ArcelorMittal Sheet Piling

ArcelorMittal

Design & Execution Manual
AS 500® straight web steel sheet piles

Steel Foundation Solutions for Projects

Cover:
2nd Incheon Bridge, South Korea

Table of content

Project: Marina Pez Vela, Costa Rica
Sections: AS 500 - 11.0 & AS 500 - 12.7
Quantity: 3 440 tonnes

1. Introduction

Cellular cofferdams can be designed as self-supporting gravity walls not requiring any supplementary waling and anchoring. They can be founded directly on bedrock, without any embedment. They are economical solutions for works in deep waters, high retaining works, and long structures.

The applications of straight web steel sheet piles fall into two categories: for temporary works and for permanent works. When used for temporary works, a series of individual sheet pile cells form massive cellular cofferdams enabling large and deep excavations to be carried out in the dry in or alongside riverbeds, etc., where the excavations often go down to bedrock.

For permanent structures, cellular sheet pile cofferdams are used above all in the maritime-engineering sector, to build:

- massive quay walls: the structure serves as a retaining wall and as a berth for ships;
- piers and jetties which can be used to berth ships on both sides;
- dolphins: works made up of a single cell, used for berthing or guidance of ships;
- breakwaters: harbour-protection structures (berthing not usually possible).

It is less common for cells to be used on land, but they can be chosen for massive retaining structures, taking advantage of their weight to prevent slips.

There are mainly two types of cells built with straight web sheet piles:

Circular cells

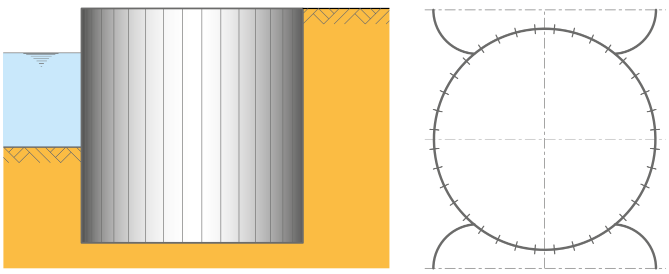


Fig. 1.1.: Elevation and plan view of a circular cell.

Diaphragm cells

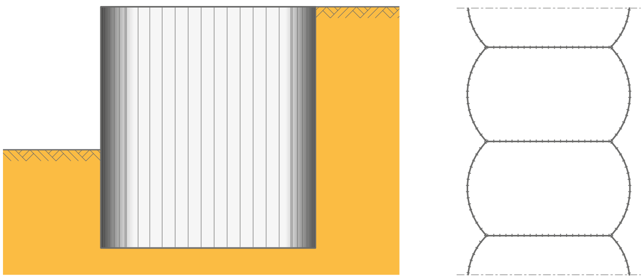


Fig. 1.2.: Elevation and plan view of diaphragm cells.

The differences between these two types of constructions will be explained in the following chapters.

The engineering department of ArcelorMittal Commercial RPS has been involved in the design and installation of major cellular structures all around the world in the past decades.

Even though this manual is meant to be an invaluable aid, project owners, design engineers and contractors can count on ArcelorMittal's dedicated civil engineers to assist with these challenging foundation projects.

Project: Arsenal of Brest, France
Sections: AS 500 - 12.7
Quantity: 675 tonnes

2. Characteristics

2.1. Straight web steel sheet piles

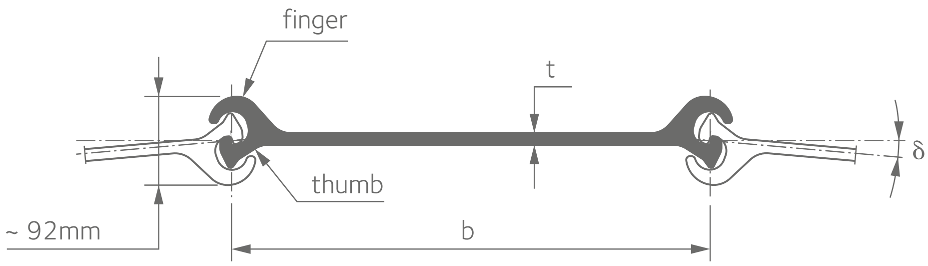


Fig. 2.1.: Characteristics of AS 500 straight web sheet piles.

Table 2.1.: Characteristics of AS 500® sections

Section	Width[1]	Web thickness	Deviation angle[2]	Perimeter	Steel section	Mass	Mass per m² of wall	Moment of inertia	Section modulus	Coating area[3]
				(single pile)				(single pile)		
	b	t	δ							
	mm	mm	°	cm	cm²	kg/m	kg/m²	cm⁴	cm³	m²/m
AS 500 - 9.5	500	9.5	4.5	138	81.3	63.8	**128**	168	46	0.58
AS 500 - 11.0	500	11.0	4.5	139	89.4	70.2	**140**	186	49	0.58
AS 500 - 12.0	500	12.0	4.5	139	94.6	74.3	**149**	196	51	0.58
AS 500 - 12.5	500	12.5	4.5	139	97.2	76.3	**153**	201	51	0.58
AS 500 - 12.7	500	12.7	4.5	139	98.2	77.1	**154**	204	51	0.58
AS 500 - 13.0[4]	500	13.0	4.5	140	100.6	79.0	**158**	213	54	0.58

Note: all straight web sections interlock with each other.

[1] The calculation width, to be taken into account for design purposes and layout, is 503 mm for all AS 500 sheet piles.
[2] Max. deviation angle 4.0° for pile length > 20 m.
[3] One side, excluding inside of interlocks.
[4] Please contact ArcelorMittal Sheet Piling for further information.

2.2. Junction piles

In general, junction piles are made by welding in accordance with EN 12063.

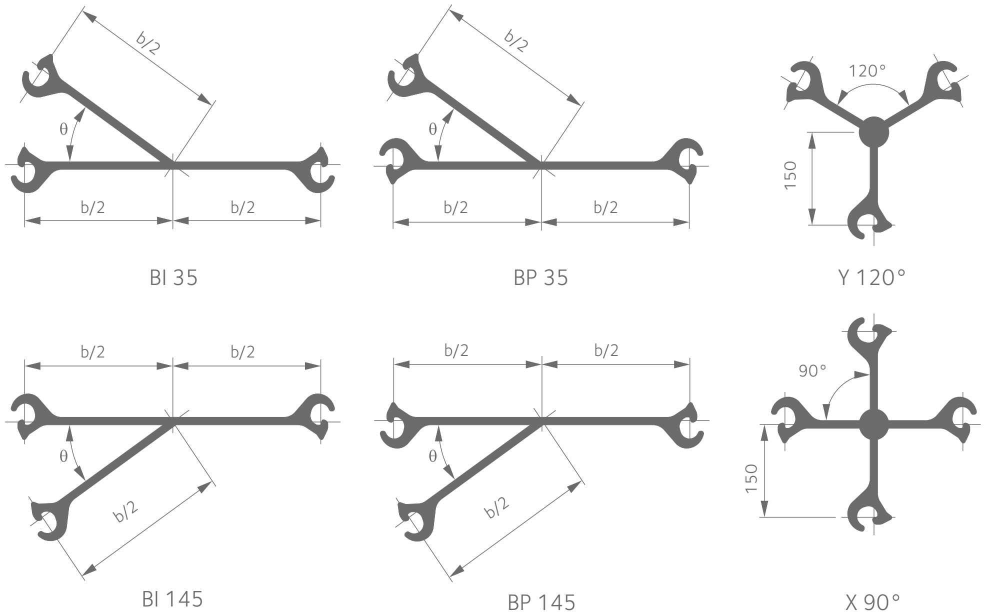


Fig. 2.2.: Characteristics of junction piles.

Connecting angles θ in the range from 30° to 45° are recommended. It is nevertheless possible to have angles up to 90°.

2.3. Bent piles

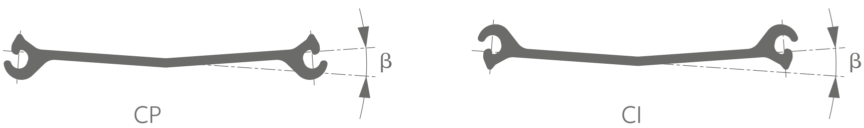


Fig. 2.3.: Bend angle β of AS 500 piles.

If deviation angles δ exceeding the values given in Table 2.1. are required, piles prebent in the mill may be used.
The maximum possible pile bend angle β is about 12°.

2.4. Delivery conditions

Interlock resistance

The following characteristic interlock resistance can be guaranteed:

Section	$R_{k,s}$ [kN/m][1)]
AS 500 - 9.5	3 500
AS 500 - 11.0	4 000
AS 500 - 12.0	5 000
AS 500 - 12.5	5 500
AS 500 - 12.7	5 500
AS 500 - 13.0	6 000

[1)] For the related steel grade and further information, please contact ArcelorMittal Sheet Piling.

For verification of the piles both, yielding of the web and failure of the interlock, should be checked.

The test procedure is based on Annex D of prEN10248-1 (2007).

Watertightness of interlocks

Due to the huge tensile forces in the interlocks of straight web sheet piles, steady contact is established between the two interlocked mating surfaces over the whole length of the sheet pile. This contact is so strong that generally no further measures are required to make the sheet piling structure watertight.

Coating

A coating system can be applied to straight web sheet piles. For further information, refer to our specific documentation.

Handling holes

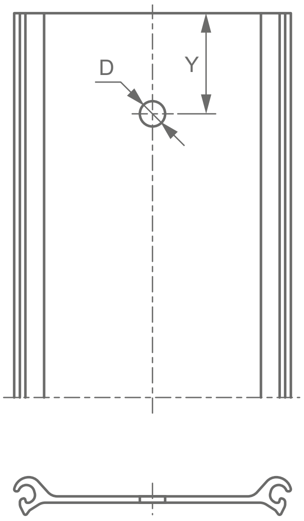


Fig. 2.4.: Dimensions of handling holes.

Sheet pile sections are normally supplied without handling holes. If requested, they can be provided with handling holes on the centreline of the section.

Diameter D [mm]	40	40	50	50	63.5	40
Distance Y [mm]	75	300	200	250	230	150

Diameter D [in]	2.5
Distance Y [in]	9

Rolling length

The maximum rolled length provided by the mill is 31.0 m. Greater length may nevertheless be made to order, by fabrication.

Special requirements

Straight web steel sheet piles are usually supplied as single piles. Double piles can nevertheless be delivered on request.

Note: Double piles call for specific care during storage, handling and lifting.

Geometric tolerances according to EN 10248

Designation	Tolerance
Mass	±5%
Length (L)	± 200 mm
Thickness (t)	t > 8.5 mm : ± 6%
Width single pile (b)	± 2% b
Width double pile (2b)	± 3% 2b
Straightness (q)	≤ 0.2% L
Ends out of square	± 2% b

Markings

The following markings can be supplied on request:

- colour marks defining section, length and steel grade;
- adhesive stickers showing the customer's name, destination, order number, type and length of profile and steel grade.

Steel grades of sheet pile sections

AS 500® sections are delivered in the steel grades based on EN 10248-1.

Steel grade EN 10248	Min. yield strength R_{eH} MPa	Min. tensile strength R_m MPa	Min. elongation $L_o = 5.65\sqrt{S_o}$ %	Chemical composition (% max)					
				C	Mn	Si	P	S	N
S 270 GP	**270**	410	24	0.27	–	–	0.055	0.055	0.011
S 320 GP	**320**	440	23	0.27	1.70	0.60	0.055	0.055	0.011
S 355 GP	**355**	480	22	0.27	1.70	0.60	0.055	0.055	0.011
S 390 GP	**390**	490	20	0.27	1.70	0.60	0.050	0.050	0.011
S 430 GP	**430**	510	19	0.27	1.70	0.60	0.050	0.050	0.011

Materials to other specifications including ASTM A572, as well as special steels with improved corrosion resistance **(ASTM A 690)**, or copper addition in accordance with EN 10248- Part 1, Chapter 10.4, can be supplied on request.

Europe	EN 10248	S 270 GP	S 320 GP	S 355 GP	S 390 GP	S 430 GP
USA	ASTM	A 328	-	A 572 Gr.50; A 690	A 572 Gr.55	A 572 Gr. 60
Canada	CSA	Gr. 260 W	Gr. 300 W	Gr. 350 W	Gr. 400 W	-
Japan	JIS	SY 295	-	-	SY 390	-

Galvanisation has an influence on the chemical composition of the steel and must therefore be specified in the purchase orders.

We strongly recommend informing us of all surface treatment to be applied to the product when placing orders.

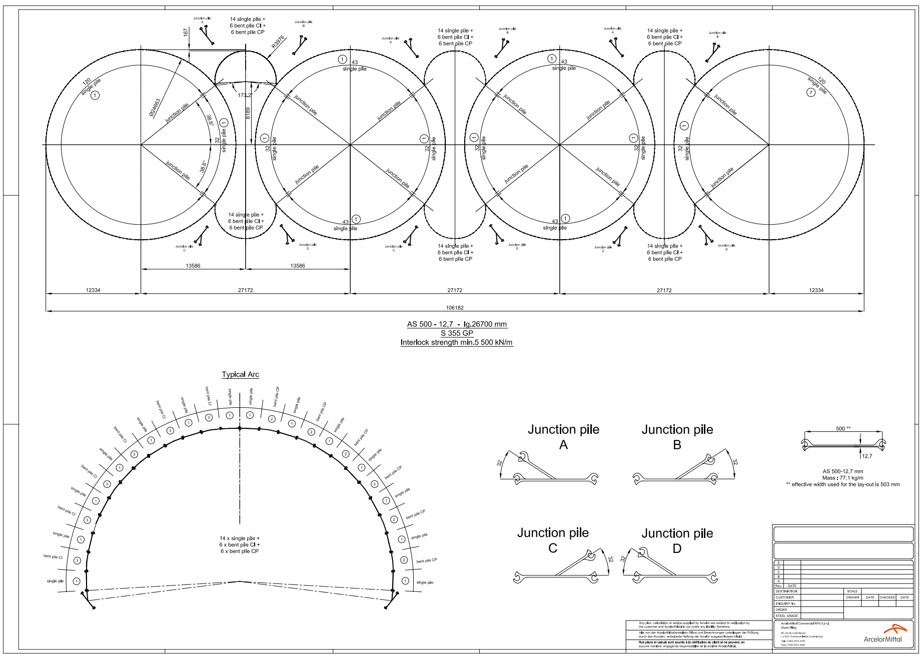


Fig. 2.5.: Example of layout.

Project: Puerto de Mejillones, Chile
Sections: AS 500 - 12.7
Quantity: 2 300 tonnes

3. Handling

Straight web sheet piles have low flexural stiffness, which means care should be taken when considering handling. Guidance is given in EN 12063.

Incorrect storage could cause permanent deformation, making interlock threading difficult if not impossible.

It is therefore vital to have a sufficient number of wood packing pieces between each bundle of stacked sheet piles, and to position these pieces above each other to limit the risk of deformation.

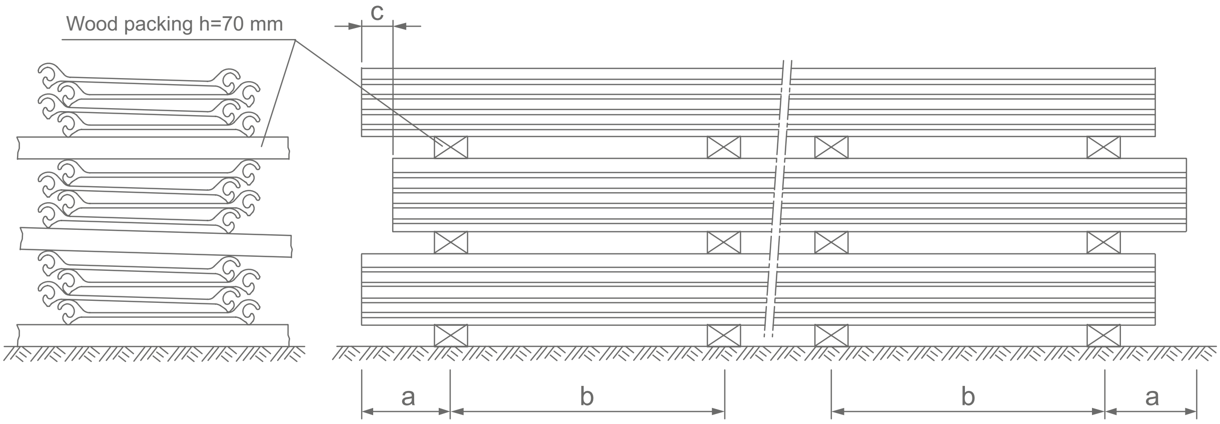


Fig. 3.1.: Storage of straight web sheet piles.

Max. bundle weight	7.5 t
Overhang	a ≤ 1.5 m
Spacing of packing	b ≤ 4.0 m
Offset of bundle	c > 0.15 m
Wood packing to be aligned in the vertical plane	

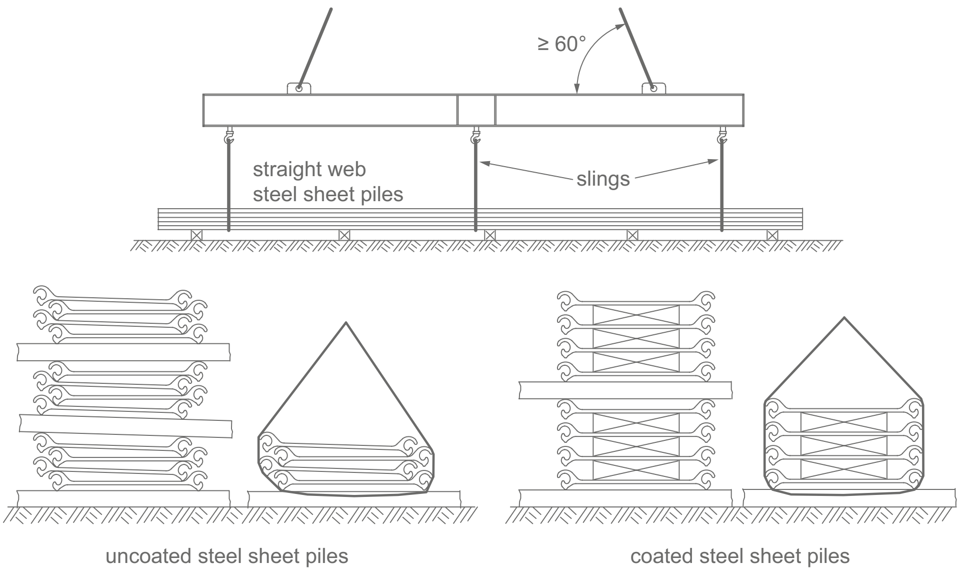


Fig. 3.2.: Handling of straight web sheet piles.

When sheet piles have to be moved from the horizontal storage position to another storage location, lifting beams or brackets made from pile sections threaded into the interlocks prior to lifting should be used.

When pitching piles up to 15 m long into the vertical position, only one point of support near the top (the handling hole) is necessary. Straight web sheet piles more than 15 m long should be lifted at two or even three points, in order to avoid plastic deformation.

