

Back-calculation of U-profile sheet pile walls stiffness

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ABSTRACT: This study investigates stiffness reduction factors for U-profile sheet pile walls, widely used in excavation support systems. U-piles exhibit reduced stiffness compared to continuous walls due to interlock slippage. Although Swiss standards acknowledge the use of reduction factors, they do not specify values, leading engineers to rely on French or German guidelines. This research bridges that gap by combining field measurements and numerical simulations from two Swiss sites with geological conditions typical of the Swiss Plateau—ground moraine, stream deposits, and lacustrine sediments. The sites—Alpnachstad and Bern Wylerfeld—were analyzed using inclinometer data, strut force measurements, and finite element (FE) modeling with Plaxis 2D. The numerical models were calibrated with field data to ensure a realistic representation of wall behavior. By comparing measured deformations with numerically predicted bending moments, stiffness reduction factors were derived for each construction stage at both sites. The resulting values ranged from 0.25 to 0.6, depending on the number of support levels. The findings indicate that uncertainties in predicting lateral wall deflections of U-profile sheet pile walls in Switzerland cannot be attributed to unusually high stiffness reduction coefficients.

KEYWORDS: Sheet piles, U-profiles, reduction factor, stiffness, lateral deformations, excavation pit

1 INTRODUCTION

Sheet pile walls are a widely used and cost-effective method to retain soil in excavations, particularly in urban areas. When U-profile single sheet piles are used, the bending stiffness and moment resistance are reduced compared to a continuous monolithic wall, due to slippage in the interlocks.

Gielly et al. (1977) and Gigan (1979) were among the first to demonstrate that sheet piles do not behave as a continuous, monolithic wall and observed partial interlock slippage leading to a reduction in bending stiffness and moment resistance, proposing orders of magnitude for reduction factors for single sheet piles.

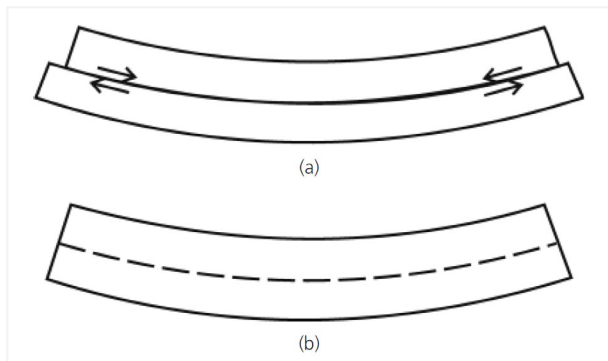


Figure 1. Schematic illustration of interlock slippage phenomenon: a) zero shear stress transfer in the interlock; b) full shear stress transfer, e.g. in the case of welded interlocks (reproduced from Bourne-Webb et al., 2010)

Some years later, Kort (2002) and Sedlacek et al. (2001) conducted intensive experiments and modelling in the Netherlands to determine reduction factors for stiffness and moment resistance for single, double and triple sheet piles, suggesting β_D values between 0.35 and 0.8, depending on soil conditions, struts or anchors level and installation effects. Laboratory tests by Byfield et al. (2003) on a small scale supported these findings for double sheet piles (oblique bending).

The Eurocode 3 Part 5 (EN 1993-5:2007) considered those observations, introducing formally reduction factors β_D (stiffness) and β_B (ultimate moment capacity). However, the values to be used are left to the discretion of each country, for example in national annexes:

- In Germany (DIN EN 1993-5/NA, DIN (2010)), β_D must be taken as 0.4 for single sheet piles, regardless of the number of anchors or struts.
- In France (NF EN 1993-5/NA, AFNOR (2002)), β_D must be between 0.4 and 0.6 for single sheet piles, depending on the number of anchors or struts.
- In Switzerland (SN EN 1993-5, SIA 2007), no reduction factors are specified, leading to discussions during the design stage because values published abroad may not reflect Swiss soil conditions. This issue forms the basis of the present research.

