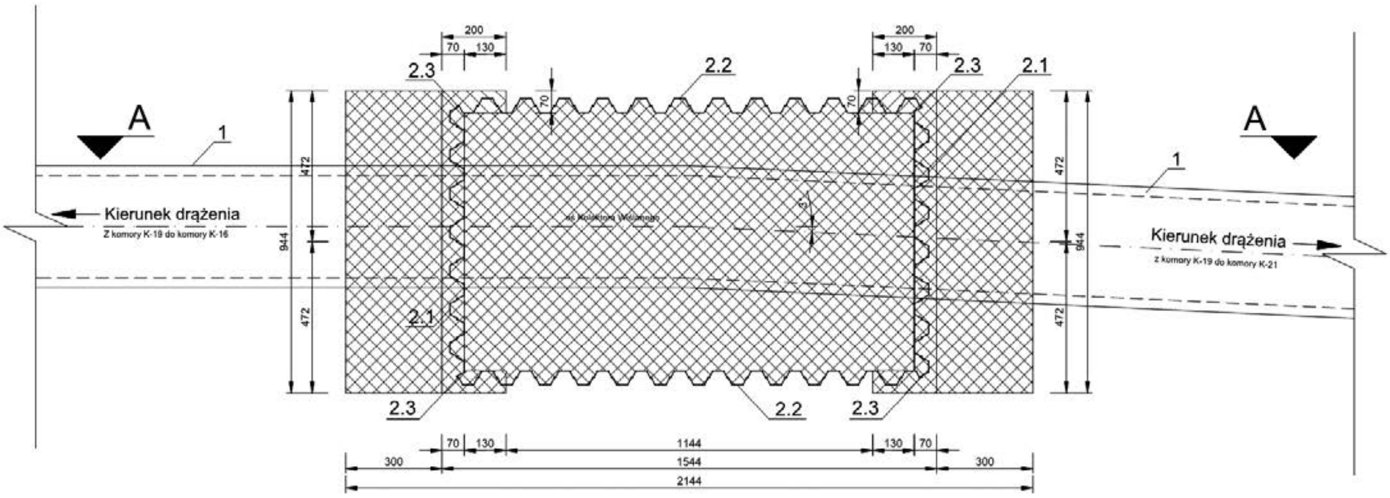

Fig. 4. Plan view of the areas treated with jet grouting

Table 1. Geo-technical design assumptions (Polish standard soil denomination)

No.	Horizon Soil type	Layer base [m npm]	E_0 [MPa]	ν	γ [kN/m^3]	c' [kPa]	ϕ′ [°]	k [m/s]
---	Natural grade	+86.62						
1	I (nN) (embankment)	+78.42	5.0	0.30	18.0	1	25	1×10^{-6}
2	VIIb (Ps, Pd, Ps+Z) (medium, fine sand, gravel)	+74.12	60.0	0.25	18.5	1	33	1×10^{-4}
3	VIIc (Ps+Z, Po+Z, Z) (medium sand, gravel)	+72.22	80	0.25	18.5	1	34	1×10^{-4}
4	Xb (I, Iπ) (clay, silty clay)	+69.90	19	0.25	20.0	26	23	1×10^{-10}
---	Jet grouting	---	1000	0.25	22	40	30	1×10^{-9}

CALCULATION ASSUMPTION

The calculation of the shaft retaining structure will be performed by the reaction modulus method using the Rido french design software.

The determination of the horizontal reaction moduli used for the calculation is based on the method proposed by Schmitt and presented in the French standard for design of retaining walls NF P 94-282.

The calculation will be performed in plane strain, for a longitudinal cross-section passing by the center of the box structure. The rigidity of the metal frame supports was determined by means of a preliminary calculation based on the resistance of materials, using the french RDM7 software method.

GEO-TECHNICAL PROPERTIES

The adopted geo-technical parameters are summarized in the tables 1 and 2.

Table 2. Estimated values of EM and α or the determination of the soil reaction modulus

No.	Horizon Soil type	E_M [MPa]	α	k_h [MPa/m]
1	I (nN) (embankment)	2.5	1/2	3 565
2	VIIb (Ps, Pd, Ps+Z) (medium, fine sand, gravel)	20	1/3	97 970
3	VIIc (Ps+Z, Po+Z, Z) (medium sand, gravel)	27	1/3	146 170
4	Xb (I, Iπ) (silty clay, clay)	19	1	21 145
---	Jet grouting	500	1/2	4 170 705

The active and passive lateral pressure coefficients K_a and K_p were determined from the charts established by Caquot-Kerisel. The orientations of the active and passive pressures assume a smooth contact between the soil and the sheet-piling.