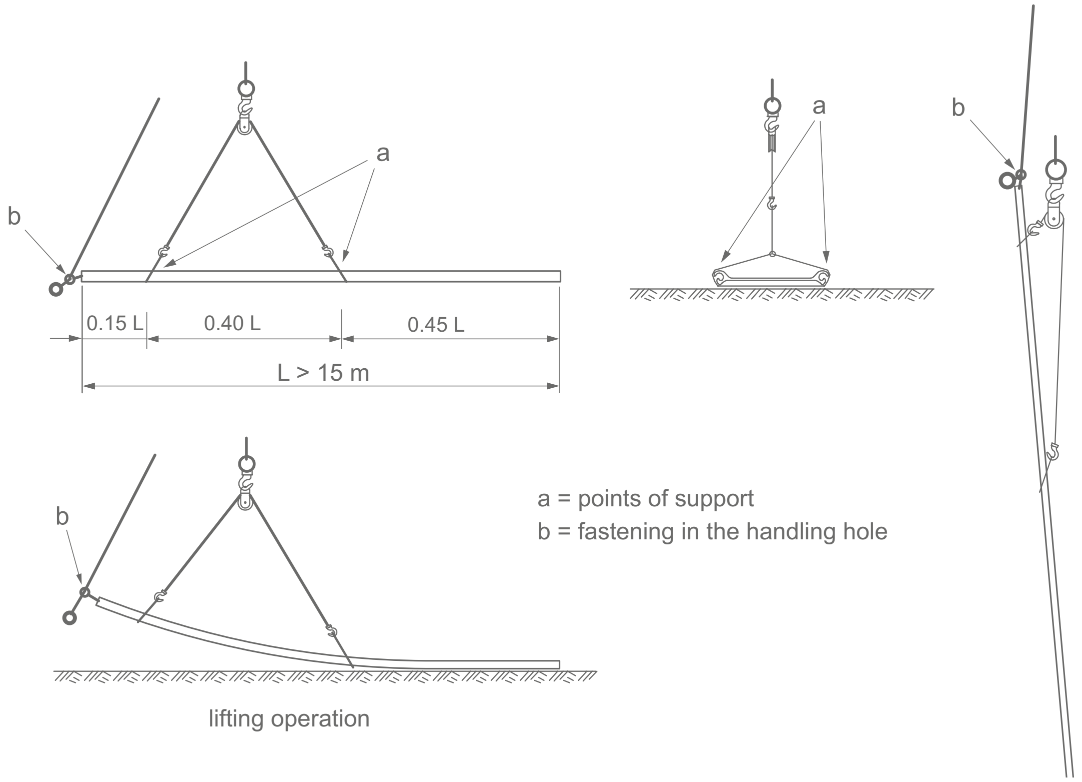


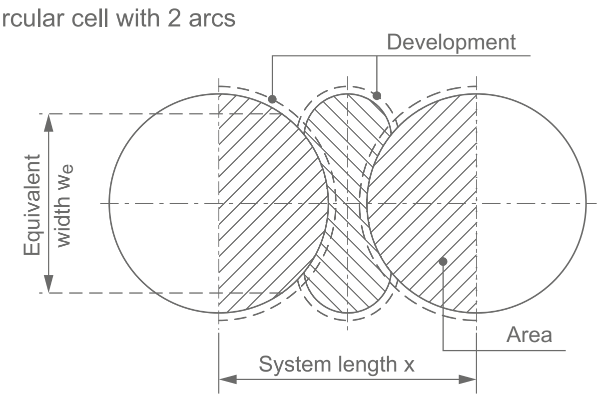
Fig. 3.3.: Lifting of long straight web sheet piles.

Project: 2nd Incheon bridge, South Korea
Sections: AS 500 - 12.7
Quantity: 1 690 tonnes

4. Geometrical parameters

4.1. Determination of Ratio and Equivalent Width w_e

Circular cells



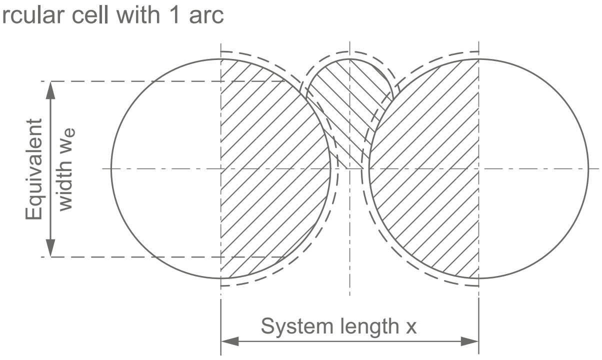


Fig. 4.1.: Determination of the Equivalent Width w_e and Ratio for a circular cell.

The **Ratio** shown on tables indicates how economical the chosen cellular construction will be. It is defined as follows:

$$\text{Ratio} = \frac{\text{Development 1 cell + Development 1 (or 2) arc(s)}}{\text{System length x}}$$

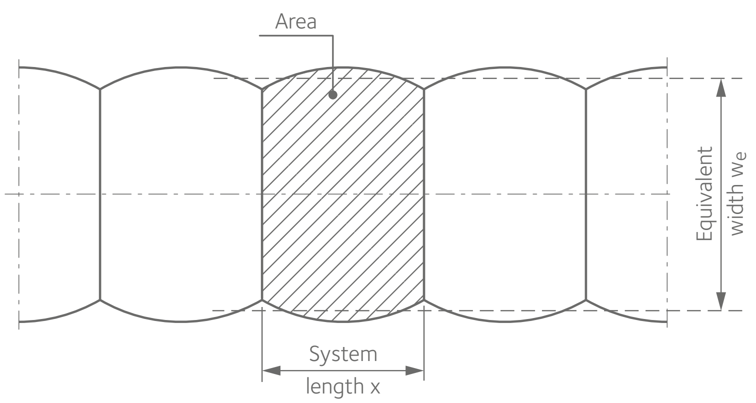
The **Equivalent Width w_e** which is required for stability verification, is determined by the geometry chosen for the cellular construction (for definitions see section 4.3.). It is calculated with:

$$w_e = \frac{\text{Area within 1 cell + Area within 1 (or 2) arc(s)}}{\text{System length x}}$$

Diaphragm cells

The **Equivalent Width w_e** for a diaphragm cell is defined as:

$$w_e = \frac{\text{Area within 1 diaphragm}}{\text{System length x}} = \text{diaphragm length (dl)} + 2 \cdot c \qquad \text{with } c = \frac{\text{Area of arc segment}}{\text{System length x}}$$



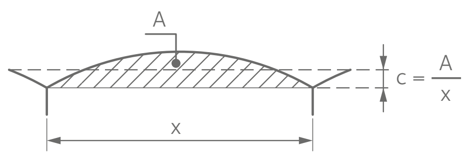


Fig. 4.2. : Determination of the Equivalent Width w_e of a diaphragm cell.

4.2. Definition of System and Standard Solution

Circular cells with 2 arcs

1 System = 2 half cells + 2 arcs

Number of piles for 1 System = 2 • number of piles for $\frac{1}{2}$ cell + 2 • number of piles for 1 arc + 4 junction piles
= 2 (L + M) + 2 • N + 4 • S

The Standard Solution for circular cells is built with an even number of piles (junction piles included) for the cell and an odd number of piles for each arc (Table 4.1.).

The connecting angle of the junction piles for the Standard Solution is: $\theta = 35°$

Diaphragm cells

1 System = 1 diaphragm + 2 arcs

Number of piles for 1 System = 1 • number of piles for 1 diaphragm + 2 • number of piles for 1 arc + 2 junction piles.
= N + 2 • M + 2

The Standard Solution for diaphragm cells is built with an odd number of piles (junction piles not included) for the diaphragm, an odd number of piles for each arc and 2 junction piles (Table 4.3.).

The connecting angle of the Y-junction piles for the Standard Solution is 3 • 120°.

4.3. Geometrical values

Having completed the design process to determine the Equivalent Width (w_e), the geometry of the cell can be chosen. This can be done with the help of tables or with computer programs. Several solutions are possible for both circular and diaphragm cells with a given equivalent width.

4.3.1. Circular cells with junction piles

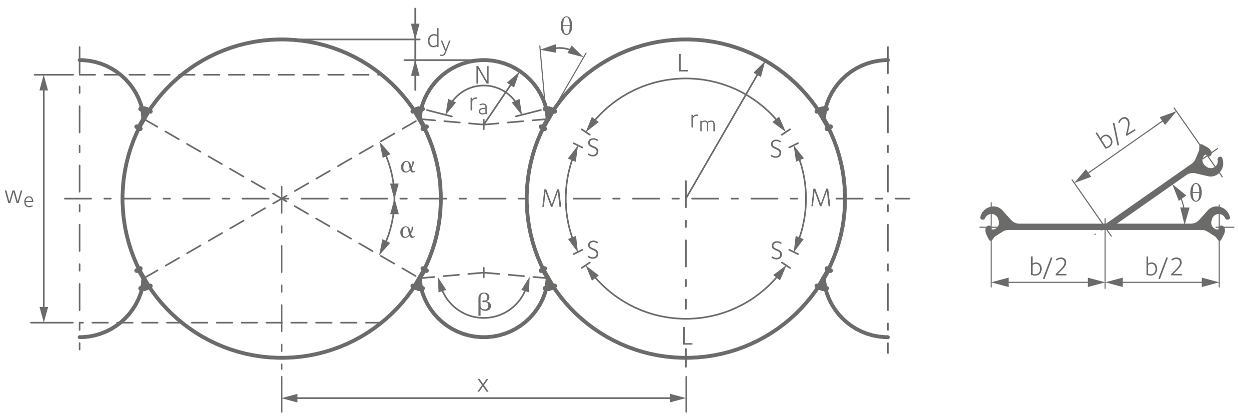


Fig. 4.3.: Geometrical values for circular cells.

The most important parameters for **circular cells** are (Fig. 4.3.):

- the radius of the main cell (r_m);
- the radius of the connecting arcs (r_a);
- the angle between the main cell and the connecting arc (θ);
- the system length (x);
- the positive or negative offset between the connecting arcs and the tangent planes of the main cells (d_y);
- the Equivalent Width (w_e).

The following relationships apply :

- the greater the angle (θ) between cell and arc, the greater the ratio of r_a/r_m. For $\theta = 90°$ and $d_y = 0$: $r_m = r_a$;
- with constant r_m and increasing r_a, the system length (x); also increases and the equivalent width decreases, if $d_y = 0$;
- the governing circumferential tensile force increases as the r_a/r_m ratio increases;
- the developed pile wall surface per metre of cofferdam decreases as the r_a/r_m ratio increases;
- with respect to circumferential tensile force, the solution with the smallest possible angle θ is the optimum for a given Equivalent Width (w_e), but also the most unfavourable with respect to the quantities of material required;
- if the straight web piles have any residual resistance to be mobilized, the optimum solution will have an angle between 30° and 45°. For design reasons (welding), this angle may not be less than $\theta = 30°$.

Note: A cellular cofferdam is a flexible structure. After the closure of the cell structure and eventual filling, the cell will undergo horizontal movements of the piling ring at the top of the structure resulting in an increase of the cell diameter, as well as local deformations due to the barrelling effect (section 6.1.2.2., fig. 6.12.). This has to be taken into consideration while designing cellular constructions by assuming that the theoretically designed geometry of the cell will be slightly different from the geometry practically obtained on site. The calculation width of 503 mm has been used in following tables (Table 4.1. to 4.3.).

Table 4.1.: Circular cells with $\theta = 35°$ standard junction piles

No. of piles per						Geometrical values						Interlock deviation		Design values	
Cell				Arc	System							Cell	Arc	2 Arcs	
	L	M	S	N		$d=2\cdot r_m$	r_a	x	d_y	α	β	δ_m	δ_a	w_e	R_a
pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	m	m	m	m	°	°	°	°	m	
52	17	7	1	11	74	8.33	2.09	11.52	0.40	27.69	165.38	6.92	13.79	**6.90**	3.32
52	17	7	1	13	78	8.33	2.44	12.21	0.10	27.69	165.38	6.92	11.82	**7.07**	3.30
52	19	5	1	15	82	8.33	3.04	13.68	0.39	20.77	151.54	6.92	9.47	**6.64**	3.09
56	19	7	1	13	82	8.97	2.50	13.01	0.44	25.71	161.43	6.43	11.54	**7.35**	3.25
56	19	7	1	15	86	8.97	2.86	13.71	0.14	25.71	161.43	6.43	10.09	**7.52**	3.23
56	21	5	1	17	90	8.97	3.49	15.18	0.46	19.29	148.57	6.43	8.26	**7.07**	3.05
60	21	7	1	15	90	9.61	2.92	14.50	0.49	24.00	158.00	6.00	9.88	**7.79**	3.19
60	21	7	1	17	94	9.61	3.28	15.22	0.19	24.00	158.00	6.00	8.78	**7.96**	3.17
60	23	5	1	19	98	9.61	3.95	16.68	0.53	18.00	146.00	6.00	7.30	**7.49**	3.01
64	21	9	1	15	94	10.25	2.77	14.54	0.27	28.13	166.25	5.63	10.39	**8.64**	3.32
64	23	7	1	17	98	10.25	3.35	16.00	0.54	22.50	155.00	5.63	8.61	**8.22**	3.14
64	23	7	1	19	102	10.25	3.72	16.73	0.25	22.50	155.00	5.63	7.75	**8.39**	3.13
64	25	5	1	21	106	10.25	4.41	18.19	0.60	16.88	143.75	5.63	6.54	**7.91**	2.99
68	21	11	1	15	98	10.89	2.66	14.56	0.07	31.76	173.53	5.29	10.85	**9.46**	3.45
68	23	9	1	17	102	10.89	3.18	16.04	0.31	26.47	162.94	5.29	9.06	**9.09**	3.26
68	23	9	1	19	106	10.89	3.54	16.74	0.01	26.47	162.94	5.29	8.15	**9.27**	3.24
68	25	7	1	21	110	10.89	4.16	18.23	0.31	21.18	152.35	5.29	6.93	**8.83**	3.09
72	23	11	1	17	106	11.53	3.05	16.06	0.10	30.00	170.00	5.00	9.45	**9.92**	3.38
72	25	9	1	19	110	11.53	3.60	17.54	0.35	25.00	160.00	5.00	8.00	**9.53**	3.21
72	25	9	1	21	114	11.53	3.96	18.25	0.05	25.00	160.00	5.00	7.27	**9.72**	3.20
72	27	7	1	23	118	11.53	4.61	19.74	0.38	20.00	150.00	5.00	6.25	**9.25**	3.06
76	25	11	1	19	114	12.17	3.45	17.56	0.13	28.42	166.84	4.74	8.34	**10.38**	3.32
76	27	9	1	21	118	12.17	4.03	19.04	0.40	23.68	157.37	4.74	7.16	**9.97**	3.19
76	27	9	1	23	122	12.17	4.39	19.76	0.11	23.68	157.37	4.74	6.56	**10.15**	3.16
80	27	11	1	19	118	12.81	3.51	18.37	0.47	27.00	164.00	4.50	8.20	**10.66**	3.29
80	27	11	1	21	122	12.81	3.87	19.07	0.17	27.00	164.00	4.50	7.46	**10.83**	3.27
80	29	9	1	23	126	12.81	4.46	20.54	0.46	22.50	155.00	4.50	6.46	**10.41**	3.13
84	27	13	1	19	122	13.45	3.39	18.40	0.27	30.00	170.00	4.29	8.50	**11.49**	3.39
84	29	11	1	21	126	13.45	3.93	19.87	0.51	25.71	161.43	4.29	7.34	**11.10**	3.24
84	29	11	1	23	130	13.45	4.28	20.57	0.21	25.71	161.43	4.29	6.73	**11.28**	3.23
88	27	15	1	19	126	14.09	3.28	18.42	0.08	32.73	175.45	4.09	8.78	**12.30**	3.50
88	29	13	1	21	130	14.09	3.79	19.90	0.30	28.64	167.27	4.09	7.61	**11.94**	3.34
88	31	11	1	23	134	14.09	4.35	21.37	0.56	24.55	159.09	4.09	6.63	**11.54**	3.20
88	31	11	1	25	138	14.09	4.71	22.08	0.26	24.55	159.09	4.09	6.12	**11.72**	3.19

No. of piles per						Geometrical values						Interlock deviation		Design values	
Cell				Arc	System							Cell	Arc	2 Arcs	
	L	M	S	N		$d=2 \cdot r_m$	r_a	x	d_y	α	β	δ_m	δ_a	w_e	R_a
pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	m	m	m	m	°	°	°	°	m	
92	31	13	1	23	138	14.73	4.20	21.40	0.34	27.39	164.78	3.91	6.87	**12.40**	3.29
92	31	13	1	25	142	14.73	4.55	22.09	0.03	27.39	164.78	3.91	6.34	**12.58**	3.28
96	31	15	1	21	138	15.37	3.73	20.74	0.44	30.00	170.00	3.75	7.73	**13.06**	3.40
96	31	15	1	23	142	15.37	4.07	21.42	0.13	30.00	170.00	3.75	7.09	**13.23**	3.38
96	33	13	1	25	146	15.37	4.61	22.90	0.38	26.25	162.50	3.75	6.25	**12.84**	3.25
100	31	17	1	21	142	16.01	3.63	20.76	0.25	32.40	174.80	3.60	7.95	**13.87**	3.49
100	33	15	1	23	146	16.01	4.13	22.23	0.47	28.80	167.60	3.60	6.99	**13.52**	3.35
100	33	15	1	25	150	16.01	4.47	22.92	0.16	28.80	167.60	3.60	6.45	**13.69**	3.34
104	33	17	1	23	150	16.65	4.01	22.26	0.27	31.15	172.31	3.46	7.18	**14.33**	3.43
104	35	15	1	25	154	16.65	4.53	23.73	0.50	27.69	165.38	3.46	6.36	**13.97**	3.31
104	35	15	1	27	158	16.65	4.88	24.42	0.20	27.69	165.38	3.46	5.91	**14.14**	3.30
108	33	19	1	21	150	17.29	3.59	21.62	0.41	33.33	176.67	3.33	8.03	**14.97**	3.54
108	33	19	1	23	154	17.29	3.91	22.27	0.09	33.33	176.67	3.33	7.36	**15.14**	3.52
108	35	17	1	25	158	17.29	4.41	23.76	0.30	30.00	170.00	3.33	6.54	**14.79**	3.39
108	37	15	1	27	162	17.29	4.94	25.23	0.54	26.67	163.33	3.33	5.83	**14.41**	3.27
112	35	19	1	23	158	17.93	3.97	23.11	0.43	32.14	174.29	3.21	7.26	**15.44**	3.48
112	35	19	1	25	162	17.93	4.30	23.77	0.11	32.14	174.29	3.21	6.70	**15.61**	3.47
112	37	17	1	27	166	17.93	4.81	25.25	0.33	28.93	167.86	3.21	6.00	**15.25**	3.35
116	35	21	1	23	162	18.57	3.88	23.13	0.25	34.14	178.28	3.10	7.43	**16.23**	3.57
116	37	19	1	25	166	18.57	4.35	24.60	0.45	31.03	172.07	3.10	6.62	**15.90**	3.43
116	37	19	1	27	170	18.57	4.69	25.27	0.13	31.03	172.07	3.10	6.15	**16.08**	3.42
120	35	23	1	23	166	19.21	3.80	23.14	0.09	36.00	182.00	3.00	7.59	**17.02**	3.65
120	37	21	1	25	170	19.21	4.26	24.62	0.27	33.00	176.00	3.00	6.77	**16.71**	3.51
120	39	19	1	27	174	19.21	4.75	26.09	0.47	30.00	170.00	3.00	6.07	**16.36**	3.39
120	39	19	1	29	178	19.21	5.08	26.77	0.16	30.00	170.00	3.00	5.67	**16.54**	3.38
124	37	23	1	25	174	19.85	4.17	24.63	0.10	34.84	179.68	2.90	6.91	**17.50**	3.59
124	39	21	1	27	178	19.85	4.64	26.12	0.28	31.94	173.87	2.90	6.21	**17.17**	3.47
124	41	19	1	29	182	19.85	5.14	27.59	0.50	29.03	168.06	2.90	5.60	**16.82**	3.35
128	39	23	1	25	178	20.49	4.22	25.48	0.43	33.75	177.50	2.81	6.83	**17.80**	3.55
128	39	23	1	27	182	20.49	4.55	26.13	0.11	33.75	177.50	2.81	6.34	**17.98**	3.54
128	41	21	1	29	186	20.49	5.03	27.61	0.31	30.94	171.88	2.81	5.73	**17.64**	3.42
128	43	19	1	31	190	20.49	5.55	29.09	0.53	28.13	166.25	2.81	5.20	**17.27**	3.32