The present study aims to back-calculate the reduction factor β_D for single and fully grouted U-pile walls using data from two Swiss construction sites. Field measurements are combined with numerical simulations (Plaxis 2D) to estimate the effective stiffness of the walls and compare them with values proposed in French and German national annexes.

2 METHODOLOGY

2.1 Theoretical framework

Following classical beam theory, the effective bending stiffness EI_{eff} of a sheet pile wall can be expressed as follows:

$$EI_{eff} \cdot \frac{d^2 w(z)}{dz^2} = M(z) \rightarrow EI_{eff} = \beta_D \cdot EI \quad (1)$$

Where:

- $w(z)$: lateral deflection of the sheet pile
- $M(z)$: bending moment distribution
- EI_{eff} : effective bending stiffness of the sheet pile
- EI : bending stiffness of a continuous wall
- β_D : reduction factor due to interlock effects

2.2 Data

Data from two Swiss construction sites were analyzed: Alpnachstad and Bern Wylerfeld.

For each site, empirical deflection curves from inclinometer data were interpolated with a ninth-degree polynomial. The curvature was then obtained by taking the second derivative of this polynomial.

Simulated moment distributions were taken directly from finite element models.

The influence of wall stiffness on earth pressure (due to the soil-structure interaction, as highlighted for example by Gigan

(1979) or Bourne-Webb et al. (2010)) and therefore on bending moment, was also considered, by introducing a stiffness reduction factor β_{Plaxis} in the numerical model.

2.3 Combination

Curvature and moment distribution are combined to iteratively back-calculate β_D according to equation (1), as proposed in Boissier et al. (1978). The convergence between β_D obtained from the combination and β_{Plaxis} (used as input in the numerical model) was sought.

3 ALPNACHSTAD

3.1 Context

For the construction of a real estate complex in Alpnachstad (Canton of Obwalden), a 340-meter-long sheet pile wall was installed for an excavation depth of 3.5 m between June 2021 and April 2022. The sheet pile wall consisted of single U-piles, except for a test section where 10 sheet pile interlocks were completely grouted.

The subsurface consists of fill, followed by alternating silty sediments and gravelly stream deposits, both containing about 10% organic matter.

Two inclinometers were installed directly on the sheet piles: one on single sheet piles and one on the section of grouted sheet piles.

The excavation was carried out in a single stage. A strut level was added later after the wall had reached its maximum deformation; therefore it was not considered in the numerical model.



Figure 2. Excavation pit Alpnachstad. Picture, BUAS.

3.2 Curvature

As mentioned above, the displacements measured by the inclinometers were interpolated using a 9th degree polynomial (Figure 3). The curvature was obtained by taking the second derivative of this polynomial.

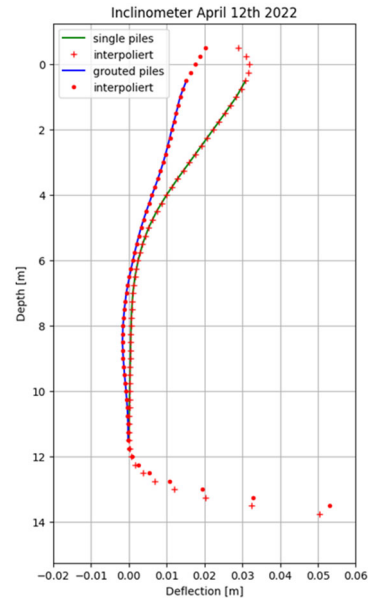


Figure 3. Interpolation of inclinometer displacements using a 9th degree polynomial

3.3 Geotechnical Model

The geological model is summarized in Table 1 and Figure 4. The groundwater table is located 1.0 m below the surface.