The at rest pressure coefficient K_0 was determined by the formula proposed by Jaky for normally consolidated soils:

$$K_0 = 1 - \sin \phi'$$

The adopted pressure coefficients are summarized in the table 3.

Table 3. Earth pressure coefficients

No.	Horizon Soil type	ϕ' [°]	δ_a	K_a	K_0	δ_p	K_p
1	I (nN)	25	0	0.406	0.577	-1/3	3.10
2	VIIb (Ps, Pd, Ps+Z)	33	0	0.296	0.455	-2/3	6.92
3	VIIc (Ps+Z, Po+Z, Z)	34	0	0.283	0.441	-2/3	7.43
4	Xb (I, Iπ)	23	0	0.440	0.609	-1/3	
---	Jet grouting	30	0	0.333	0.500	-2/3	

MATERIAL PROPERTIES

The strength properties of the materials used for shaft construction are given in the table 4.

Table 4. Material properties of box structure

No.	Material	E [MPa]	ν	γ [kN/m³]	$I^{(*)}$ [cm⁴]	$W^{(*)}$ [cm³]
1	Sheet-piling GU23N	210 000	0.25	79	52 510	2 335
2	Frame and bracing HEB 300	210 000	0.25	79	25 170 (y-y) 8 563 (z-z)	1 678 (y-y) 570.9 (z-z)
3	Strut Pipe 508/12.5 mm	210 000	0.25	79	59 755	2 353
4	Concrete base slab	32 000	0.20	25	10 417	---

Note: (*) For the sheet-piling and the concrete slab, the moment of inertia I and the section modulus W are expressed in cm⁴ per meter. For the H-beams, these parameters are expressed in cm⁴.

According to Eurocode 3 – Part 5 and French standard NF P 94-282, the rigidity of U profile sheet-piling is reduced by a coefficient β_D:

$$EI_{eff} = \beta D \, \mathbf{EI}$$

The acceptable bending moment $M_{c;Rd}$ of U profile sheetpiling is equally reduced by a coefficient β_B, which depends on the number of bracing levels. The adopted values for the β_D and β_B coefficients are summarized in the table 5.

Table 5. Reduction factors β_B and β_D

Type of sheet-piling	No. of bracing levels	β_B	β_D
Single U profile	0	0.6	0.4
	1	0.7	0.5
	≥ 2	0.8	0.6

The rigidity of the metal framing and bracing, including the center strut, was determined from a preliminary calculation using the RDM7 software. The stiffness properties of the bracing are presented in the table 6.

Table 6. Stiffness of bracing elements

Material	A [cm²]	L brace [m]	α [°]	K [kN/m]
Frame and bracing HEB 300	149.1	2.80	45	1 118 250
Strut Pipe 508/12.5 mm	194.6	7.44	0	1 098 450

Based on the RDM7 calculation, the rigidity of the metal frame adopted for the counter calculation is equal to:

$$k = 33\,330 \text{ kPa/m.}$$

The box structure is assumed to be temporary retaining structures. A reduction of the thickness of the metallic elements was not therefore considered in the counter calculation.

APPLIED LOAD

For the calculation, a distributed load of 33 kPa (load q_2) was applied to simulate machinery loads in the vicinity of the box structure. The load was applied over a width of 4 m, starting 1 m behind the box structure.

CALCULATION SEQUENCE

In order to allow placement of the metal frames, the excavation of the soil within the box structure will be performed in successive stages. For each stage, the excavation was considered to a depth of 0.3 below the base of the frame to be installed. The construction sequence adopted of the counter calculation is as follows:

- Step 1: Calculation of initial stresses before construction of the retaining structure,
- Step 2: Placement of jet grouted layers and installation of the sheet-pile box structure,
- Step 3: Excavation to a depth of the first frame,
- Step 4: Installation of first frame and excavation to a depth of the second frame,
- Step 5: Installation of second frame and excavation to a depth of the third frame,

– Step 6: Installation of third frame and excavation to a depth of the fourth frame,
– Step 7: Installation of fourth frame and excavation to the bottom of the shaft.