No. of piles per						Geometrical values						Interlock deviation		Design values	
Cell				Arc	System							Cell	Arc	2 Arcs	
	L	M	S	N		d=2·r_m	r_a	x	d_y	α	β	δ_m	δ_a	w_e	R_a
pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	m	m	m	m	°	°	°	°	m	
132	41	23	1	27	186	21.13	4.60	26.97	0.44	32.73	175.45	2.73	6.27	**18.28**	3.51
132	41	23	1	29	190	21.13	4.93	27.63	0.12	32.73	175.45	2.73	5.85	**18.45**	3.50
132	43	21	1	31	194	21.13	5.42	29.11	0.33	30.00	170.00	2.73	5.31	**18.10**	3.39
136	41	25	1	27	190	21.77	4.51	26.99	0.27	34.41	178.82	2.65	6.39	**19.07**	3.58
136	43	23	1	29	194	21.77	4.98	28.46	0.46	31.76	173.53	2.65	5.79	**18.74**	3.46
136	43	23	1	31	198	21.77	5.31	29.12	0.14	31.76	173.53	2.65	5.42	**18.92**	3.45
136	45	21	1	33	202	21.77	5.82	30.61	0.36	29.12	168.24	2.65	4.95	**18.56**	3.35
140	41	27	1	27	194	22.42	4.43	27.00	0.11	36.00	182.00	2.57	6.50	**19.86**	3.65
140	43	25	1	29	198	22.42	4.89	28.48	0.28	33.43	176.86	2.57	5.90	**19.55**	3.53
140	45	23	1	31	202	22.42	5.37	29.95	0.48	30.86	171.71	2.57	5.37	**19.21**	3.43
140	45	23	1	33	206	22.42	5.71	30.62	0.17	30.86	171.71	2.57	5.05	**19.39**	3.42
144	43	27	1	27	198	23.06	4.48	27.85	0.43	35.00	180.00	2.50	6.43	**20.17**	3.61
144	43	27	1	29	202	23.06	4.80	28.49	0.11	35.00	180.00	2.50	6.00	**20.34**	3.60
144	45	25	1	31	206	23.06	5.27	29.97	0.29	32.50	175.00	2.50	5.47	**20.02**	3.49
144	47	23	1	33	210	23.06	5.76	31.45	0.50	30.00	170.00	2.50	5.00	**19.67**	3.39
148	45	27	1	29	206	23.70	4.85	29.34	0.44	34.05	178.11	2.43	5.94	**20.64**	3.57
148	45	27	1	31	210	23.70	5.18	29.99	0.12	34.05	178.11	2.43	5.57	**20.81**	3.56
148	47	25	1	33	214	23.70	5.66	31.47	0.31	31.62	173.24	2.43	5.10	**20.48**	3.45
148	47	25	1	35	218	23.70	5.99	32.13	0.00	31.62	173.24	2.43	4.81	**20.67**	3.44
152	45	29	1	29	210	24.34	4.77	29.35	0.28	35.53	181.05	2.37	6.04	**21.43**	3.63
152	47	27	1	31	214	24.34	5.23	30.83	0.45	33.16	176.32	2.37	5.51	**21.11**	3.52
152	47	27	1	33	218	24.34	5.56	31.48	0.13	33.16	176.32	2.37	5.19	**21.29**	3.51
152	49	25	1	35	222	24.34	6.05	32.97	0.34	30.79	171.58	2.37	4.77	**20.95**	3.42
156	45	31	1	29	214	24.98	4.70	29.37	0.13	36.92	183.85	2.31	6.13	**22.21**	3.70
156	47	29	1	31	218	24.98	5.14	30.84	0.28	34.62	179.23	2.31	5.60	**21.91**	3.59
156	49	27	1	33	222	24.98	5.61	32.32	0.47	32.31	174.62	2.31	5.14	**21.58**	3.49
156	49	27	1	35	226	24.98	5.94	32.98	0.15	32.31	174.62	2.31	4.85	**21.76**	3.48
160	47	31	1	29	218	25.62	4.75	30.22	0.45	36.00	182.00	2.25	6.07	**22.53**	3.66
160	47	31	1	31	222	25.62	5.07	30.86	0.13	36.00	182.00	2.25	5.69	**22.69**	3.65
160	49	29	1	33	226	25.62	5.52	32.34	0.29	33.75	177.50	2.25	5.22	**22.38**	3.55
160	51	27	1	35	230	25.62	6.00	33.81	0.49	31.50	173.00	2.25	4.81	**22.05**	3.45
160	51	27	1	37	234	25.62	6.33	34.48	0.17	31.50	173.00	2.25	4.55	**22.23**	3.44

No. of piles per						Geometrical values						Interlock deviation		Design values	
Cell				Arc	System							Cell	Arc	2 Arcs	
	L	M	S	N		$d=2 \cdot r_m$	r_a	x	d_y	α	β	δ_m	δ_a	w_e	R_a
pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	m	m	m	m	°	°	°	°	m	
164	49	31	1	33	230	26.26	5.44	32.35	0.13	35.12	180.24	2.20	5.30	**23.17**	3.61
164	51	29	1	35	234	26.26	5.90	33.83	0.31	32.93	175.85	2.20	4.89	**22.86**	3.51
164	53	27	1	37	238	26.26	6.39	35.31	0.51	30.73	171.46	2.20	4.51	**22.51**	3.42
164	53	27	1	39	242	26.26	6.72	35.98	0.20	30.73	171.46	2.20	4.29	**22.69**	3.41
168	49	33	1	31	230	26.90	5.04	31.72	0.29	36.43	182.86	2.14	5.72	**23.79**	3.68
168	51	31	1	33	234	26.90	5.49	33.20	0.46	34.29	178.57	2.14	5.25	**23.48**	3.58
168	51	31	1	35	238	26.90	5.81	33.84	0.14	34.29	178.57	2.14	4.96	**23.66**	3.57
168	53	29	1	37	242	26.90	6.28	35.33	0.32	32.14	174.29	2.14	4.59	**23.32**	3.47
168	53	29	1	39	246	26.90	6.61	35.99	0.01	32.14	174.29	2.14	4.36	**23.51**	3.47
168	55	27	1	41	250	26.90	7.12	37.48	0.23	30.00	170.00	2.14	4.05	**23.15**	3.38
172	51	33	1	33	238	27.54	5.41	33.21	0.29	35.58	181.16	2.09	5.33	**24.27**	3.63
172	53	31	1	35	242	27.54	5.86	34.69	0.47	33.49	176.98	2.09	4.92	**23.95**	3.54
172	53	31	1	37	246	27.54	6.19	35.34	0.15	33.49	176.98	2.09	4.66	**24.13**	3.63
172	55	29	1	39	250	27.54	6.67	36.82	0.35	31.40	172.79	2.09	4.32	**23.79**	3.44
172	55	29	1	41	254	27.54	7.00	37.49	0.03	31.40	172.79	2.09	4.11	**23.98**	3.43
176	51	35	1	33	242	28.18	5.34	33.22	0.14	36.82	183.64	2.05	5.40	**25.05**	3.69
176	53	33	1	35	246	28.18	5.78	34.70	0.30	34.77	179.55	2.05	4.99	**24.75**	3.59
176	55	31	1	37	250	28.18	6.24	36.18	0.48	32.73	175.45	2.05	4.62	**24.42**	3.50
176	55	31	1	39	254	28.18	6.57	36.83	0.16	32.73	175.45	2.05	4.39	**24.60**	3.50
176	57	29	1	41	258	28.18	7.06	38.32	0.37	30.68	171.36	2.05	4.08	**24.26**	3.41
180	53	35	1	35	250	28.82	5.70	34.71	0.14	36.00	182.00	2.00	5.06	**25.53**	3.65
180	55	33	1	37	254	28.82	6.15	36.19	0.31	34.00	178.00	2.00	4.68	**25.23**	3.56
180	57	31	1	39	258	28.82	6.62	37.67	0.50	32.00	174.00	2.00	4.35	**24.89**	3.47
180	57	31	1	41	262	28.82	6.96	38.33	0.18	32.00	174.00	2.00	4.14	**25.07**	3.46
180	59	29	1	43	266	28.82	7.46	39.82	0.40	30.00	170.00	2.00	3.86	**24.72**	3.39
184	55	35	1	35	254	29.46	5.75	35.57	0.46	35.22	180.43	1.96	5.01	**25.84**	3.62
184	55	35	1	37	258	29.46	6.07	36.21	0.14	35.22	180.43	1.96	4.75	**26.01**	3.61
184	57	33	1	39	262	29.46	6.53	37.69	0.32	33.26	176.52	1.96	4.41	**25.69**	3.52
184	57	33	1	41	266	29.46	6.86	38.34	0.00	33.26	176.52	1.96	4.20	**25.88**	3.52
184	59	31	1	43	270	29.46	7.35	39.83	0.20	31.30	172.61	1.96	3.92	**25.54**	3.43
188	57	35	1	37	262	30.10	6.12	37.05	0.47	34.47	178.94	1.91	4.71	**26.32**	3.58
188	57	35	1	39	266	30.10	6.44	37.70	0.15	34.47	178.94	1.91	4.47	**26.49**	3.58
188	59	33	1	41	270	30.10	6.91	39.18	0.34	32.55	175.11	1.91	4.17	**26.17**	3.49
188	59	33	1	43	274	30.10	7.24	39.84	0.02	32.55	175.11	1.91	3.98	**26.35**	3.48
188	61	31	1	45	278	30.10	7.74	41.33	0.23	30.64	171.28	1.91	3.72	**26.00**	3.41

Table 4.2.: Circular cells with θ = 90° junction piles

No. of piles per						Geometrical values						Interlock deviation		Design values	
Cell				Arc	System							Cell	Arc	2 Arcs	
	L	M	S	N		$d=2\cdot r_m$	r_a	x	d_y	α	β	δ_m	δ_a	w_e	R_a
pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	m	m	m	m	°	°	°	°	m	
52	11	13	1	9	70	8.33	2.97	9.97	0.05	48.46	96.92	6.92	9.70	**7.65**	3.63
56	13	13	1	11	78	8.97	3.84	11.77	0.19	45.00	90.00	6.43	7.50	**8.03**	3.42
56	13	13	1	13	82	8.97	4.48	12.68	0.00	45.00	90.00	6.43	6.43	**8.15**	3.33
60	13	15	1	11	82	9.61	3.60	11.78	0.04	48.00	96.00	6.00	8.00	**8.81**	3.59
64	13	17	1	9	82	10.25	2.84	10.90	0.12	50.63	101.25	5.63	10.13	**9.45**	3.88
64	15	15	1	11	86	10.25	3.84	12.68	0.38	45.00	90.00	5.63	7.50	**9.09**	3.49
64	15	15	1	13	90	10.25	4.48	13.58	0.19	45.00	90.00	5.63	6.43	**9.19**	3.41
68	15	17	1	11	90	10.89	3.63	12.70	0.24	47.65	95.29	5.29	7.95	**9.86**	3.64
68	15	17	1	13	94	10.89	4.23	13.59	0.04	47.65	95.29	5.29	6.81	**9.98**	3.56
72	15	19	1	11	94	11.53	3.46	12.71	0.11	50.00	100.00	5.00	8.34	**10.62**	3.80
72	17	17	1	13	98	11.53	4.48	14.49	0.38	45.00	90.00	5.00	6.43	**10.25**	3.47
76	17	19	1	13	102	12.17	4.26	14.51	0.23	47.37	94.74	4.74	6.77	**11.03**	3.61
76	17	19	1	15	106	12.17	4.87	15.40	0.04	47.37	94.74	4.74	5,92	**11.14**	3.53
80	17	21	1	13	106	12.81	4.07	14.51	0.11	49.50	99.00	4.50	7.07	**11.79**	3.74
80	19	19	1	15	110	12.81	5.12	16.30	0.38	45.00	90.00	4.50	5.63	**11.41**	3.46
84	17	23	1	13	110	13.45	3.92	14.52	-0.01	51.43	102.86	4.29	7.35	**12.54**	3.88
84	19	21	1	15	114	13.45	4.89	16.32	0.23	47.14	94.29	4.29	5.90	**12.19**	3.58
88	19	23	1	15	118	14.09	4.69	16.32	0.10	49.09	98.18	4.09	6.14	**12.96**	3.70
88	21	21	1	17	122	14.09	5.76	18.11	0.38	45.00	90.00	4.09	5.00	**12.57**	3.44
92	19	25	1	15	122	14.73	4.53	16.32	-0.02	50.87	101.74	3.91	6.36	**13.71**	3.82
92	21	23	1	17	126	14.73	5.52	18.13	0.23	46.96	93.91	3.91	5.22	**13.36**	3.55
96	21	25	1	15	126	15.37	4.73	17.24	0.30	48.75	97.50	3.75	6.10	**14.01**	3.73
96	21	25	1	17	130	15.37	5.32	18.13	0.10	48.75	97.50	3.75	5.42	**14.13**	3.66
100	21	27	1	17	134	16.01	5.14	18.13	-0.03	50.40	100.80	3.60	5.60	**14.88**	3.77
100	23	25	1	19	138	16.01	6.16	19.94	0.23	46.80	93.60	3.60	4.68	**14.52**	3.53
104	23	27	1	17	138	16.65	5.35	19.05	0.29	48.46	96.92	3.46	5.39	**15.18**	3.70
104	23	27	1	19	142	16.65	5.95	19.94	0.09	48.46	96.92	3.46	4.85	**15.29**	3.63
108	23	29	1	19	146	17.29	5.76	19.94	-0.04	50.00	100.00	3.33	5.00	**16.05**	3.73
108	25	27	1	21	150	17.29	6.79	21.75	0.23	46.67	93.33	3.33	4.24	**15.68**	3.52

No. of piles per						Geometrical values						Interlock deviation		Design values	
Cell				Arc	System							Cell	Arc	2 Arcs	
	L	M	S	N		d=2•r_m	r_a	x	d_y	α	β	δ_m	δ_a	w_e	R_a
pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	m	m	m	m	°	°	°	°	m	
112	25	29	1	19	150	17.93	5.98	20.86	0.29	48.21	96.43	3.21	4.82	16.34	3.66
112	25	29	1	21	154	17.93	6.57	21.75	0.09	48.21	96.43	3.21	4.38	16.46	3.61
116	25	31	1	19	154	18.57	5.80	20.87	0.16	49.66	99.31	3.10	4.97	17.10	3.76
116	25	31	1	21	158	18.57	6.38	21.75	-0.04	49.66	99.31	3.10	4.52	17.22	3.70
116	27	29	1	23	162	18.57	7.43	23.56	0.22	46.55	93.10	3.10	3.88	16.85	3.50
120	25	33	1	19	158	19.21	5.65	20.87	0.05	51.00	102.00	3.00	5.10	17.85	3.86
120	27	31	1	21	162	19.21	6.60	22.67	0.28	48.00	96.00	3.00	4.36	17.51	3.64
120	27	31	1	23	166	19.21	7.20	23.56	0.08	48.00	96.00	3.00	4.00	17.62	3.59
124	27	33	1	21	166	19.85	6.42	22.68	0.16	49.35	98.71	2.90	4.49	18.27	3.73
124	27	33	1	23	170	19.85	7.01	23.56	-0.05	49.35	98.71	2.90	4.11	18.39	3.67
128	27	35	1	21	170	20.49	6.26	22.68	0.04	50.63	101.25	2.81	4.60	19.02	3.81
128	29	33	1	23	174	20.49	7.23	24.48	0.28	47.81	95.62	2.81	3.99	18.67	3.62
132	29	35	1	21	174	21.13	6.46	23.60	0.35	49.09	98.18	2.73	4.46	19.32	3.75
132	29	35	1	23	178	21.13	7.04	24.49	0.15	49.09	98.18	2.73	4.09	19.44	3.70
136	29	37	1	23	182	21.77	6.87	24.49	0.03	50.29	100.59	2.65	4.19	20.19	3.78
136	31	35	1	25	186	21.77	7.86	26.29	0.28	47.65	95.29	2.65	3.67	19.84	3.60
140	29	39	1	21	182	22.42	6.16	23.61	0.12	51.43	102.86	2.57	4.68	20.82	3.92
140	31	37	1	23	186	22.42	7.08	25.41	0.35	48.86	97.71	2.57	4.07	20.49	3.72
140	31	37	1	25	190	22.42	7.67	26.30	0.15	48.86	97.71	2.57	3.76	20.60	3.67
144	31	39	1	23	190	23.06	6.92	25.41	0.23	50.00	100.00	2.50	4.17	21.24	3.80
144	31	39	1	25	194	23.06	7.49	26.30	0.02	50.00	100.00	2.50	3.85	21.36	3.75
144	33	37	1	27	198	23.06	8.49	28.10	0.27	47.50	95.00	2.50	3.39	21.00	3.58
148	31	41	1	23	194	23.70	6.77	25.42	0.11	51.08	102.16	2.43	4.26	21.99	3.88
148	33	39	1	25	198	23.70	7.70	27.22	0.34	48.65	97.30	2.43	3.74	21.66	3.70
148	33	39	1	27	202	23.70	8.29	28.10	0.14	48.65	97.30	2.43	3.48	21.77	3.65
148	35	37	1	29	206	23.70	9.35	29.90	0.41	46.22	92.43	2.43	3.08	21.39	3.50
152	31	43	1	23	198	24.34	6.64	25.42	0.01	52.11	104.21	2.37	4.34	22.73	3.96
152	33	41	1	25	202	24.34	7.53	27.22	0.22	49.74	99.47	2.37	3.83	22.41	3.77
152	33	41	1	27	206	24.34	8.11	28.11	0.01	49.74	99.47	2.37	3.55	22.53	3.72
152	35	39	1	29	210	24.34	9.12	29.91	0.27	47.37	94.74	2.37	3.17	22.17	3.57
156	33	43	1	25	206	24.98	7.38	27.23	0.10	50.77	101.54	2.31	3.91	23.16	3.84
156	35	41	1	27	210	24.98	8.32	29.02	0.34	48.46	96.92	2.31	3.45	22.82	3.67
156	35	41	1	29	214	24.98	8.92	29.91	0.14	48.46	96.92	2.31	3.23	22.94	3.63

4.3.2. Diaphragm cells with Y 120° junction piles

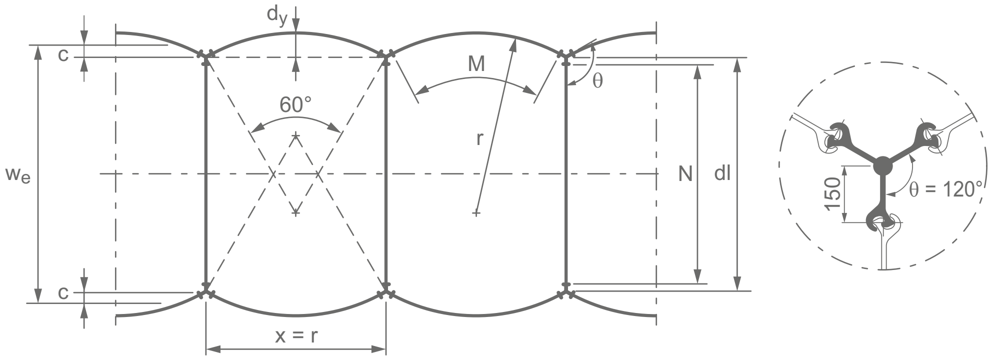


Fig. 4.4.: Geometrical values for diaphragm cells.

The most important parameters for **diaphragm cells** are (see Fig. 4.4.):

- the radius (r);
- the angle between the arc and the diaphragm (θ);
- the Equivalent Width (w_e);
- the arc height (d_y);
- the system length (x);
- the equivalent arc height (c);
- the diaphragm wall length (dl).