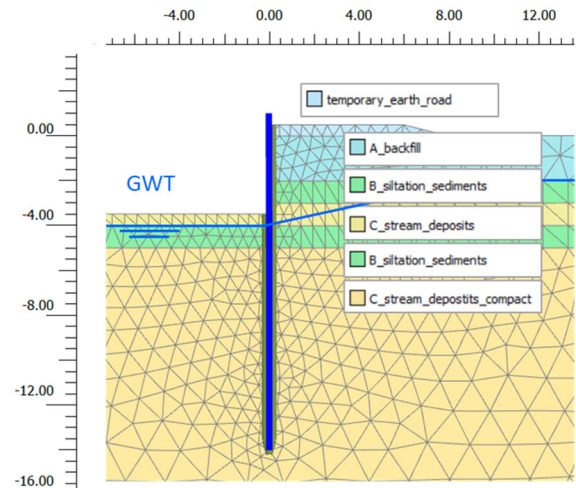


Figure 4. Selected geotechnical profile for Alpnachstad (Plaxis 2D)

Table 1. Geotechnical parameters Alpnachstad (HS-Small model Plaxis 2D)

	A) backfill	B) silt. sedim., organic	C) stream deposits, organic	C) stream deposits, compact	temp. road
γ [kN/m ³]	18	15	18	20	20
γ_{sat} [kN/m ³]	19.5	18.5	19.5	21.5	20.5
c [kN/m ²]	8	8	8	8	2
ϕ [°]	31	32	35	35	35
ψ [°]	1	2	5	5	5
E_{50}^{ref} [MN/m ²]	40	1.5	26	30	40
$E_{\text{oed}}^{\text{ref}}$ [MN/m ²]	40	1.5	26	30	40
$E_{\text{ur}}^{\text{ref}}$ [MN/m ²]	120	4.5	78	90	120
power m [-]	0.5	0.5	0.5	0.5	0.5

G_0^{ref} [MN/m ²]	190	5	190	190	190
$\gamma_{0.7}$ [-]	0.2E-3	0.2E-3	0.2E-3	0.2E-3	0.2E-3
interface R_{inter}	0.67	0.67	0.67	0.67	0.67

Table 2. Sheet pile wall (plate) parameters
PU 22

Material type	Elastic
w, unit weight [kN/m/m]	1.41
EA1 [kN/m]	3.84E6
EI [kNm ² /m]	103.9E3
ν [-]	0.3

3.4 Bending Moment

The construction site in Alpnachstad was simulated with the FE software Plaxis 2D using Hardening Soil small (HS-small) constitutive law, to estimate the bending moment. No consolidation effects were modeled: all subsoil layers were assumed to be fully drained, which is reasonable given that the displacements were measured 7.5 months after end of dewatering phase.

The parameters for the sheet pile wall, modelled as a plate, are available in Table 2. The simulations were carried out with varying values of β_{Plaxis} (and hence varying the bending stiffness of the plate).

The model showed a good match between the displacements measured by the inclinometer and those predicted by the model, as shown in Figure 5.