CALCULATION ASSUMPTIONS OF SHEET-PILING BOX STRUCTURE

The calculation was performed without partial safety factors on the loadings and materials. The results correspond therefore to the Service Limit State for determining the horizontal displacement of the retaining structure.

For the justification of the structural elements, the design values of the internal forces E_d (bending moment and shear force) were determined at the Ultimate Limit State by means of the following equation:

$$E_d(\text{ULS}) = 1.35 \cdot E_k(\text{SLS})$$

where:
E_k – the characteristic value of the internal forces for a given calculation phase, performed without partial safety factors.

The justifications of the sheet-piling were performed in accordance with Eurocode 3 – Part 5 and the French national appendix. The classification of the transversal cross-section is determined according to Table 5.1 of the Eurocode.

The value of $(b / t_f) / \varepsilon$ for the type of sheet-piling considered (GU 23N) is equal to 24.3 and the sheet-piling is therefore Class 2. For Class 2 sheet-piling, the design moment resistance is given by the following equation:

$$M_{C,Rd} = \beta_B \frac{W_{pl} f_y}{\gamma_{M0}}$$

where:
W_{pl} – the plastic section modulus,
β_B – is a reduction coefficient (see Table 4),
f_y = 235 MPa (nuance S235),
γ_{M0} – is a partial safety factor taken equal to 1.0.

The design bending moments generated in the sheetpiling are acceptable if the following condition is satisfied:

$$M_{Ed} \le M_{c;Rd}$$

The design shear resistance is given by the following equation:

$$V_{pl,Rd} = \frac{A_v f_y}{\sqrt{3}\gamma_{M0}}$$

where:
$A_v = t_w (h - t_f)$.
t_w – the web thickness,
h – the overall height,
t_f – the flange thickness.

The design shear forces generated in the sheetpiling are acceptable if the following condition is satisfied:

$$V_{Ed} \le V_{pl,Rd}$$

If the condition $V_{Ed} < 0.5\ V_{pl,Rd}$, is satisfied, no reduction is required to take into account the interaction between the bending moment and the shear force.

In certain cases, it may be necessary to consider shear buckling of the web section. However, this verification in not required if the following condition in satisfied:

$$(c / t_w) / \varepsilon \le 72$$

where:
$c = (h - t_f) / (2 \sin \alpha)$ for U profile sheet-piling.

The design resistance for the type of sheet-piling considered is summarized in the table 7.

Table 7. Design resistance of the sheet-piling

Type of sheet-piling	$M_{c,Rd}$ [kN·m/ml]			$V_{pl,Rd}$ [kN/ml]	$(c / t_w) / \varepsilon$
	No. of bracing levels				
	0	1	≥ 2		
GU 23N	386	450	514	593	24.7

The value of $(c / t_w) / \varepsilon$ is less than 72. The verification of shear buckling is not therefore required.

CALCULATION ASSUMPTIONS OF METAL FRAMING

The Rido software for the 2-D design of retaining structures calculates the axial force in the bracing but does not determine the bending moments and shear forces in the frame. The efforts in the framing system were therefore calculated using the RDM 7 software.

The pressure exerted on the frame for the calculation of the internal forces was considered equal to the soil pressure obtained from Rido at the depth of each frame.

The structural justification of the frame was performed in accordance with Eurocode 3 – Part 1 and the French national appendix. The classification of the transversal cross-section is determined according to Table 5.2 of the Eurocode.

The cross-section classification of the different elements composing the frame are as follows:

– HEB 300 h-beams: $(d / t_w) / t_w = 18.9 < 72$ ◊ Class 1.
– Steel pipe: $(d / t) / \varepsilon^2 = 40.6 < 50$ ◊ Class 1.

For Class 1 h-beams, the design resistance is verified if the following condition is satisfied:

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} + \frac{M_{z,Ed}}{M_{z,Rd}} \le 1$$

where:
$N_{Rd} = A f_y / \gamma_{M0}$,
$M_{y,Rd} = M_{pl,Rd} = W_{pl} f_y / \gamma_{M0}$,
A – the cross-sectional area of the beam,
W_{pl} – the plastic section modulus,
f_y = 235 MPa (nuance S235),
γ_{M0} – a partial safety factor taken equal to 1.0.

It is assumed that the frame will be welded to the box structure, in which case the moment M_z can be neglected in the structural verification.