The following relationships apply:

- the greater the angle (θ) between arc and diaphragm, the smaller the arc radius;
- the system length (x) of the diaphragm cells follows from the number of sections in the arc and the corresponding radius;
- the total width of the cell follows from the appropriate arc height (d_y) and the number of sections in the diaphragm;
- the optimum material usage is with an angle $\theta = 120°$. In this particular case, the system length (x) of the diaphragm cell is equal to the radius (r); the tensile forces in the arc and diaphragm are balanced.

Tables 4.3. a) and 4.3. b): Diaphragm cells with Y 120° junction piles

Geometry diaphragm wall	
Number of piles	Wall length
N	dl
pcs.	m
11	5.83
13	6.84
15	7.85
17	8.85
19	9.86
21	10.86
23	11.87
25	12.88
27	13.88
29	14.89
31	15.89
33	16.90
35	17.91
37	18.91
39	19.92
41	20.92
43	21.93
45	22.94
47	23.94
49	24.95
51	25.95
53	26.96
55	27.97
57	28.97
59	29.98

Table 4.3. a) Geometrical values.

Geometry arc (Standard Solution)				
Number of piles	Radius System length	Arc height	Equivalent arc height	Interlock deviation
M	x = r	d_y	c	δ_a
pcs.	m	m	m	°
11	5.57	0.75	0.51	5.17
13	6.53	0.87	0.59	4.41
15	7.49	1.00	0.68	3.85
17	8.45	1.13	0.77	3.41
19	9.41	1.26	0.86	3.06
21	10.37	1.39	0.94	2.78
23	11.33	1.52	1.03	2.54
25	12.29	1.65	1.12	2.34
27	13.26	1.78	1.20	2.17
29	14.22	1.90	1.29	2.03
31	15.18	2.03	1.38	1.90
33	16.14	2.16	1.46	1.79
35	17.10	2.29	1.55	1.69
37	18.06	2.42	1.64	1.60
39	19.02	2.55	1.73	1.52
41	19.98	2.68	1.81	1.44
43	20.94	2.81	1.90	1.38

Table 4.3. b) Geometrical values for arc of diaphragm cells.

Both tables should be used separately following the required number of piles for the arc and the diaphragm wall.

Note: Total width = diaphragm length (dl) + 2 d_y

Project: Damietta, Egypt
Sections: AS 500 - 12.0
Quantity: 6 430 tonnes

5. Layout considerations

The two most common layouts for cellular structures are circular cells and diaphragm cells.

5.1. Circular cell structures

The cofferdam is made up of a series of relatively closely-spaced circular cells linked by connecting arcs. Each cell is self-supporting once it is filled. It is therefore independent of adjacent cells, which makes it easy to build this type of cofferdam in water.

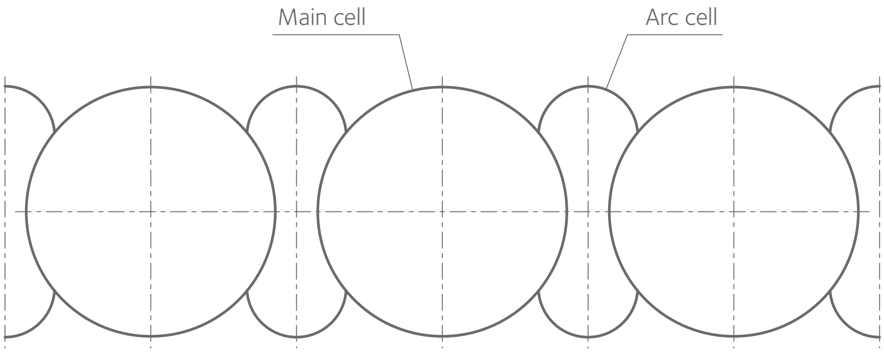


Fig. 5.1.: Components of circular cells.

Some applications where circular cell structures may be used are: deep quay wall structures, deep maritime locks, harbour front structures, breakwaters, temporary cofferdams and dry docks.

Circular cells in the construction of cofferdams offer several advantages:

- circular cells may be filled immediately after they have been built, regardless of the relative height of fill in adjacent cells;
- filled cells can be used as the working platform for the installation of the new cells.

The diameter of the cell is limited by the characteristic interlock resistance.

The junction piles are a key element which require special attention.

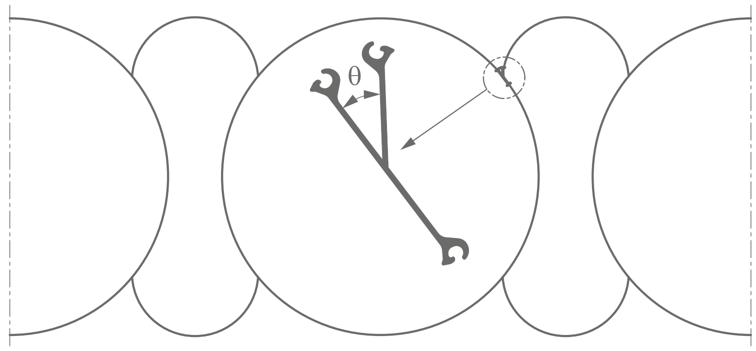


Fig. 5.2.: Detail of junction piles.

A 90° junction makes it easy to have a cofferdam whose main circular cells and arc cells have the same radius (with $d_y = 0$), giving a more regular face. However, forces are balanced in the junction pile only if it undergoes significant deformation. For this reason 90° junction piles are only used in the case of low tensile forces, i.e. for small radii. Please contact our technical department for further information.

If high tensile forces have to be transmitted, angles between 30° and 45° are recommended. This configuration transmits less stress to the main cell than the 90° junction pile and, by forming a longer connecting arc, provides more flexibility during the installation process.

It is easy to change the direction of a cofferdam alignment by simply changing the position of the junction piles on the circular cells (Fig. 5.3.).

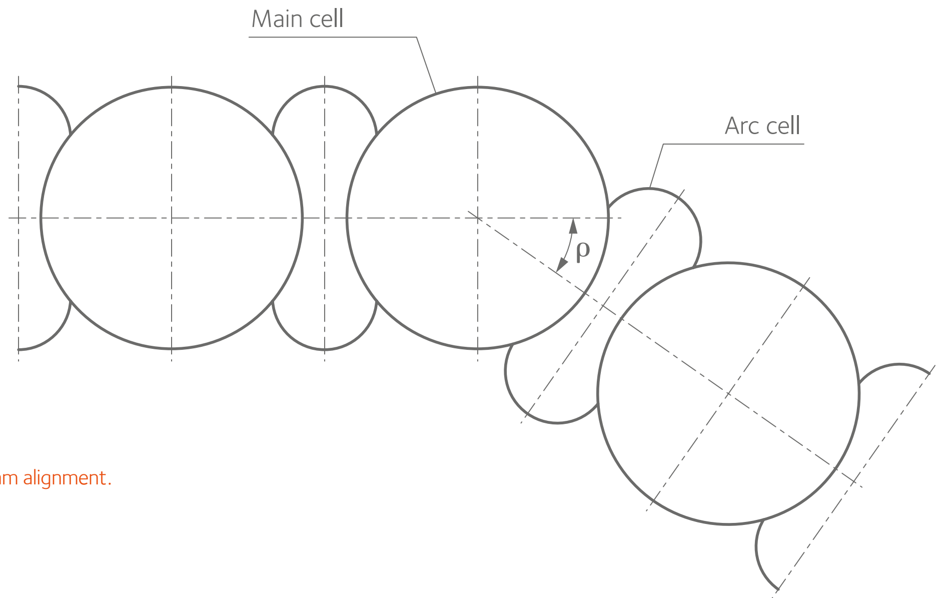


Fig. 5.3.: Changing cofferdam alignment.

5.2. Diaphragm cell structures

Diaphragm cell structures consist of a series of two circular arcs normally joined by 120° junction piles and straight transverse sheet-pile diaphragms.

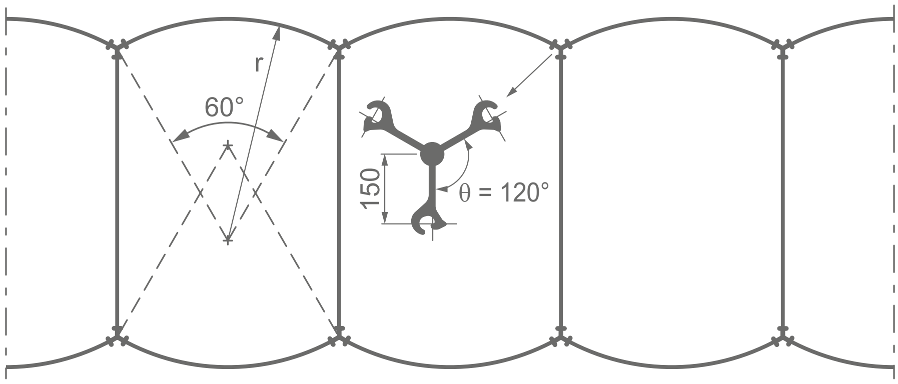


Fig. 5.4.: Diaphragm cells.

With this layout the cells are not self-supporting during the construction phase, which makes it difficult to build such a cofferdam in water, without building an embankment beforehand.

However, the diaphragm cell layout does have two major advantages :

- since the length of the common wall within the straight diaphragm does not impact the tensile force in the sheet piles, its length is not limited. This solution is therefore an alternative to circular cells when the maximum diameter allowed by the interlock resistance is exceeded;
- tensile forces in the 120° Y-type junction piles are balanced.

The ends of a diaphragm-cell structure must consist of a circular closure cell, or a clover-leaf type closure cell, if the cofferdam is very wide.

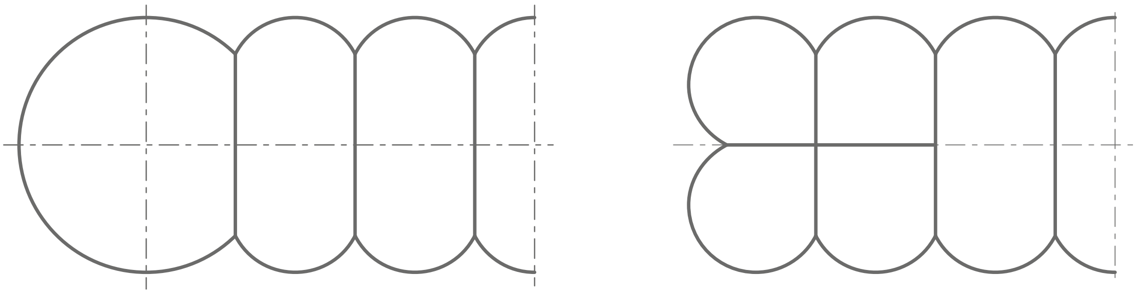


Fig. 5.5.: Closures of diaphragm cell structures.

5.3. Additional layouts

Circular cells without rear arcs

This layout makes savings by dispensing with the rear arcs and junction piles. This must be taken into account when calculating the equivalent width (see § 4.).

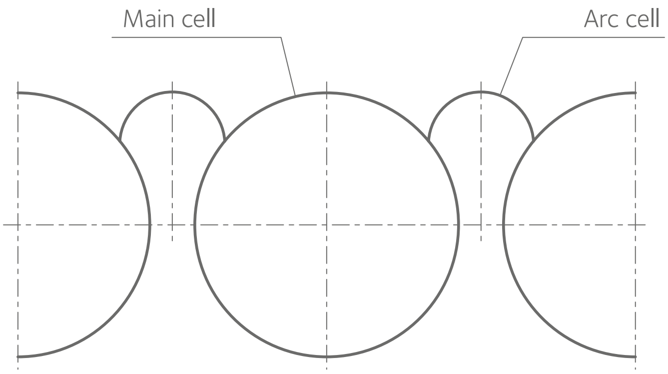


Fig. 5.6.: Circular cells without rear arcs.

Cloverleaf-type cells

The cloverleaf-type cell is normally used where the height and mass required for stability prohibit the use of circular cells. The cloverleaf-type cell will require more piling than the standard cell, but like the circular cell, it has the advantage of being a self-supporting unit.

Because of its stability, the half-cloverleaf cell is often used for end cells, corner cells and tie-ins for diaphragm-cell structures.

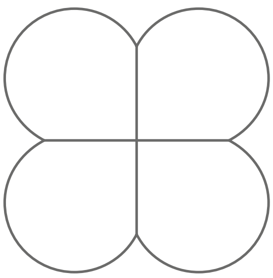


Fig. 5.7.: Cloverleaf-type cell.

Single circular cells

Single circular cells are used in the construction of piers or dolphins, and can be used as foundations for offshore windmills, as they are self-supporting units. For the introduction of the weight of the superstructure, please refer to section 6.2.2.

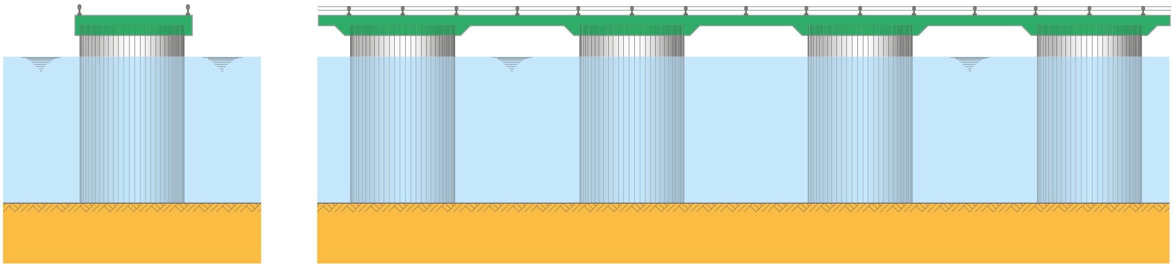


Fig. 5.8.: Single circular cells in the construction of piers.

5.4. Optimization

Optimization may be achieved through staggering of steel sheet pile length.

In certain situations, like a sloped bedrock, staggered steel sheet piles can be utilised.

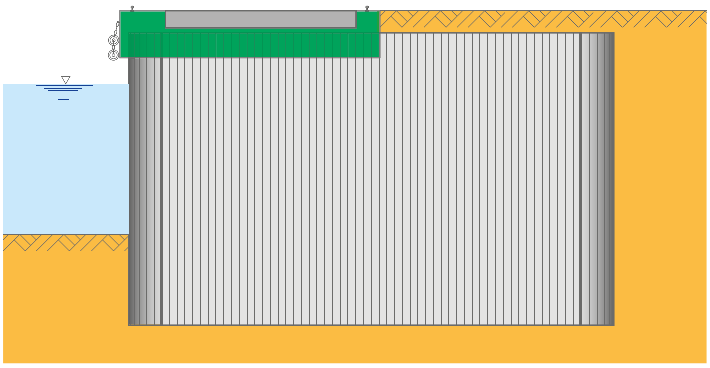


Fig. 5.9.a: Normal layout of straight web steel sheet piles.

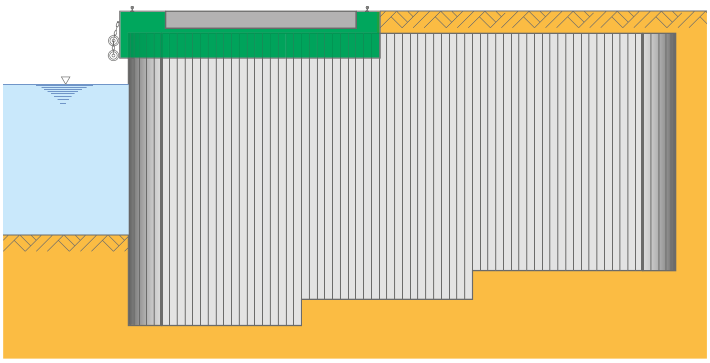
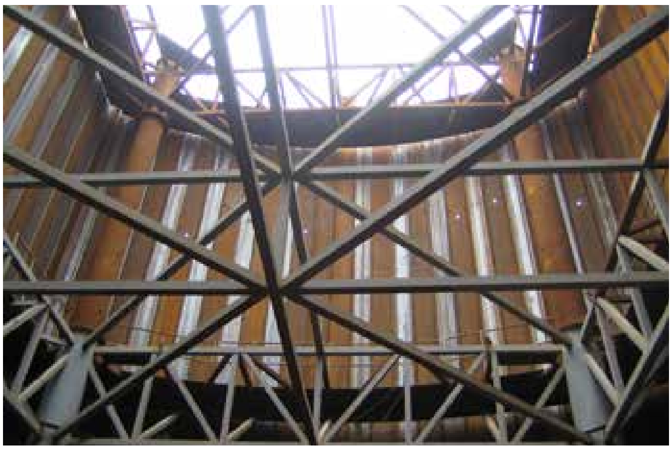


Fig. 5.9.b: Staggered layout of straight web steel sheet piles.



Project: Mussafah, Abu Dhabi
Sections: AS 500 - 12.7
Quantity: 2 320 tonnes

6. Design

6.1. Functional characteristics and stability analysis

The more or less horizontal forces induced by the pressure of water and earth are counteracted by self-weight and the lateral passive earth pressure mobilized by the cofferdam.

Within the individual cells, lateral earth pressure and, if present, water pressure develop on the air or water side of the sheet pile wall as a result of soil self-weight and any relevant surcharges. These pressures are taken up by the straight-web sheet piles, arranged in circles, and are transmitted to the individual cells as horizontal tensile forces (circumferential tensile force). In the case of diaphragm cells, when calculating the tensile forces in the diaphragm wall, the tensile forces exerted by the arc are integrated vectorially.

The design of a cellular cofferdam requires consideration of the following failure modes at the design stage:

Overall stability

a) Sliding as a rigid body, if there is little or no penetration of the sheet piles

b) Tilting due to shear failure in the fill/foundation soil

c) Bearing capacity failure

d) Overall stability

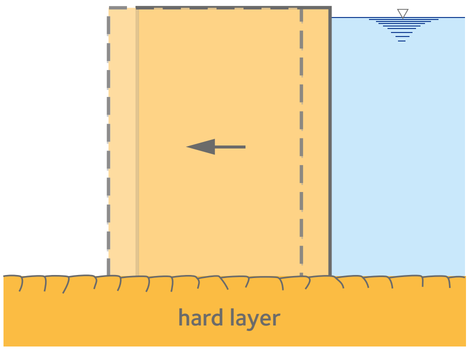


Fig. 6.1.: Failure mode a) on rock or bearing soil.

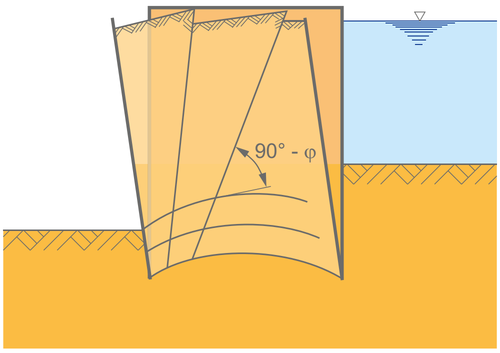


Fig. 6.2.: Failure mode b) on bearing soil.

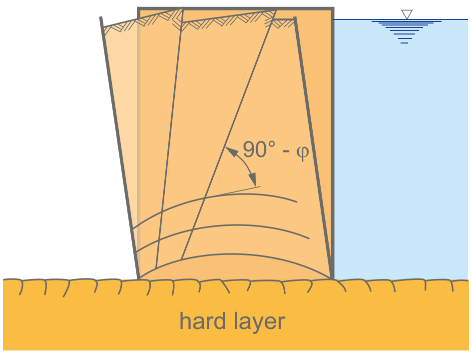


Fig. 6.3.: Failure mode b) on rock.