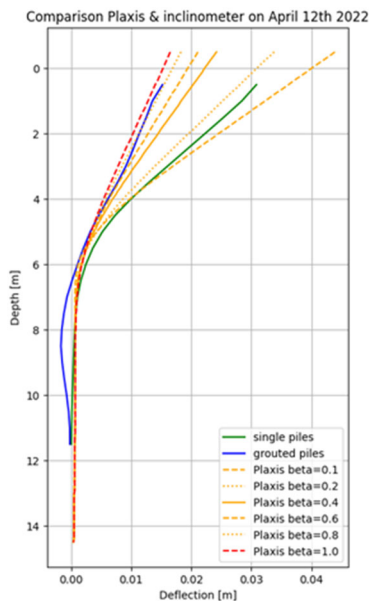


Figure 5. Lateral deformations in Alpnachstad. Measurements vs. predictions

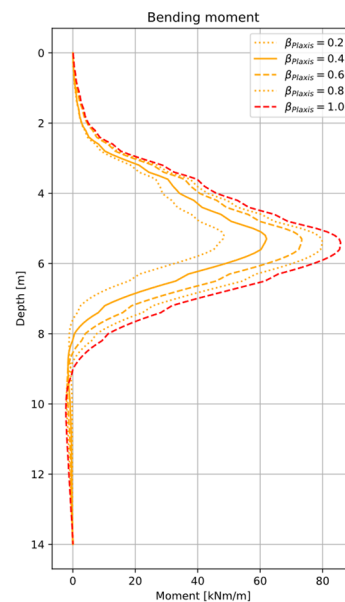


Figure 6. Bending moment in Alpnachstad. Predictions from the Plaxis 2D model

4 BERN WYLERFELD

4.1 Context

The Bern Wylerfeld “disentanglement” construction site took place between the beginning of 2016 and mid-2023 at the outskirts of the Swiss capital. The disentanglement structure was planned to eliminate crossing conflicts on the Thun-Bern, Olten-Bern, and Biel-Bern railway routes (Breitenmoser, (2023)). The core element was a 300 m long cut-and-cover tunnel with two ramps of 290 m each, whereby the excavation pit was secured with the help of sheet pile walls.

This case study focuses exclusively on the deformation behaviour of the sheet pile wall in section B, block 52, one of the lowest points in the vertical alignment of the tunnel. This section is retained with 2 struts levels, for a total excavation depth of 12.3m.

The excavation support and the surrounding terrain were monitored with numerous sensors during the construction works:

- Inclinometers: I-52N (North sheet pile wall) and I-52S (South sheet pile wall)
- Geodetic measurements
- Vibrating wire sensors (temperature and force in the struts)
- Piezometers

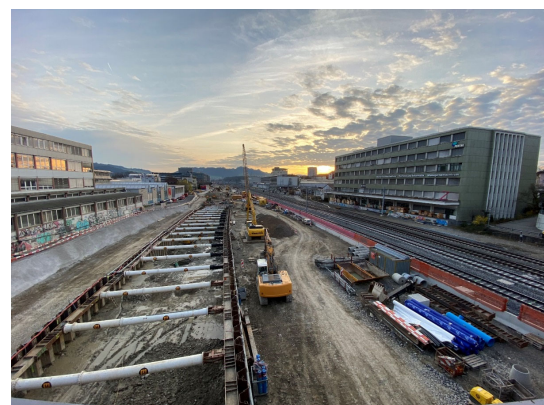


Figure 7. Bern Wylerfeld construction site on March 17th 2020, eastward viewing direction (Picture, P. Breitenmoser — SBB)

4.2 Excavation steps

The construction process took place into seven distinct steps, as summarized in Table 3.

Table 3. Excavation stages, Bern Wylerfeld

Excavation step	Description	Inclin. meas. date	Nbr of support levels before date
Phase 1 - piles installation	The U-piles are driven into the ground and the upper strut is installed, with a prestress load of -130 kN	06.03.2020 (zero)	0
Phase 2 - excavation	Start excavation around 15.03.2020. 8.5m excavation depth. The water pressure from the upper groundwater table is activated.	25.03.2020	1
Phase 3 - lower strut	The lower strut is installed, with a prestress load of -350 kN.	17.04.2020	1
Phase 4-5-6 excavation-slab	12.3m excavation depth, lowering of the lower GWT, installation of a drainage layer, construction of the foundation slab.	15.05.2020	2
Phase 7	The lower strut is dismantled.	16.06.2020	2

4.3 Curvature

The curvature was obtained using the same procedure as in Alpnachstad (see section 3.2).

4.4 Geotechnical Model

The geological model is summarized in Table 4 and Figure 8. The subsoil is characterized by two different groundwater levels: upper in the schotter and lower above the moraine. The installation of sheet piles blocks groundwater flow, resulting in asymmetry in the reference piezometric levels between north and south sides after pile installation, as illustrated in Figure 8.