The design shear resistance is given by the following equation:

$$V_{pl,Rd} = \frac{A_v f_y}{\sqrt{3}\gamma_{M0}}$$

where:
$A_v = A - 2\,b\,t_f + (t_w + 2r)\,t_f$,
b – the flange width,
t_f – the flange thickness,
t_w – the web thickness,
r – the root radius.

The design shear forces generated in the framing are acceptable if the following condition is satisfied:

$$V_{Ed} \leq V_{pl,Rd}$$

If the condition $V_{Ed} < 0.5\ V_{pl,Rd}$, is satisfied, no reduction is required to take into account the interaction between the bending moment and the shear force.

For the steel pipe, the required structural verification's are comparable to those of the h-beams, except that the risk of buckling must also be considered in the calculation of the design compressive resistance:

$$N_{Rd} = N_{b,Rd} = \chi A\,f_y / \gamma_{M1}$$

where:
χ – the reduction factor for the relevant buckling mode.
γ_{M1} – is a partial safety factor taken equal to 1.0.

The value of χ is determined according to §6.3.1.2 of the Eurocode.

CALCULATION RESULTS SHEET-PILING BOX STRUCTURE

The detailed calculation results obtained with Rido software. The principle results are summarized in the table 8.

Table 8. Calculation results for the sheet pile box structure (SLS)

Parameter	Calculated value				
Phase no.	3	4	5	6	7
δ top [mm]	0.3	-0.2	-0.3	-0.2	-0.2
δ max [mm]	2.8	7.1	8.8	9.0	20.6
M max [kN m/ml]	23.2	62.5	95.2	72.5	242.0
V max [kN/ml]	18.0	60.4	104.9	70.5	229.3

CALCULATION RESULTS OF FRAMING SYSTEM

The detailed calculation results obtained with RDM7 software. The principle results are summarized in the table 9.

Table 9. Calculation results for the metal framing (SLS)

Element	Parameter	Calculated values			
	Frame no.	1 (top)	2	3	4 (bottom)
Frame (HEB 300)	δ*x* [mm]	-0.4	-0.7	-1.2	-1.3
	δ*y* [mm]	0.9	1.9	2.9	3.5
	N max [kN]	67.6	124.0	192.0	232.0
	V max [kN]	44.4	86.0	133.2	161.0
	M max [kN m]	42.5	82.3	127.6	153.9
Corner bracing (HEB 300)	*N* max [kN]	70.8	137.2	212.5	256.8
	V max [kN]	1.5	2.9	4.5	5.4
	M max [kN m]	5.0	9.8	15.1	18.2
Center strut (pipe 508/12.5 mm)	*N* max [kN]	88.8	172.0	266.4	322.0
	V max [kN]	0	0	0	0
	M max [kN m]	0	0	0	0

The structural verifications of the box structure and framing were performed with the forces corresponding to the Ultimate Limit State.

Box structure

- δ max = 20.6 mm < 25 mm: Condition satisfied.
- M_{Ed} max = 327 kN m/ml < $M_{c,Rd}$ = 386 kN m/ml: Condition satisfied.
- V_{Ed} max = 310 kN/ml < $V_{pl,Rd}$ = 593 kN/ml: Condition satisfie

Framing system

HEB 300 h-beams

- $(N_{Ed} / N_{Rd} + M_{y,Ed} / M_{pl,Rd})$ max = 0.56 < 1: Condition satisfied.
- V_{Ed} max = 217 kN < $V_{pl,Rd}$ = 644 kN: Condition satisfied.

Steel pipe

- $N_{Ed} / N_{b,Rd} + M_{y,Ed} / M_{pl,Rd}$ = 0.11 < 1: Condition satisfied.
- V_{Ed} max = 0 kN < $V_{pl,Rd}$ = 1681 kN: Condition satisfied.

CONCLUSIONS

The scope of the present publication is to present the results of the counter calculation to verify the design of the typical shaft according ARCADIS's project. The shaft will be composed of a sheet-pile box structure (GU 23N), reinforced by 4 metal frames with cross bracing.

The results of the counter calculation are fully comparable to those obtained by Arcadis and validate their design of the retaining structure shafts.

The present demonstration also makes it possible to validate the idea of the implementation of sheet piles for access and exit shafts of tunnel boring machines despite the forces on the support which are developed during pushing for such a relatively flexible structure. The only remark we can make concerns the wells with respect to the forces due to the shields which must be symmetrical in order to avoid parasitic forces on the torsion-type structure.