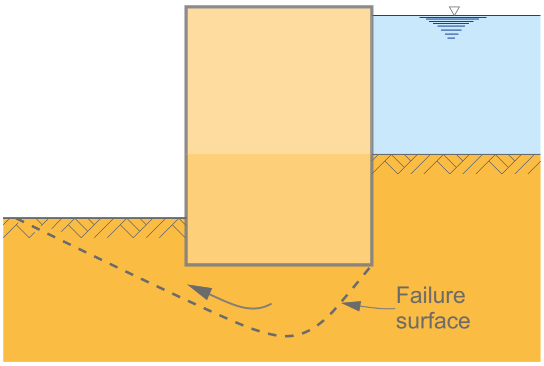


Fig. 6.4.: Failure mode c) on bearing soil.

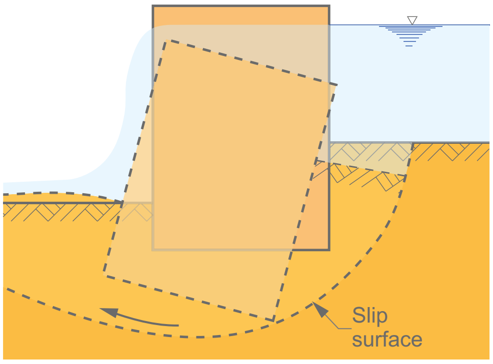


Fig. 6.5.: Failure mode d), on bearing soil.

Structural failure of the steel sheet piles under tensile stress

e) Failure by bursting of interlocks

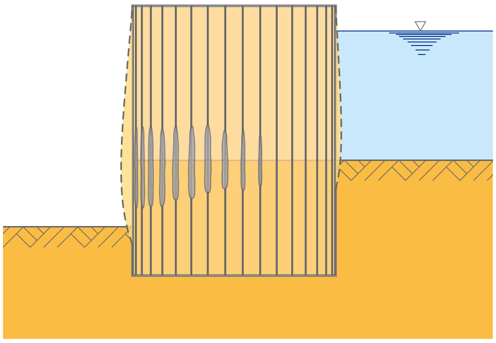


Fig. 6.6.: Failure mode e).

Failure mode a), **sliding as a rigid body**, does generally not govern design (Fig. 6.1.).

When the shear strength of the soil in the cofferdam is exceeded, as in failure mode b), **tilting due to shear failure in the fill/ foundation soil**, two different families of failure surfaces can develop within the cell, depending on embedment depth, and the structures can tilt as shown in Figs. 6.2./6.3. The failure lines can be represented as concentric sections of logarithmic spirals intercepted by a family of straight lines that intersect in the locus of the spiral [Jelinek].

Where the cofferdam is only shallowly embedded in a soil with low bearing capacity, failure mode c) can be the governing mode and thus determine the design of the cofferdam (see Fig. 6.4.). Analysis can be performed with classical **bearing capacity failure** methods, e.g. in accordance with EN 1997.

Analysis of **overall stability** d) is based on well-known procedures (Bishop, Krey, Terzaghi, etc.) (Fig. 6.5.).

As a rule of thumb, the equivalent width of a cofferdam varies between 0.9 and 1.1 times the head of water pressure.

6.1.1. Overall stability

6.1.1.1. Tilting due to shear failure in the fill / foundation soil (Figs. 6.2. and 6.3.)

The term «equivalent width» is used in relation to cofferdams designed as a series of circular or diaphragm cells. The equivalent width corresponds to the footprint of the cellular cofferdam converted to a rectangle of equal area and equal system width, as shown in Figs. 4.1. and 4.2.

Verification must take account of this equivalent width. This involves representing the cells as two parallel walls, one on the air side and one on the land side, separated by the equivalent width.

The failure surfaces can be envisaged as **arcs of logarithmic spirals intercepting the toes of both walls.**

At failure, a convex failure surface develops between the toes of the cofferdam walls. The failure surface can be assumed to be a logarithmic spiral with the corresponding internal friction angle.

A logarithmic spiral is defined as (Fig. 6.7.):

$$r = r_o \cdot e^{\theta \cdot \tan \varphi}$$

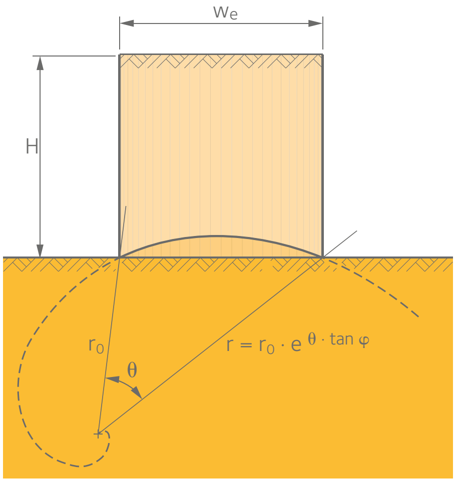


Fig. 6.7.: Failure surface: logarithmic spiral.

The advantage to use a logarithmic spiral is that the force resulting from the friction along the failure surface passes through its pole, and therefore it does not add any resisting or driving moment around the pole.

In order to verify stability, it is necessary to differentiate the types of strata the cofferdam is founded in:

a) The cofferdam rests directly on bedrock (Fig. 6.8.)

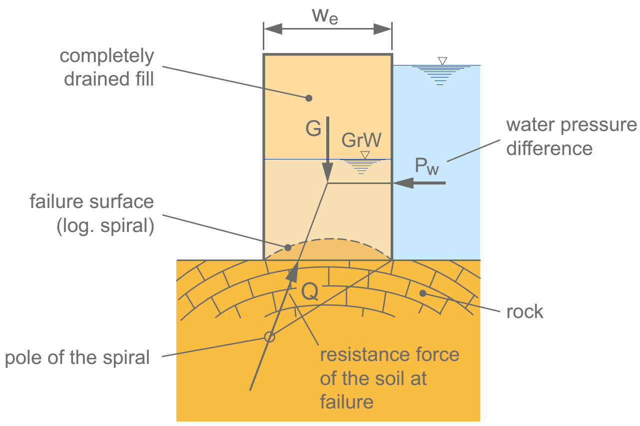


Fig. 6.8.: Cofferdam resting on rock.

b) The cofferdam rests on bedrock overlain by further strata, or is shallowly embedded in load-bearing soil (Figs. 6.9. and 6.10.)

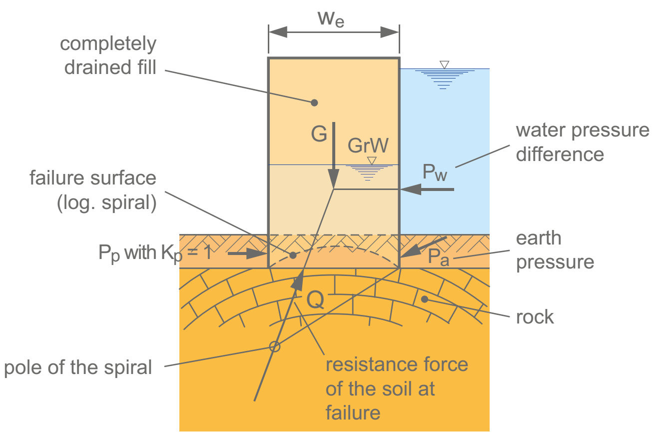


Fig. 6.9.: Cofferdam resting on rock overlain with other soil strata.

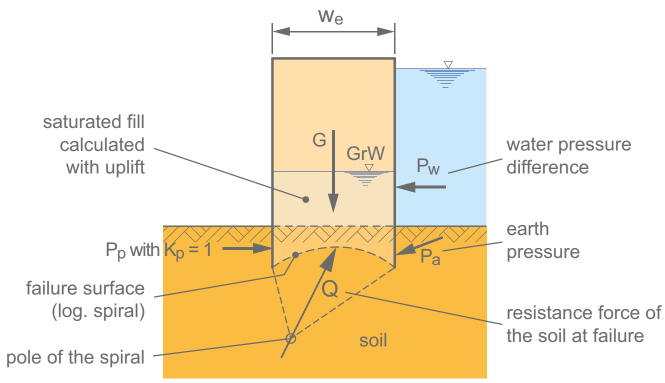


Fig. 6.10.: Cofferdam embedded a shallow depth into load-bearing soil.

In this case, the active earth pressure and laterally compensating passive earth pressure are to be considered, as well as the forces acting on the load side. Considering the low deformation values, the passive earth pressure should be assumed to be low, generally with $K_p = 1$ and, for deeper embedment into the load bearing soil, with K_p for $\delta_p = 0°$.

c) The cofferdam is embedded deeply into the load bearing soil (Fig. 6.11.)

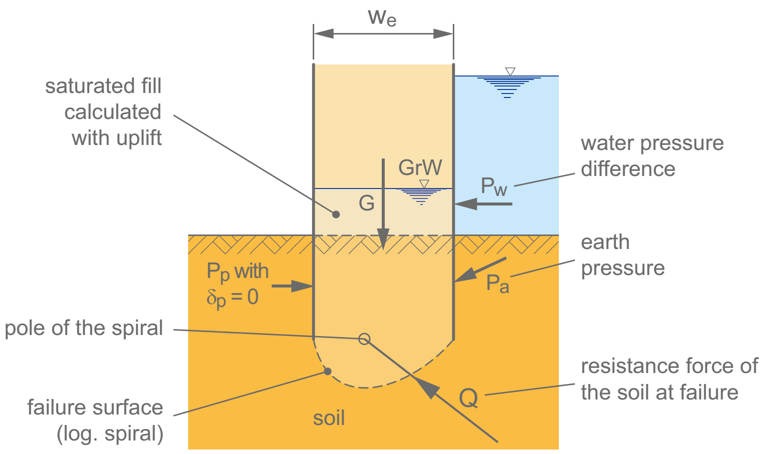


Fig. 6.11.: Additional investigation in case of deep embedment.

One means of increasing the stability of the cofferdam is to embed the sheet piles more deeply. In this case, verifications should also be run with a concave failure surface.

General considerations

This stability analysis verifies both tilting and sliding safety. Cofferdam stability can also be increased by **widening the structure** and by **selecting more suitable fill material.** Where possible, up to a certain level, greater embedment depth may increase stability.

The verification is carried out with the ratio of moments about the appropriate pole of the spiral. This procedure can be used for analysis both with a global safety factor and with partial safety factors and must satisfy the following conditions:

$M_r \geq M_s \cdot S_F$ for analysis with a global safety factor and

$M_{R,d} \geq M_{E,d}$ for analysis with partial safety factors.

If modelling is performed using partial safety factors, suitable decremental or incremental factors are to be applied to the resisting and driving forces and moments given below. The values of these safety factors are to be taken from the appropriate regulations.

The resisting moments (**M_r or $M_{R,d}$**) include the moments resulting from:

- self-weight of the cell (fill material), respectively friction and cohesion resistance along the failure surface;
- passive earth pressure in front of the cell;
- permanent surcharge loads on the cell;
- resisting single loads and pressures;
- resistance of anchors or piles that intersect the sliding surface.

The driving moments (**M_S or $M_{E,d}$**) include the moments resulting from:

- active earth pressure behind the cell;
- excess water pressure, resulting from differential head;
- variable surcharge loads, single loads or pressures, behind the cofferdam;
- bollard loads.

As there are several spirals intercepting the toes of the front and rear walls, analysis is an iterative process carried out until the pole is found where the ratio

$$\frac{M_{R,d}}{M_{E,d}}$$

reaches a minimum. When a global safety factor is used, the iteration process is continued until the minimum safety factor S_F is obtained.

6.1.1.2. Bearing capacity failure and deep-seated sliding (Figs. 6.4. and 6.5.)

Analysis of d) (Fig 6.5.), deep-seated sliding should be performed with circular or polygonal failure or slip lines. In most cases, the critical failure line will pass through the toe of the front or rear cell wall, depending on the geometry of the structure.

For shallowly embedded cells on soil other than bedrock, bearing capacity analysis c) (Fig 6.4.) must also be performed.

For structures founded on bedrock, both of these analyses are generally unnecessary.

6.1.1.3. Piping due to heave

Depending on the embedment depth (generally for shallow embedment), the soil conditions (sandy soil) and the magnitude of the water pressure difference, it can be necessary to perform an analysis on **piping due to heave** following EN 1997.

6.1.2. Verification of resistance to structural failure (Fig. 6.6.)

The following design approach is based on the partial safety factor method as given in the Eurocodes, but other methods may be acceptable.

6.1.2.1. Resistance of straight web steel sheet piles

The tensile resistance $F_{ts,Rd}$ of straight web steel sheet piles (other than junction piles) shall be taken as the lesser of the interlock resistance and the resistance of the web, using:

$$F_{ts,Rd} = \beta_R \cdot R_{k,s} / \gamma_{M0} \quad \text{but} \quad F_{ts,Rd} \leq t_w \cdot f_y / \gamma_{M0} \qquad [6.1.]$$

Where:

f_y : yield strength

$R_{k,s}$: characteristic interlock resistance

t_w : web thickness

β_R : reduction factor for interlock resistance, taken as 0.8

γ_{M0} : partial safety factor, taken as 1.0

The characteristic resistance of the interlock $R_{k,s}$ depends upon the cross-section of the interlock and the steel grade adopted. The characteristic interlock resistance $R_{k,s}$ is determined by testing according to Annex D of prEN 10248-1 (2007).

Note: β_R and γ_{M0} may be specified in National Annexes of Eurocodes or local standards.

6.1.2.2. Verification of piles used in single cells

The verification of the piles used in single cells should be done in the governing horizontal plane of the structure. From field observations, it appears that the plane of maximum expansion is located between 1/3 H and 1/4 H for cells built on rock (Fig. 6.12.). It can be assumed that the maximum piling tension also occurs in this plane (barrelling effect). In a safe-sided approach, the horizontal plane located at H/4 is therefore used for verification of cells built on rock.

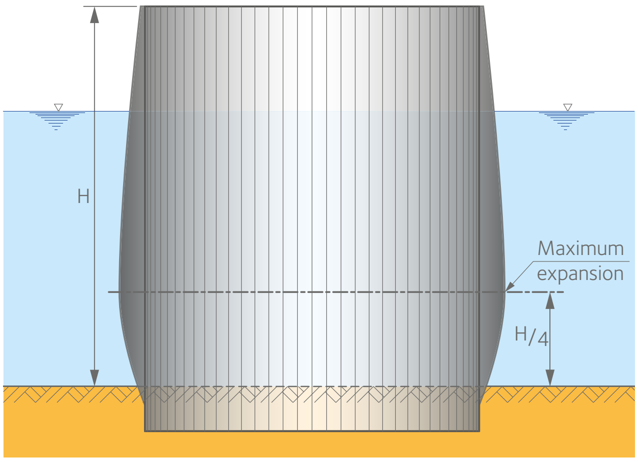


Fig. 6.12.: Plane of maximum piling tension for cells built on rock.

If the cell structure is not built on rock, a safe-sided approach uses the tension at the excavation/dredge level.

Plain straight web piles should be verified using:

$$F_{t,Ed} \leq F_{ts,Rd} \qquad [6.2.]$$

Where:

$F_{ts,Rd}$: design tensile resistance according to expression [6.1.]

$F_{t,Ed}$: the design value of the circumferential tensile force determined with

$$F_{t,Ed} = p_{m,Ed} \cdot r_m \qquad [6.3.]$$

where:

$p_{m,Ed}$: design value of the internal pressure acting in the main cell at the governing horizontal plane due to water pressure and due to the at-rest pressure of the fill (Fig. 6.13.)

r_m : the radius of the main cell (Fig. 6.13.)

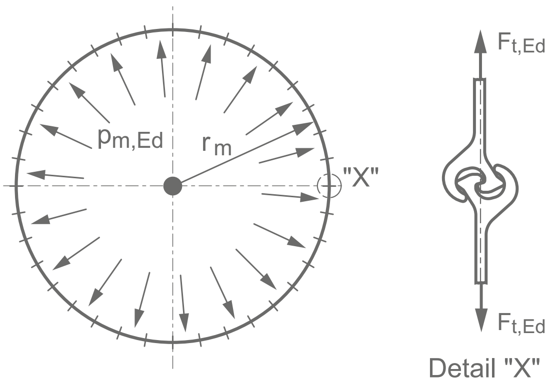
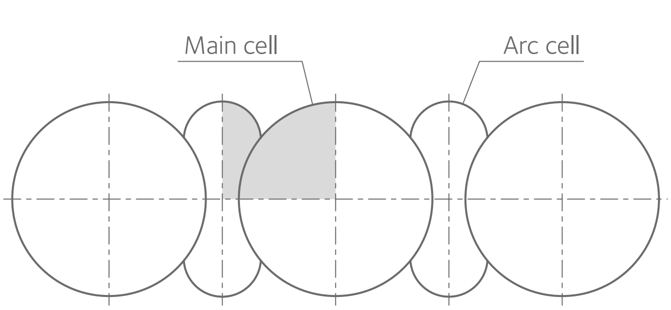


Fig. 6.13.: Circumferential tensile force.

6.1.2.3. Verification of piles used in cellular cofferdams

The verification of piles used in circular cells should be done in the governing horizontal plane as explained in section 6.1.2.2.



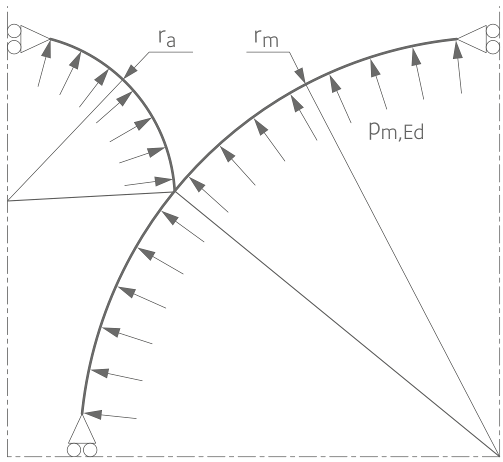


Fig. 6.14.: Geometry and definitions for circular cells.

Verification of the arc cell and main cell

For the verification of the arc cell and main cell, straight web piles should be verified using expression [6.2.] which requires:

$$F_{t,Ed} \leq F_{ts,Rd}$$

Verification of welded junction piles

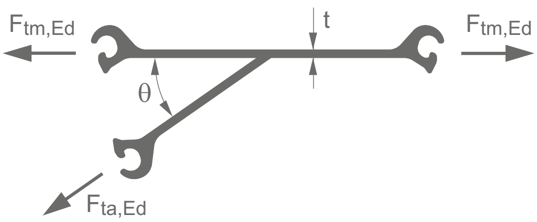


Fig. 6.15.: Typical junction piles for circular cells.

The following design concept regarding verification of welded junction piles is based on the results of a numerical model calibrated by extensive laboratory tests on welded junction piles (bi-axial tensile strength tests) forming part of an international research project.

The numerical model takes account of the filling procedure of the cells, the behaviour of the fill and the non-linear behaviour of the junction pile itself. The cofferdam is assumed to be loaded by the self-weight of the fill only.

Provided that the following criteria are fulfilled:

- welding is carried out according to the procedure given in section B.6. of EN 12063:1999 (see Fig. B.5.);
- the steel sheet pile material is in accordance with EN 10248, the welded junction pile can be verified using:

$$F_{tm,Ed} \leq \beta_T \cdot F_{ts,Rd} \qquad [6.5.]$$

where:

$F_{ts,Rd}$: design tensile resistance of the pile according to expression [6.1.]

$F_{tm,Ed}$: design tensile force in the main cell given by

$$F_{tm,Ed} = p_{m,Ed} \cdot r_m \qquad [6.6.]$$

where:

$p_{m,Ed}$: design value of the internal pressure acting in the main cell at the governing horizontal plane due to water pressure and due to the at-rest pressure of the fill (Fig. 6.13.)

r_m : radius of the main cell (Fig. 6.14.)