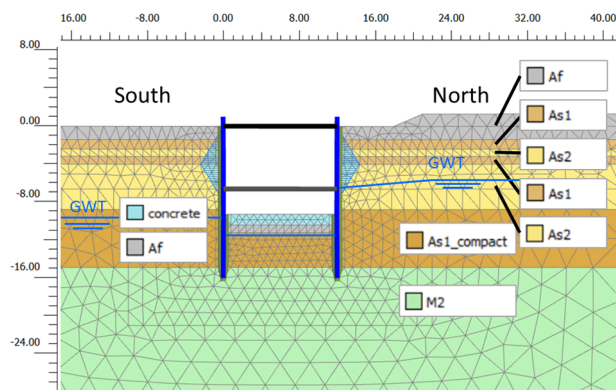


Figure 8. Selected geotechnical profile for Bern Wylerfeld (Plaxis 2D)

Table 4. Geotechnical parameters Bern Wylerfeld (HS model Plaxis 2D)

	Af Felder- schotter	As1 back. sedim	As2 back. sedim	M2 compact moraine
γ [kN/m ³]	20.5	20	21	22
γ_{sat} [kN/m ³]	21.5	21	22	22.5
c [kN/m ²]	1	1	10	8

ϕ [°]	30	30	27	36
ψ [°]	0	0	0	0
permeability (isotropic) [m/day]	9	0.5	0.2E-3	0.6E-3
E_{50}^{ref} [MN/m ²]	37	18; compact 23	8.1	90
E_{oed}^{ref} [MN/m ²]	37	18; compact 23	8.1	90
E_{ur}^{ref} [MN/m ²]	111	54; compact 69	24	270
power m [-]	0	0	0	0
interface	0.5	0.5	0.5	0.5
R_{inter}				

Table 5. Sheet pile wall (plate) parameters

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Material type	Elastic
w , unit weight [kN/m/m]	1.84
EA1 [kN/m]	5.012E6
EI [kNm ² /m]	153.9E3
ν [-]	0.3

4.5 Consolidations speed

Due to the low permeability of the As2 layer, a rough estimate of the consolidation time was carried out to ensure that subsequent calculations under fully drained conditions were justified, given the frequency of the available deformation measurements (Table 3).

Table 6 gives the duration in days for which 90% of the consolidation is reached (t_{90}) for the first and second excavations (phases 2 and 4-5-6), compared to the frequency of inclinometer measures.

Table 6. Consolidation speed assessment

Excavation phase	2	4-5-6
Thickness layer As2 [m]	3	5
drainage conditions	one-sided	one-sided
t_{90} [day]	33	92
Phase measure inclinometer	3	7
Time elapsed since the start of excavation [day]	33	93

It can therefore be considered that 90% of consolidation had been achieved at the time of the inclinometer measurement.

4.6 Bending Moment

The bending moments in the piles were estimated using a finite element model in Plaxis 2D in drained conditions, as discussed previously. The chosen soil model is Hardening Soil (HS model, see Table 4), the sheet piles are elastic plates (Table 5).

The model parameters were calibrated to ensure good agreement with the measured displacement (Figure 9) and forces in the struts (Table 7).

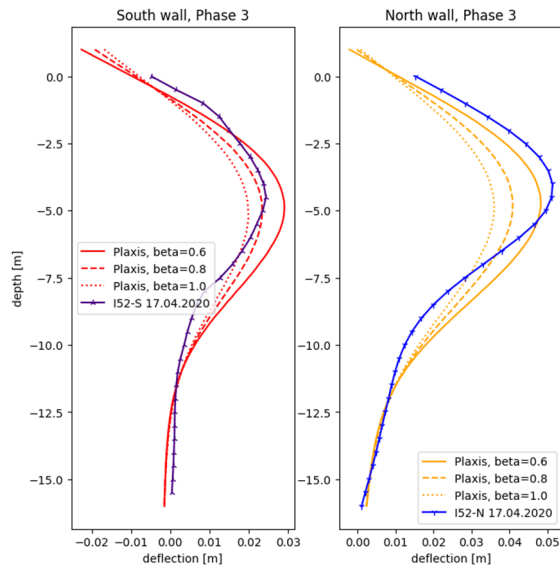


Figure 9. Lateral deformations in Bern Wylerfeld. Measurements vs. predictions

Table 7. Forces in struts in Bern Wylerfeld

Force in strut [kN]	Measured	Model Plaxis		
		$\beta_{Plaxis}=0.6$	$\beta_{Plaxis}=0.8$	$\beta_{Plaxis}=1.0$
Upper	1000 - 1200	860	850	840
Lower	2750	2955	2930	2915

5 RESULTS & DISCUSSION

5.1 β_D distribution

According to equation (1), knowing the bending moment, the curvature, and the flexural rigidity EI of an equivalent continuous wall allows the distribution of β_D to be plotted with depth.