β_T : reduction factor taking into account the behaviour of the welded junction pile at ultimate limit states, and which should be taken as follows:

$$\beta_T = 0.9 \cdot \left(1.3 - 0.8 \cdot \frac{r_a}{r_m}\right) \cdot (1 - 0.3 \cdot \tan\varphi_k) \qquad [6.7.]$$

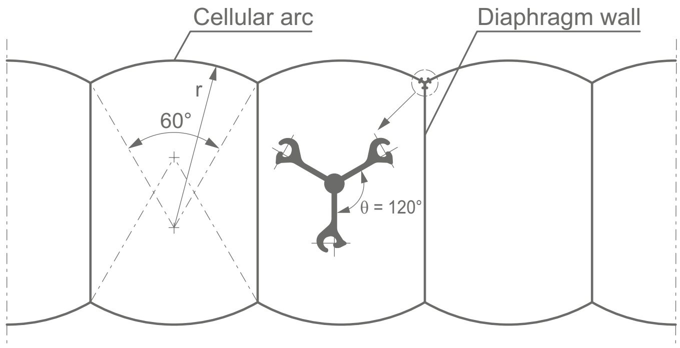
in which r_a and r_m are the radii of the connecting arc and of the main cell according to Fig. 6.14. and φ_k is the characteristic value of the internal friction angle of the fill material.

Notes :

[1] Factor β_T takes account of the rotation capacity (ductility) of the junction pile as well as the rotation demand (up to 20°) according to the model described above.

[2] Although developed for cellular structures with aligned arcs (Fig. 6.14.) expression [6.7.] yields acceptable results for alternative configurations.

6.1.2.4. Verification of piles used in diaphragm cells



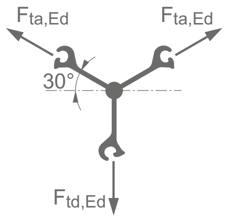


Fig. 6.16.: Diaphragm cells.

The verification of piles used in cellular cofferdams should be done in the governing horizontal plane as explained in section 6.1.2.2.

Verification of the piles in the arc

The verification of the piles located in the arc may be carried out using an expression similar to [6.2.]:

$$F_{ta,Ed} \leq F_{ts,Rd} \qquad [6.2'.]$$

where:

$F_{ts,Rd}$: tensile resistance according to expression [6.1.]

$F_{ta,Ed}$: design value of the hoop tension determined according to an expression similar to [6.3.]:

$$F_{ta,Ed} = p_{m,Ed} \cdot r \qquad [6.3'.]$$

Verification of the piles in the diaphragm wall

No verification of the piles used in the diaphragm wall is required due to the fact that the tension forces acting in the diaphragm wall have the same magnitude as the forces acting in the arc wall:

$$F_{td,Ed} = 2 \cdot \sin 30° \cdot F_{ta,Ed}$$
$$= F_{ta,Ed}$$

Verification of the welded Y-pile

If the Y-pile is fabricated in accordance with section B.6. of EN 12063:1999 (Fig. B.5.), it requires no further verification.

6.2. Design criteria

One important criterion is the required equivalent width (w_e), as this influences the entire geometry of the proposed cofferdam. The larger the equivalent width (w_e), the larger the corresponding radii and stresses in the circular-cell sections will become. For diaphragm cells, the length (dl) of the diaphragms increases in proportion to the equivalent width (w_e). The necessary equivalent width (w_e) is influenced on the one hand by the friction angle of the in-situ soil and fill, and on the other hand by external loads such as earth pressure and excess water pressure. The larger the friction angle and the smaller the loads, the smaller the required equivalent width (w_e). It is obvious from the above that cellular cofferdams are not well suitable for cohesive and soft soils such as highly plastic clays or mud, for instance.

6.2.1. Soil conditions

Cellular cofferdams should be erected on ground of sufficient bearing capacity. Where cohesive soil is present, an attempt should be made to replace this with granular material, or at least to improve it by the appropriate means and thus increase the friction angle and initiate consolidation. Coarse material should be used for the fill. The stability of the cofferdam also depends on the buoyant (effective) unit weight and the internal friction angle φ_k of the fill material. **A material of high unit weight and high friction angle should therefore be used for the fill.**

6.2.2. Horizontal and vertical loads

Straight web sheet piles can only resist horizontal loads and are in principle not foreseen to transmit vertical loads. Decks and superstructures can be founded directly on the fill material, crane rails shall be founded on separate bearing piles. Appropriate detailing provisions should be made to keep the straight web sections free of vertical loads (Fig. 6.17.).

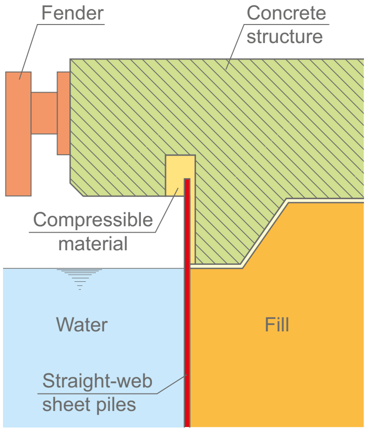


Fig. 6.17.: Detailing for transfer of vertical loads.

Hydrostatic pressure and earth pressure within the cells have an influence on the stresses in the sheet piles. To keep stresses as low as possible, when water pressures are high, it is recommended that suitable measures be taken to reduce the water pressures as much as possible. If embankments are necessary, only granular material with a high friction angle should be used.

Cell structures are considered to be rigid and to allow little displacement, at least in the toe area. For this reason, the mobilized passive earth pressures on the outside of cells with only shallow socketing into the foundation should be calculated with $K_{ph} = 1$ only, or with a wall / soil friction angle of $\delta_p = 0°$ for deeper embedment.

6.2.3. Earthquake effects

Additional horizontal forces develop during earthquakes. Active earth pressure on the structure increases and the passive earth pressure decreases due to horizontal mass acceleration. The water level behind and within the cell rises, and the water level in front of the cell sinks.

When dealing with cohesive soils, analysis of additional forces should include confined pore water in the determination of the masses at play.

It is assumed that the soil / water response behaviour for granular soils is uncoupled. As long as the soils do not display a tendency to liquefy, design values for the friction angle and cohesion need not be reduced further.

For more information on the design in seismic regions, please contact our technical department.

6.2.4. Durability

Like all steel structures, unprotected cell structures are subject to corrosion.

Corrosion phenomena depend on the location of the structure and on the surrounding medium. Material loss resulting from atmospheric corrosion is negligible. Structures in fresh water are less susceptible to corrosion than those in sea water.

Moreover, the distribution of material loss across the affected surfaces is variable: for example, the highest corrosion rates on cells in water are to be expected in the low water and splash zones, whereas losses are substantially lower in the area of permanent immersion.

The highest corrosion rates are fortunately in areas where the stresses in the sections are relatively small. The effects of corrosion are to be considered in the analysis of permanent structures.

Corrosion rates can be taken from the literature or the appropriate standards.

Unless otherwise specified, the reduction in thickness for parts of sheet pile walls in contact with soil (with or without groundwater), or in contact with river or sea water can be taken from Tables 6.1. and 6.2. (table 4.1. and 4.2. from EN 1993-5(2007)) which vary with the required design working life.

Table 6.1.: Loss of thickness [mm] due to corrosion for piles and sheet piles in soils, with or without groundwater

Required design working life	5 years	25 years	50 years	75 years	100 years
Undisturbed natural soils (sand, silt, clay, schist, ...)	0.00	0.30	0.60	0.90	1.20
Polluted natural soils and industrial sites	0.15	0.75	1.50	2.25	3.00
Aggressive natural soils (swamp, marsh, peat, ...)	0.20	1.00	1.75	2.50	3.25
Non-compacted and non-aggressive fills (clay, schist, sand, silt, ...)	0.18	0.70	1.20	1.70	2.20
Non-compacted and aggressive fills (ashes, slag, ...)	0.50	2.00	3.25	4.50	5.75

Notes:
[1)] *Corrosion rates in compacted fills are lower than those in non-compacted ones. In compacted fills the figures in the tables should be divided by two.*
[2)] *The values given for 5 and 25 years are based on measurements, whereas the other values are extrapolated.*

Table 6.2.: Loss of thickness [mm] due to corrosion for piles and sheet piles in fresh water or in sea water

Required design working life	5 years	25 years	50 years	75 years	100 years
Common fresh water (river, ship canal, ...) in the zone of high attack (water line)	0.15	0.55	0.90	1.15	1.40
Very polluted fresh water (sewage, industrial effluent, ...) in the zone of high attack (water line)	0.30	1.30	2.30	3.30	4.30
Sea water in temperate climate in the zone of high attack (low water and splash zones)	0.55	1.90	3.75	5.60	7.50
Sea water in temperate climate in the zone of permanent immersion or in the intertidal zone	0.25	0.90	1.75	2.60	3.50

Notes:
[1] The highest corrosion rate is usually found in the splash zone or at the low water level in tidal waters. However, in most cases, the highest stresses are in the permanent immersion zone (Fig.6.18.).
[2] The values given for 5 and 25 years are based on measurements, whereas the other values are extrapolated.

If required, the influence of corrosion on the tensile resistance $F_{ts,Rd}$ of straight web sheet piles can be determined by applying the reduction factor β_{cor} to the governing equation [6.1.].

$$F_{ts,Rd,cor} = \beta_{cor} \cdot \beta_r \cdot \frac{R_{k,s}}{\gamma_{M0}} \qquad [6.8.]$$

where:

$$\beta_{cor} = 1 - \frac{\Delta t}{t_w} \qquad [6.9.]$$

t_w : web thickness

Δt : reduction in thickness due to corrosion

Note: Formula 6.9. has been established based on tests which have been evaluated statistically based on a numerical method in accordance with ANNEX D of EN 1990.

The verification of the tensile resistance in the governing horizontal plane should take into account the variation of both the tensile forces due to fill and the corrosion rates over the height of the cell (Fig. 6.12. and 6.18.).

In order to maximize the design working life of the structure several solutions may be analysed: coating the sections in the low water zone, and, if necessary, cathodic protection of the permanently submerged zone may be considered. This can be done by means of sacrificial anodes or impressed current.

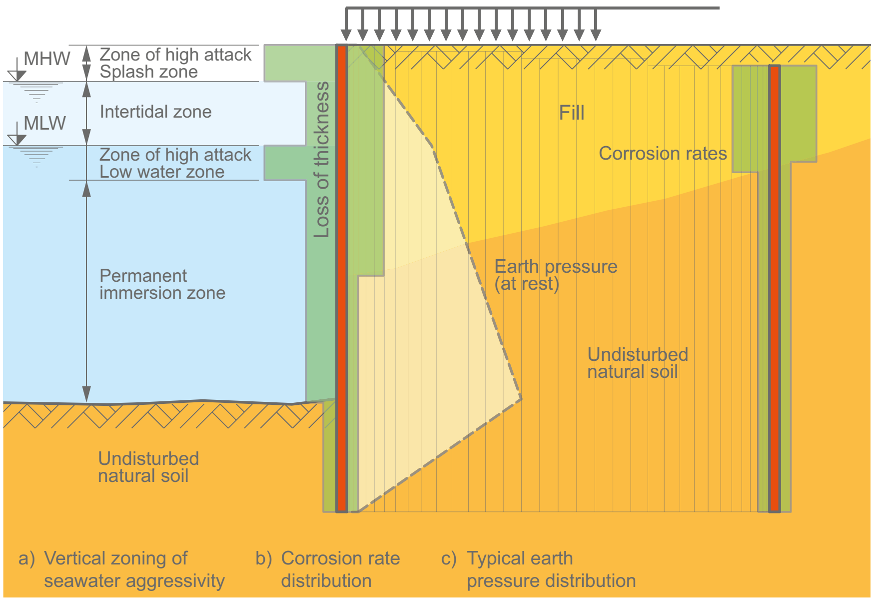
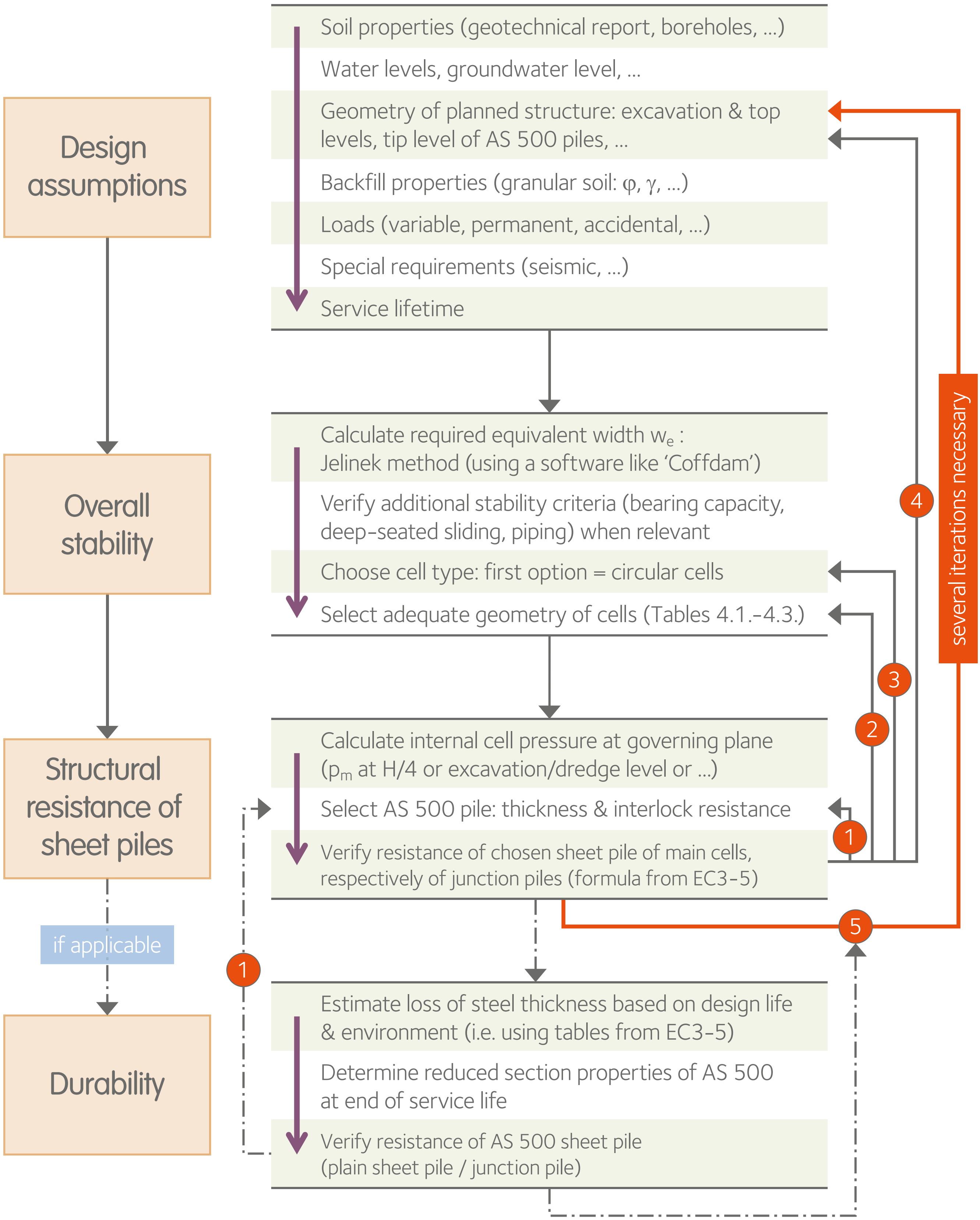


Fig. 6.18.: Typical corrosion rate distribution in marine environment.
MHW = Mean High Water
MLW = Mean Low Water

Design Flowchart



1 Optimize AS 500 sheet pile section: if safety factor is too low, choose a larger section & vice versa

If highest interlock resistance available for AS 500 is insufficient ⇒ 2) or 3) or 4)

2 Change cell geometry: reduce diameter of arcs / main cell, etc

3 Change cell type: circular ⇒ diaphragm

4 Change assumptions (i.e. tip of steel sheet piles, structure geometry, loads, etc)

5 Optimization of cell structure = iterative process: vary parameters to determine the most cost-effective solution

6.3. Examples of applications: partial safety factors approach

Following examples are based on the design according to EAU 2004 [8], working with the partial safety factors recommended by the committee of the EAU. The verification of the steel sheet pile is based on EN 1993 – Part 5, version 2007 [2]. Please note that the verification of the resistance of the pile in EN 1993-5 (2007) and EAU 2004 are different.

Besides, for the design of the cells, it is important to consider local regulations and applicable standards.

In Europe, partial safety factors are recommended in the Eurocodes, but some may be changed by the different countries in their NAD (National Application Document). Furthermore, the overall stability of the cells may have to be verified by different formulas than the ones in the EAU 2004. It is the designer's responsibility to select the correct design method.

In other countries, the method and values described in following examples may have to be adapted to take into account local design regulations, for instance when designing based on 'global safety'.

The design method considered in the EAU utilizes following equation for the overall stability (EAU 2004: 8.3.1.3.):

$$M_{Ed} = M_{kG} \cdot \gamma_G + M_w \cdot \gamma_G + M_{kQ} \cdot \gamma_Q \leq \frac{M^R_{kG}}{\gamma_{Gl}} \qquad [6.10.]$$

However, the formula should be adapted to take into account the earth resistance in front of the cells when the embedment of the sheet piles is not negligible. ArcelorMittal proposes following revised equation:

$$M_{Ed} \leq M_{Rd} \qquad [6.10\text{-a.}]$$

$$M_{Ed} = M_{kG} \cdot \gamma_G + M_w \cdot \gamma_G + M_{kQ} \cdot \gamma_Q$$

$$\leq \frac{M^R_{kG}}{\gamma_{Gl}} + \frac{M^R_{Ep}}{\gamma_{Ep}} + \frac{M^R_c}{\gamma_c} = M_{Rd} \qquad [6.10\text{-b.}]$$

where:

M_{Ed} : design value of the moment effect

M_{Rd} : design value of the moment resistance

M_{kG} : characteristic value of single moment due to active earth pressure forces

M_w : characteristic value of single moment due to water pressure forces

M_{kQ} : characteristic value of single moment due to external variable forces

M^R_{kG} : characteristic value of single moment due to the force of cofferdam fill

M^R_{Ep} : characteristic value of single moment due to passive earth pressure forces

M^R_c : characteristic value of single moment due to cohesion on the failure surface

and: γ_G = 1.35 (under some circumstances, could be reduced to $\gamma_{G,red}$ = 1.20 for the water)

γ_Q = 1.50

γ_{Gl} = 1.10

γ_{Ep} = 1.40

γ_c = 1.25

Above partial safety factors are taken from load case "LS 1B – LC 1" (EAU 2004).

Furthermore, as mentioned in previous chapters, chosen factors for use with EN 1993-5 are:

β_R = 0.8

γ_{M0} = 1.0

Note: It is important to first determine the resultant of an action in order to verify whether the force generates a driving or a resisting moment.

6.3.1. Example 1: permanent circular cells

A quay wall is to be erected in water at a spot with shallow bedrock. Fill will be placed behind the quay wall. The bedrock is overlain by an approximately 4 m thick layer of medium-dense sand and a 2 m to 3 m thick tidal mud deposit. Design life of the structure is 50 years.

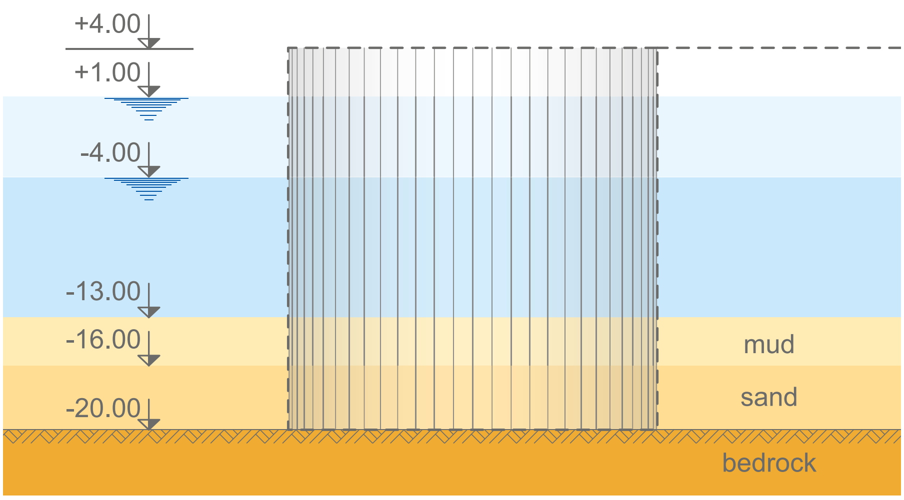


Fig. 6.19.: Initial conditions.

6.3.1.1. Assumptions

Before erection the tidal mud deposit is dredged from the cofferdam footprint and from the area behind it.

Characteristic soil properties:

	γ / γ' kN/m³	φ_k °	δ_k °	c'_k kPa
in-situ sand layer	18 / 10	35.0	± 12	0
sand fill	18 / 10	32.5	0	0

Because of the shallow embedment depth, the passive earth pressure is calculated with $K_p = 1.0$.

Water levels: HWL = +1.00 m
LWL = −4.00 m

Water levels for overall stability & for interlock resistance verification:

- water in front of wall: -4.00 m
- water behind wall: -1.50 m
  [= (HWL + LWL)/2. Simplified assumption]

Dredge level:

- nominal depth: -17.00 m
- design depth = nominal depth – dredging tolerance
  = -17.00 - 0.80
  = -17.80 m

with: assumed dredging tolerance = 0.80 m
(differs from EAU 2004, chap. 6.7.3.)

Variable vertical loads: $P_1 = P_2 = 40$ kN/m².

Note: Variable load P_1 is required for analysis of the internal cell pressure, but it has to be neglected for the stability analysis because of its stabilizing effect.

The line pull (from bollard) is assumed to have a horizontal component of 40 kN/m and a vertical, upwards component of 20 kN/m. The vertical component acts as a resistance, but does not have any significant influence on the overall stability analysis, and therefore is neglected.

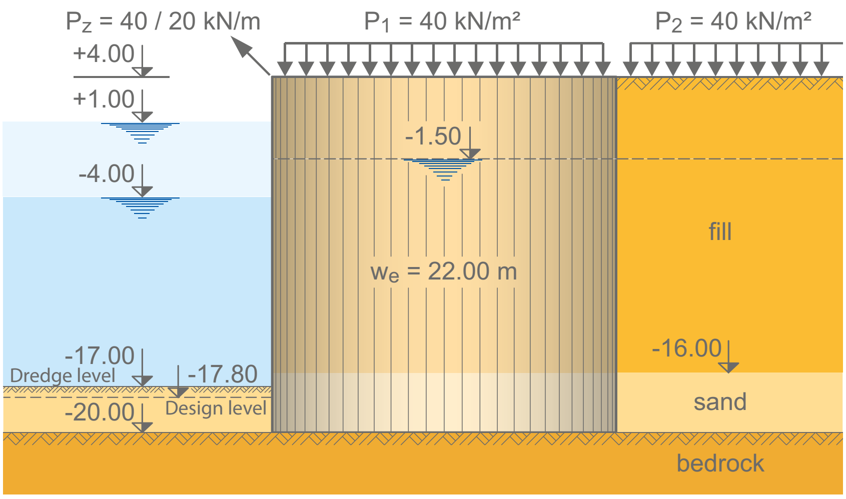


Fig. 6.20.: Final conditions.

6.3.1.2. Overall stability

a) Calculation of required equivalent width, verification of resistance to tilting due to shear failure in the fill/foundation soil

Analysis is performed with computer software based on the assumptions given above. For an equivalent width **w_e = 22.0 m,** following moments can be determined:

M_{kG} = 15,977 kNm/m

M_w = 6,960 kNm/m

M_{kQ} = 6,495 kNm/m

M^R_{kG} = 50,457 kNm/m

M^R_{Ep} = 180 kNm/m

Using formula from EAU 2004 with the suggested change [6.10-b.] and the partial safety factors:

$$M_{Ed} = 15{,}977 \cdot 1.35 + 6{,}960 \cdot 1.35 + 6{,}495 \cdot 1.50 = 40{,}707 \text{ kNm/m}$$

$$M_{Rd} = 50{,}457 / 1.10 + 180 / 1.40 = 45{,}999 \text{ kNm/m}$$

$$M_{Ed} = 40{,}707 < M_{Rd} = 45{,}999 \Rightarrow \text{OK}$$

Note: If the embedment of the flat sheet piles is small, M^R_{Ep} does not have a significant influence on the result and might be neglected.

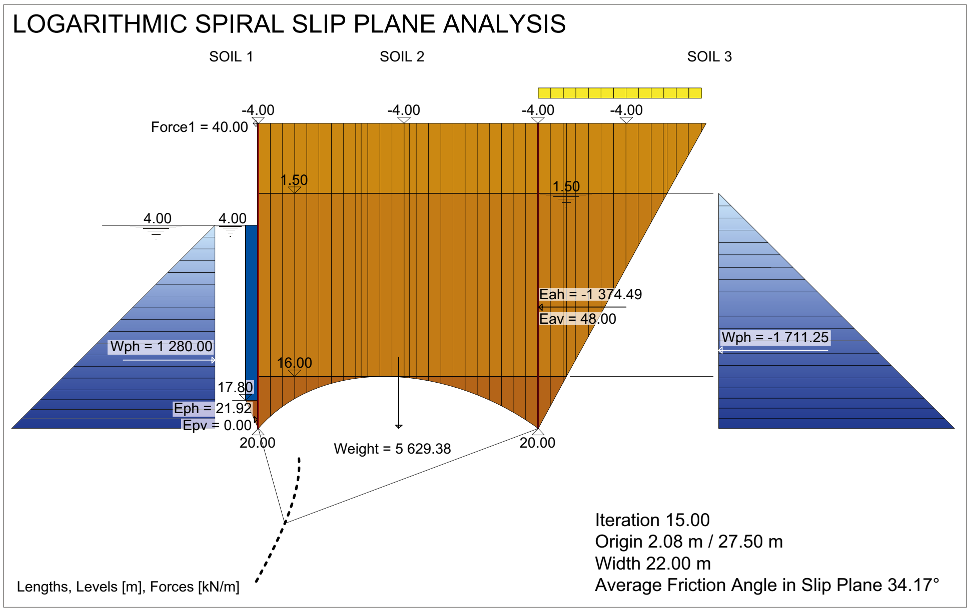


Fig. 6.21.: Computer calculation of required equivalent width w_e, verification of resistance to tilting due to shear failure in the fill/foundation soil. Software: 'Coffdam 4.0.' [10].

As the cell structure is founded on bedrock, bearing capacity and deep-seated sliding analyses are not required.

b) Determination of cell geometry

The angle of the junction piles is chosen as $\theta = 35.0°$.
From Table 4.1., following geometry can be selected for an equivalent width $\mathbf{w_e = 22.53}$ **m.**

No. of piles per						Geometrical values						Interlock deviation		Design values	
Cell				Arc	System							Cell	Arc	2 Arcs	
	L	M	S	N		$d=2 \cdot r_m$	r_a	x	d_y	α	β	δ_m	δ_a	w_e	R_a
pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	m	m	m	m	°	°	°	°	m	
160	47	31	1	29	218	25.62	4.75	30.22	0.45	36.00	182.00	2.25	6.07	**22.53**	3.66

- cell diameter $d = 25.62$ m
- radius of the main cell $r_m = 12.81$ m
- radius of connecting arc $r_a = 4.75$ m
- system length $x = 30.22$ m
- offset $d_y = 0.45$ m
- angle $\alpha = 36.00$ °
- angle deviation in arc $\delta_a = 6.07$ °

Nb. of ssp for 1 system 218
Nb. of ssp for cell 160 = $2 \cdot (L+M) + 4 \cdot S$ (including 4 junction piles)
Nb. of ssp for 2 arcs 58 = $2 \cdot N$

6.3.1.3. Verification against structural failure

a) Calculation of governing internal cell pressure

As the cell is founded directly on bedrock, the governing internal pressure can be assumed to be that exerted one-quarter of the height of the cell above the bedrock surface, i.e. at **elevation -14.00 m.**

However, under certain circumstances, it might be advisable to consider a deeper elevation, and in some cases the dredge elevation is used.

Vertical stresses at -14.00 m:

- weight of soil $\sigma_{v1} = 5.5 \cdot 18.0 + 12.5 \cdot 10.0 = 224.0 \text{ kN/m}^2$
- variable loads $\sigma_{v2} = 40.0 \text{ kN/m}^2$
- design value $\sigma_v = \gamma_G \cdot \sigma_{v1} + \gamma_Q \cdot \sigma_{v2} = 1.35 \cdot 224.0 + 1.50 \cdot 40.0 = 362.4 \text{ kN/m}^2$

Coefficient of earth pressure at-rest:

$$K_o = 1 - \sin \varphi_k = 1 - \sin 32.5° = 0.4627$$

Horizontal earth pressure:

$$\sigma_h = K_O \cdot \sigma_v = 0.4627 \cdot 362.4 = 167.7 \text{ kN/m}^2$$

Hydrostatic pressure:

- characteristic value $p_{w1} = 2.5 \cdot 10 = 25.0 \text{ kN/m}^2$
- design value $p_w = \gamma_G \cdot p_{w1} = 1.35 \cdot 25.0 = 33.8 \text{ kN/m}^2$

Total horizontal stress:

$$\sigma_{h,tot} = \sigma_h + p_w = 167.7 + 33.8$$

$$\mathbf{= 201.5 \text{ kN/m}^2 = p_{m,Ed}}$$

b) Analysis of resistance of straight web sheet piles

AS 500-12.5 straight web sheet piles are selected with:

- $R_{k,s}$ = 5,500 kN/m
- t_w = 12.5 mm
- f_y = 355 N/mm²

$$F_{t,Ed} \leq F_{ts,Rd} \quad [6.2.]$$

Interlock resistance:

$$F_{ts,Rd} = \beta_R \cdot R_{k,s} / \gamma_{M0} = 0.8 \cdot 5{,}500 / 1.0 = 4{,}400 \text{ kN/m} \quad [6.1.]$$

Resistance of web:

$$F_{ts,Rd} = t_w \cdot f_y / \gamma_{M0} = 12.5 \cdot 355 / 1.0 = 4{,}438 \text{ kN/m} \quad [6.1.]$$

Determining resistance: $F_{ts,Rd} = 4{,}400$ kN/m

Junction pile:

r_m = cell radius = 12.81 m

r_a = connecting arc radius = 4.75 m

$$\beta_T = 0.9 \cdot (1.3 - 0.8 \cdot \frac{r_a}{r_m}) \cdot (1 - 0.3 \cdot \tan \varphi_k)$$

$$\beta_T = 0.9 \cdot (1.3 - 0.8 \cdot 4.75/12.81) \cdot (1 - 0.3 \cdot \tan(32.5°)) = 0.7304$$

$$F_{tm,Ed} = p_{m,Ed} \cdot r_m = 201.5 \cdot 12.81 = 2{,}581 \text{ kN/m}$$

$$< \beta_T \cdot F_{ts,Rd} = 0.730 \cdot 4{,}400 = 3{,}212 \text{ kN/m} \Rightarrow \text{OK} \quad [6.5.]$$

6.3.1.4. Durability

Loss of thickness due to corrosion of steel is based on tables 4.1. and 4.2. from EN 1993-5. The design life assumed for this structure is **50 years** without any additional protection (sacrificial steel thickness exclusively). Verification of the sheet pile is done in the area where the interlock tension is highest, which is in the permanent immersion zone.

Assuming that the backfill is not aggressive and that it will be compacted, the loss of steel thickness can be estimated as follows:

- front: permanent immersion zone 1.75 mm
- back: non aggressive and compacted fill 0.60 mm

Total loss of steel thickness:

$$\Delta t = 1.75 + 0.60 = 2.35 \text{ mm}$$

Reduced interlock resistance due to corrosion of the AS 500-12.5:

$$\beta_{cor} = \frac{t_w - \Delta t}{t_w}$$

$$\beta_{cor} = (12.50 - 2.35) / 12.50 = 0.812$$

$$F_{ts,Rd,cor} = \beta_{cor} \cdot F_{ts,Rd} = 0.812 \cdot 4{,}400 \quad [6.8.]$$

$$F_{ts,Rd,cor} = 3{,}573 \text{ kN/m}$$

Verification of the junction pile:

$$F_{tm,Ed} = 2{,}581 \text{ kN/m}$$

$$< \beta_T \cdot F_{ts,Rd,cor} = 0.730 \cdot 3{,}573 = 2{,}608 \text{ kN/m} \Rightarrow \text{OK}$$

6.3.2. Example 2: diaphragm cell structure

The excavation for a dry-dock is to be supported by means of a cofferdam. The soil consists of loose to medium-dense sands to approx. -15.00 m. Below this layer follows medium-dense to dense sands. The NGL (natural ground level) is at El. +2.00 m. Design life of the structure is 50 years.

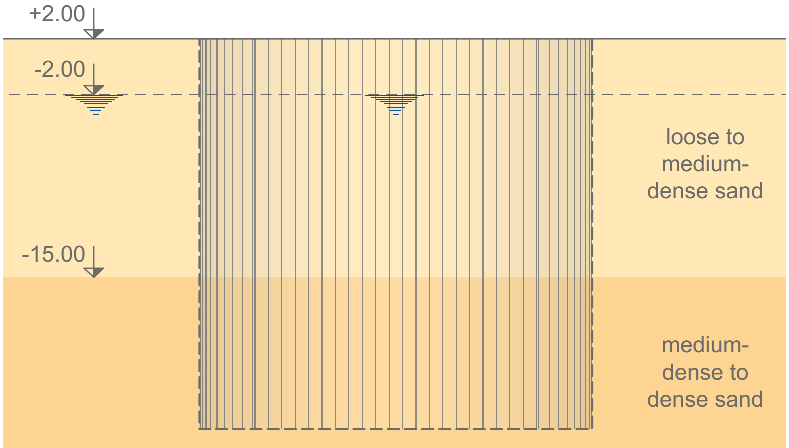


Fig. 6.22.: Initial conditions.

6.3.2.1. Assumptions

Characteristic soil properties:

	γ / γ' kN/m³	φ_k °	δ_k °	c'_k kPa
upper sand layer	18 / 10	30.0	0	0
lower sand layer	19 / 11	35.0	0	0

Because of the relative large embedment depth, the passive earth pressure is calculated with K_p ($\delta_p = 0°$).

Water levels: groundwater at -2.00 m

Excavation level:
- nominal depth: -17.00 m
- design depth = nominal depth - excavation tolerance
  = -17.00 - 0.50
  = -17.50 m

with: excavation tolerance = 0.50 m (EN 1997 [3].
Local standards might impose different values)

Variable vertical loads: $P_1 = P_2 = 20$ kN/m².

Note: Variable load P_1 is required for analysis of the internal cell pressure, but it has to be neglected for the stability analysis because of its stabilizing effect.

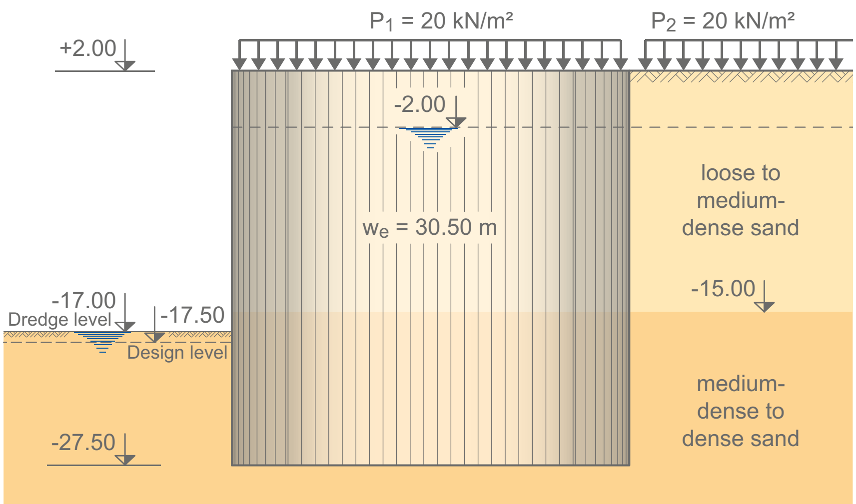


Fig. 6.23.: Final conditions.

6.3.2.2. Overall stability

a) Calculation of required equivalent width, verification of resistance to tilting due to shear failure in the fill/foundation soil

Analysis is performed with computer software using the assumptions given above. For an **equivalent width w_e = 30.5 m,** following moments can be determined:

M_{kG} = 36,542 kNm/m
M_w = 60,360 kNm/m
$M_{k,Q}$ = 5,179 kNm/m
M^R_{kG} = 125,070 kNm/m
M^R_{Ep} = 37,015 kNm/m

Using formula from EAU 2004 with the suggested change [6.10.-b] and the partial safety factors:

$$M_{Ed} = 36{,}542 \cdot 1.35 + 60{,}360 \cdot 1.35 + 5{,}179 \cdot 1.50 = 138{,}586 \text{ kNm/m}$$

$$M_{Rd} = 125{,}070 / 1.10 + 37{,}015 / 1.40 = 140{,}139 \text{ kNm/m}$$

$$M_{Ed} = 138{,}586 < M_{Rd} = 140{,}139 \Rightarrow \text{OK}$$

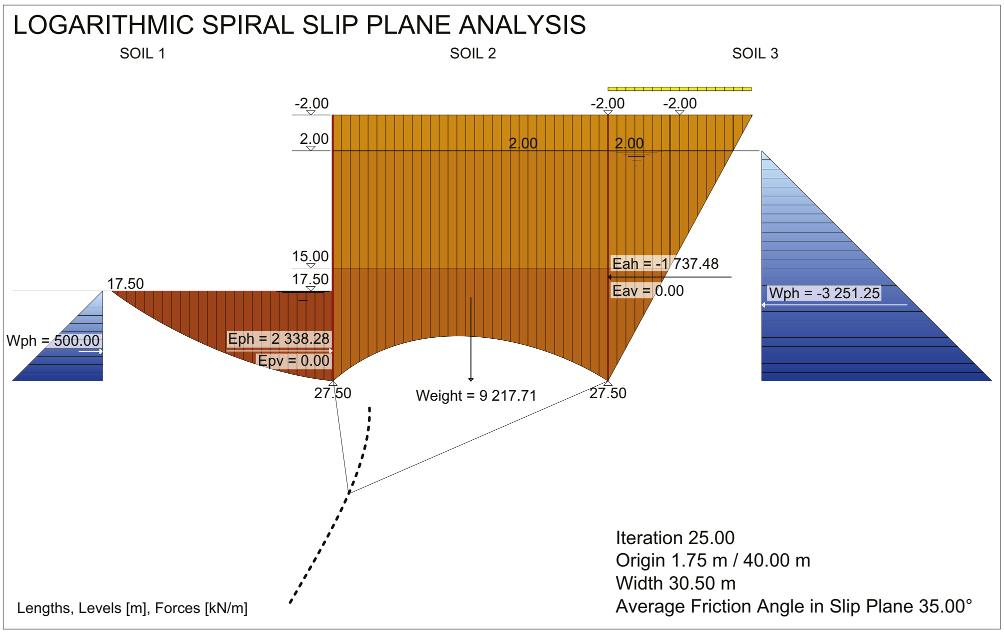


Fig. 6.24.: Computer calculation of required equivalent width w_e, verification of resistance to tilting due to shear failure in the fill/foundation soil. Software: 'Coffdam 4.0.' [10].