Two examples are given for Alpnachstad (Figure 10, for $\beta_{Plaxis}=1.0$) and Wylerfeld Nord (Figure 11, excavation phase 3).

Following Kort (2002), β_D is estimated at the local minimum close to the maximum bending moment (grayed area on Figure 10 and Figure 11).

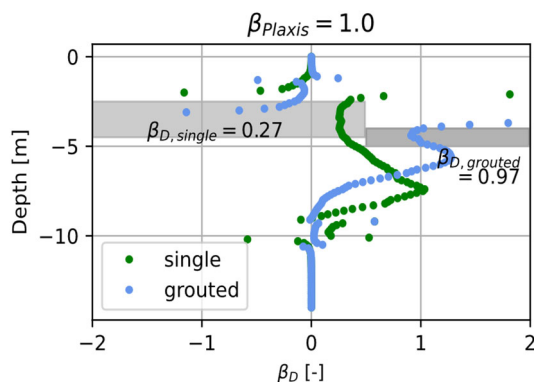


Figure 10. β_D distribution Alpnachstad

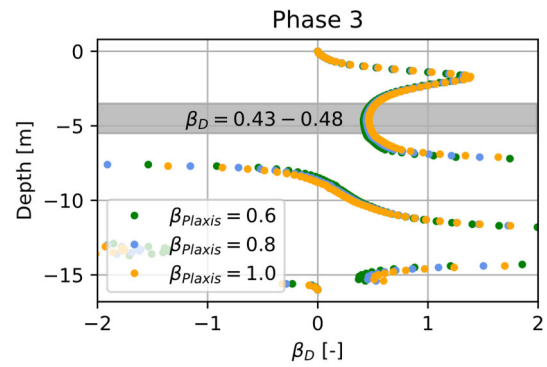


Figure 11. β_D distribution Wylerfeld North, Phase 3

The results are summarized in Table 8, for β_D that match approximately β_{Plaxis} .

Table 8. Stiffness reduction factors β_D for Alpnachstad and Bern Wylerfeld

Construction site	Type pile	Number supports	β_D [-]
Alpnachstad	single	0	0.2*
*cannot theoretically be under 0.25			
Alpnachstad	grouted	0	0.95
Wylerfeld, North, Phase 3	single	1	0.4
Wylerfeld, North, Phase 7	single	2	0.45
Wylerfeld, South, Phase 3	single	1	0.7
Wylerfeld, South, Phase 7	single	2	0.8

5.2 Discussion

It is worth noting that the derived β_D are subject to the following uncertainties:

- the local minimum near the depth of the maximum moment was selected. However, the distribution of β_D with depth may still vary locally (see Figure 10 – grouted, for example)
- the bending moments were estimated numerically rather than directly measured

Despite these limitations, it can be observed that the reduction coefficients tend to increase with the number of supports.

The value obtained for the single sheet piles in Alpnachstad appears lower than the minimum theoretical value of 0.25 (PU22 profiles). However, we do not believe that the numerical model needs to be structurally overhauled, as for the same bending moment profile, the grouted sheet piles have a reduction coefficient of 0.95. Therefore, the corrected value of 0.25 is proposed for these single sheet piles.

For Bern Wylerfeld, the numerical model does not fully capture the north-south heterogeneity (see also Figure 8), likely due to a global tilting effect of the cut-and-cover trench that is not represented in the model. It is proposed to use the average of the north and south results as a representative value, as presented in Table 9.

5.3 Comparison with recommended values

Table 9. Comparison of β_D for single sheet piles

Number supports	β_D [-]		
	present study	German NA	French NA
0	0.25	0.4	0.4
1	0.55	0.4	0.5
2	0.6	0.4	0.6

The final values of β_D (Table 9) are in good agreement with the values recommended in the French national annexes NF EN 1993-5/NA, AFNOR (2002), except for $\beta_D=0.25$ for Alpnachstad (without support) instead of $\beta_D=0.4$ in the norm. This may be explained by the local geology (high organic content, few sand), which does not allow soil particles to become blocked in the locks.

6 CONCLUSIONS

The study, conducted on two construction sites in Switzerland with soils typical of the Swiss Plateau and four distinct profiles, enabled the derivation of stiffness reduction factors β_D for single sheet piles and one grouted wall.

For the grouted piles, the reduction factor is 0.95, close to 1.0.

For single sheet piles, the results indicate that the magnitude of the stiffness reduction factor increases with the number of supports. We found a variation of $\beta_D=0.25$ to 0.6 for 0 to 2 supports, which does not exceed the values recommended in the French national annex. $\beta_D=0.25$ is the theoretical minimum value for single sheet pile without interlocking and can be attributed in this study to specific soil conditions.

Consequently, the hypothesis of a Swiss-specific behaviour suggesting higher stiffness reduction factors due to soil characteristics can be reasonably dismissed. In the author's opinion, if the measured deformations of the sheet piles are smaller than those predicted by the calculations, the geotechnical model and drainage conditions should certainly be reassessed before questioning the relevance of the stiffness reduction factors.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

- AFNOR (Association Française de Normalisation). 2002. NF EN 1993-5/AN. Annexe Nationale - Eurocode 3 - Calcul des structures en acier - Partie 5: Pieux et palplanches.
- Boissier, D., Gielly, J., Kastner, R., Mangin, J. C. 1978. Détermination des moments et des pressions exercées sur un écran à partir de mesures inclinométriques. *Canadian Geotechnical Journal*, 15, 522-536.
- Bourne-Webb, P. J., Potts, D. M., Rowbottom, D. 2010. Eurocode reduction factors for U-profile sheet pile walls. *ICE Proceedings, Structures and Buildings*, Volume 164 December 2011, 377-390. DOI: 10.1680/stbu.2011.164.6.377
- Breitenmoser, P. 2023. Entflechtung Wylerfeld: Eine Operation am offenen Herzen in Bern, *Eisenbahn Ingenieur Kompendium EIK 2023*, Verband Deutscher Eisenbahn-Ingenieure E.V.
- Byfield, M. P., Crawford, R. J. 2003. Oblique bending in U-shaped steel sheet piles. *Proceedings of the Institution of Civil Engineers, Structures & Buildings 156*, Issue SB3, 255-261.
- DIN (Deutsches Institut für Normung). 2010. DIN EN 1993-5/NA, Nationaler Anhang– Eurocode 3: Bemessung und Konstruktion von Stahlbauten – Teil 5: Pfähle und Spundwände.
- Gielly, J., Kastner, R., Ferrand, J. 1977. Expérimentation en vrai grandeur sur écrans souples. *Proceedings of the 9th International Conference of Soil Mechanics and Foundation Engineering*. Vol. 2, 75-78.
- Gigan, J. P. 1979. Expérimentation en vrai grandeur d'un rideau de palplanches. *Revue française de géotechnique*, Numéro 8.
- Kort, D.A. (2002). Sheet pile walls in soft soil. Doctoral thesis. Delft: DUP Science.

- Sedlacek, G., Hartmann-Linden, R., van Tol, F., Kort, A., Schmitt, A., Meyrer, M. 2001. Development of unified design rules for steel sheet piles for introduction into Eurocode 3, Part 5. EUR20034 – *Steel structures, European Commission*.
- SIA (Schweizerischer Ingenieur- und Architektenverein). 2007. SN EN 1993-5:2007 Eurocode 3: Bemessung und Konstruktion von Stahlbauten - Teil 5: Pfähle und Spundwände.