As the cell structure is not founded on bedrock, bearing capacity and deep-seated sliding analyses should be performed.
In addition, piping (hydraulic failure) should also be verified for this type of structure.

b) Determination of cell geometry

As the structure is very deep and the equivalent width is large, a diaphragm wall is selected. The angle of the Y-junction piles is chosen as θ = 120°.

From Table 4.3. a) and 4.3. b), following geometry can be chosen for an equivalent width **w_e = 30.85 m**:

Geometry diaphragm wall		Geometry arc				
Number of piles	Wall length	Number of piles	Radius System length	Arc height	Equivalent arc height	Interlock deviation
N pcs.	dl m	M pcs.	x = r m	d_y m	c m	δ_a °
55	27.97	19	9.41	1.26	0.86	3.06
57	28.97	21	10.37	1.39	0.94	2.78
59	29.98	23	11.33	1.52	1.03	2.54

- arc radius r = 10.37 m
- system length x = 10.37 m
- diaphragm wall length dl = 28.97 m
- angle deviation in arc δ_a = 2.78 °
- arc height d_y = 1.39 m
- equivalent arc height c = 0.94 m

Nb. of ssp for 1 diaphragm 57 = N
Nb. of ssp for 2 arcs 42 = 2 · M
Nb. of junction piles 2
Nb. of ssp for 1 system 101 = N + 2 · M + 2

Thus: $w_e = dl + 2\,c = 28.97 + 2 \cdot 0.94 = 30.85$ m

6.3.2.3. Verification against structural failure

a) Calculation of governing internal cell pressure

As the cell is embedded in the soil (and not founded directly on bedrock), the governing internal pressure can be assumed to be that exerted at the bottom of the excavation, i.e. at **elevation -17.50 m.**

Vertical stress at -17.50 m:

- weight of soil $\sigma_{v1} = 4.0 \cdot 18.0 + 13.0 \cdot 10.0 + 2.50 \cdot 11.0 = 229.5 \text{ kN/m}^2$
- variable loads $\sigma_{v2} = 20.0 \text{ kN/m}^2$
- design value $\sigma_v = \gamma_G \cdot \sigma_{v1} + \gamma_Q \cdot \sigma_{v2} = 1.35 \cdot 229.5 + 1.50 \cdot 20.0 = 339.8 \text{ kN/m}^2$

Coefficient of earth pressure at-rest:

$$K_o = 1 - \sin\varphi_k = 1 - \sin 35.0° = 0.4264$$

Horizontal earth pressure:

$$\sigma_h = K_o \cdot \sigma_v = 0.4264 \cdot 339.8 = 144.9 \text{ kN/m}^2$$

Hydrostatic pressure:

- characteristic value

$$p_{w1} = 15.5 \cdot 10 = 155.0 \text{ kN/m}^2$$

- design value $p_w = \gamma_G \cdot p_{w1} = 1.35 \cdot 155.0 = 209.3 \text{ kN/m}^2$

Total horizontal stress:

$$\sigma_{h,tot} = \sigma_h + p_w = 144.9 + 209.3$$

$$\mathbf{= 354.2 \text{ kN/m}^2 = p_{m,Ed}}$$

b) Analysis of resistance of straight web sheet piles

AS 500-12.5 straight web sheet piles are selected with:

- $R_{k,s}$ = 5,500 kN/m
- t_w = 12.5 mm
- f_y = 355 N/mm²

$$F_{ta,Ed} \leq F_{ts,Rd} \qquad [6.2'.]$$

Interlock resistance:

$F_{ts,Rd} = \beta_R \cdot R_{k,s} / \gamma_{M0} = 0.8 \cdot 5{,}500 / 1.0 = 4{,}400$ kN/m [6.1.]

Resistance of web:

$F_{ts,Rd} = t_w \cdot f_y / \gamma_{M0} = 12.5 \cdot 355 / 1.0 = 4{,}438$ kN/m [6.1.]

Determining resistance: $F_{ts,Rd} = 4{,}400$ kN/m

Junction Y-pile with $\theta = 120°$:

$$F_{ta,Ed} = F_{td,Ed} = p_{m,Ed} \cdot r \qquad [6.3'.]$$

$p_{m,Ed} = 354.2$ kN/m²

$r = 10.37$ m

$\Rightarrow F_{ta,Ed} = 354.2 \cdot 10.37 = 3{,}673$ kN/m $< F_{ts,Rd} = 4{,}400$ kN/m

The junction pile is manufactured in accordance with Section B 6 of EN 12063 [7]; special verification of the welds is therefore not required.

6.3.2.4. Durability

Loss of thickness due to corrosion of steel is based on Tables 4.1. and 4.2. from EN 1993-5. The design life assumed for this structure is **50 years** without any additional protection (sacrificial steel thickness exclusively). Verification of the sheet pile is done in the area where the interlock tension is highest (excavation level).

Considering the elevation just below the excavation level, the loss of steel thickness can be estimated as follows:

- front: natural soil 0.60 mm
- back: natural soil 0.60 mm

Total loss of steel thickness:

$$\Delta t = 0.60 + 0.60 = 1.20 \text{ mm}$$

Reduced interlock resistance due to corrosion of the AS 500-12.5:

$$\beta_{cor} = \frac{t_w - \Delta t}{t_w}$$

$\beta_{cor} = (12.50 - 1.20) / 12.50 = 0.904$

$$F_{ts,Rd,cor} = \beta_{cor} \cdot \beta_R \cdot R_{k,s} / \gamma_{M0} \qquad [6.8.]$$

$F_{ts,Rd,cor} = 0.904 \cdot 0.8 \cdot 5{,}500 / 1.0 = 3{,}978$ kN/m

$F_{ta,Ed} = 3{,}673$ kN/m $< F_{ts,Rd,cor} = 3{,}978$ kN/m $\Rightarrow$ OK

6.4. Examples of applications: global safety factor approach

Following example is based on the **global safety method**, which uses a global safety factor for the overall stability of the cell, and two different safety factors for the structural verification of the straight web steel sheet pile. Those safety factors have been used for the design of many circular cells during the last decades and are still commonly used nowadays.

The design method considered checks the overall stability:

$$M_S \leq \frac{M_r}{S_F} \qquad [6.11.]$$

where: M_s destabilizing moment (active earth pressure, water behind the cells, variable loads,...)

M_r stabilizing moment (passive earth pressure, water in front of the cells,...)

S_F global safety factor

The overall stability is based on the logarithmic slip plane failure assumed by Jelinek, and illustrated in chapter 6.1. above and in chapter 8.3. of EAU 1990 [9].

The method is based on "standard" soil parameters, usually written as «φ'» or «cal φ'», which are values that represent the soil properties. These are not "average" values, and they should not be mixed with characteristic soil parameters or design parameters, as used in the new Eurocodes. Typical values for granular and cohesive soils used with this global safety method can be found in chapter 1, Table R.9.1., EAU 1990 for instance. Furthermore, the safety factors for the different loading cases that may have to be analysed are given in chapter 1.13. of the Recommendations EAU 1990.

As a simplification, for this chapter, the notation used for the soil parameters is φ', c'.

Many different formulae have been used worldwide for the verification of the straight web steel sheet piles. For the next example, the formulae used in EN 1993-5 (2007) have been slightly adapted to take into account the global safety method. The verification of the resistance of the straight web steel sheet pile is done with following equations (similar to [6.1.]):

Interlock resistance:

$$F_{t,R} = \frac{R_{k,s}}{S_{F,1}} \qquad [6.12.\text{-a}]$$

Resistance of web:

$$F_{t,R} = \frac{t_w \cdot f_y}{S_{F,2}} \qquad [6.12.\text{-b}]$$

where:

$F_{t,R}$ straight web steel sheet pile resistance taking into account the web and the interlock

$R_{k,s}$ interlock resistance of the straight web steel sheet pile

t_w thickness of the web of the straight web steel sheet pile

f_y yield strength

Note: The convention chosen for the parameters in this section is similar to the one from Eurocodes, yet slightly different in order to avoid confusion.

Global safety factors recommended are:

S_F = 1.50

$S_{F,1}$ = 2.00

$S_{F,2}$ = 1.50

6.4.1. Example 3: temporary circular cells

A bridge pier is to be built in the middle of a river, and a temporary cofferdam is to be erected at a spot with shallow bedrock. The cell will be backfilled with sand. Design life of the structure is only 2 years.

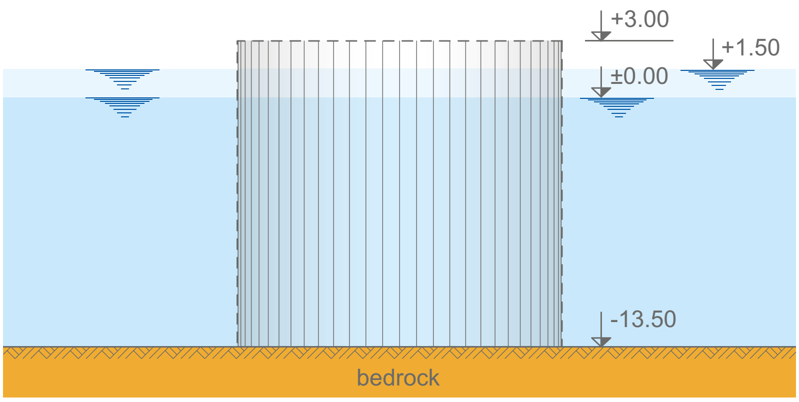


Fig. 6.25.: Initial conditions.

6.4.1.1. Assumptions

Before erection any deposit above the bedrock is dredged from the cofferdam footprint.

Soil properties:

	γ / γ' kN/m³	φ' °	δ °	c' kPa
backfill (sand)	18 / 10	30.0	0	0
bedrock	20 / 11	37.5	0	0

No embedment of the tip of the steel sheet piles in the rock is assumed. Provisions to prevent loss of fill material through gaps between the sheet pile tip and the bedrock have to be made.

Water levels: HWL = +1.50 m
LWL = +0.00 m

Water levels for overall stability & for interlock resistance verification:

- in front of wall: -14.00 m
- behind wall: +1.50 m [= HWL]
- inside the cell: -4.50 m

The water level inside the cell is an arbitrary, yet plausible, choice made by the design engineer. This assumption has to be strictly enforced during the short lifetime of the structure. Any deviation from this design criterion needs to be evaluated by the design engineer and alternative solutions have to be elaborated in case this water elevation cannot be guaranteed at any stage of the project.

Excavation level:

- nominal depth: -13.50 m
- design depth = nominal depth - excavation tolerance
  = -13.50 - 0.50
  = -14.00 m

with: assumed excavation tolerance = 0.50 m (assumption by design engineer)

Vertical loads: P = 30 kN/m².

Note: Surcharge load P is required for analysis of the internal cell pressure, but it has to be neglected for the stability analysis because of its stabilizing effect.

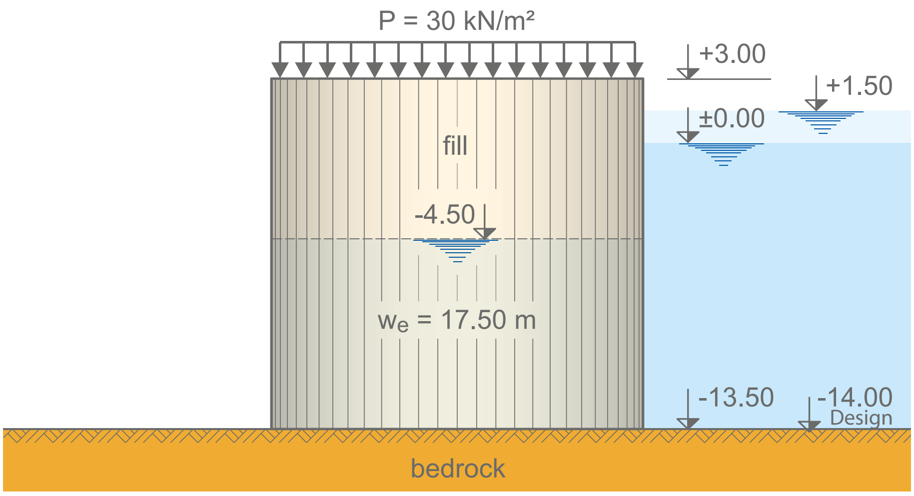


Fig. 6.26.: Final conditions.

6.4.1.2 Overall stability

a) Calculation of required equivalent width, verification of resistance to tilting due to shear failure in the fill/foundation soil

Analysis is performed with computer software based on the assumptions given above. For an equivalent width **w_e = 17.5 m**, following moments can be determined:

M_s = 20,664 kNm/m
M_r = 32,508 kNm/m

Using above formula the global safety factor of the structure is:

$$S_F = \frac{M_r}{M_s} = \frac{32{,}508}{20{,}664} = 1.57 \geq 1.50 \Rightarrow \text{OK}$$

Note: An embedment of the steel sheet pile in a thin layer overlying the bedrock has not a significant influence on the result, and in most cases it can be neglected. In this example, even if there were a thin deposit layer over the bedrock, it could be neglected.

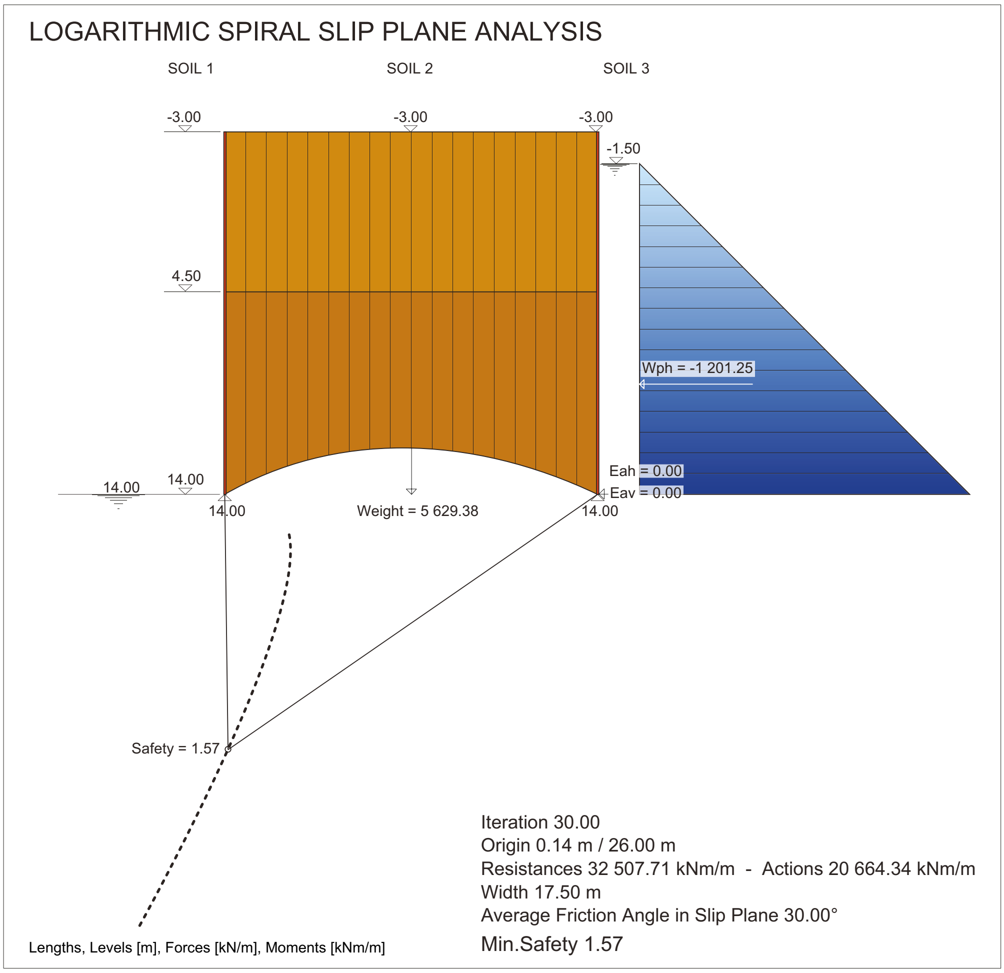


Fig. 6.27.: Computer calculation of required equivalent width we, verification of resistance to tilting due to shear failure in the fill/foundation soil. Software: "Coffdam 4.0." [10].

As the cell structure is founded on bedrock, bearing capacity and deep-seated sliding analyses are not required.

b) Determination of cell geometry

The angle of the junction piles is chosen as $\theta = 35.0°$.

From Table 4.1., following geometry can be selected for an equivalent width $\mathbf{w_e = 17.5}$ **m.**

No. of piles per						Geometrical values						Interlock deviation		Design values	
Cell				Arc	System							Cell	Arc	2 Arcs	
	L	M	S	N		$d=2 \cdot r_m$	r_a	x	d_y	α	β	δ_m	δ_a	w_e	R_a
pcs.	pcs.	pcs.	pcs.	pcs.	pcs.	m	m	m	m	°	°	°	°	m	
124	37	23	1	25	174	19.85	4.17	24.63	0.10	34.84	179.68	2.90	6.91	**17.50**	3.59
124	39	21	1	27	178	19.85	4.64	26.12	0.28	31.94	173.87	2.90	6.21	**17.17**	3.47

- cell diameter $d = 19.85$ m
- radius of the main cell $r_m = 9.93$ m
- radius of connecting arc $r_a = 4.17$ m
- system length $x = 24.63$ m
- offset $d_y = 0.10$ m
- angle $\alpha = 34.84$ °
- angle deviation in arc $\delta_a = 6.91$ °

Nb. of ssp for 1 system 174

Nb. of ssp for cell 124 $= 2 \cdot (L+M) + 4 \cdot S$ (including 4 junction piles)

Nb. of ssp for 2 arcs 50 $= 2 \cdot N$

6.4.1.3. Verification against structural failure

a) Calculation of governing internal cell pressure

As the cell is founded directly on bedrock, the governing internal pressure can be assumed to be that exerted one quarter of the height of the cell above the bedrock surface, i.e. at approximately **elevation -10.00 m.**

However, under certain circumstances, it might be advisable to consider a deeper elevation, and in some cases the excavation elevation is used.

Vertical stresses at -10.00 m:

- weight of soil $\sigma_{v1} = 7.5 \cdot 18.0 + 5.5 \cdot 10.0 = 190.0 \text{ kN/m}^2$
- variable loads $\sigma_{v2} = 30.0 \text{ kN/m}^2$
- total value $\sigma_v = \sigma_{v1} + \sigma_{v2} = 190.0 + 30.0 = 220.0 \text{ kN/m}^2$

Coefficient of earth pressure at-rest:

$$K_o = 1 - \sin\varphi' = 1 - \sin 30.0° = 0.500$$

Horizontal earth pressure:

$$\sigma_h = K_o \cdot \sigma_v = 0.500 \cdot 220.0 = 110.0 \text{ kN/m}^2$$

Hydrostatic pressure:

$$p_w = 5.5 \cdot 10 = 55.0 \text{ kN/m}^2$$

Total horizontal stress:

$$\sigma_{h,tot} = \sigma_h + p_w = 110.0 + 55.0$$

$$\mathbf{= 165.0 \text{ kN/m}^2 = p_m}$$

b) Analysis of resistance of straight web sheet piles

AS 500-12.5 straight web sheet piles are selected with:

- $R_{k,s} = 5{,}500$ kN/m
- $t_w = 12.5$ mm
- $f_y = 355$ N/mm²

$$F_t \leq F_{t,R} \qquad [6.2\text{-bis.}]$$

where:

F_t : circumferential tensile force in the main arc determined with an expression similar to [6.3.]:

$$F_t = p_m \cdot r_m \qquad [6.3\text{-bis.}]$$

Interlock resistance:

$$F_{t,R} = \frac{R_{k,s}}{S_{F,1}} = \frac{5{,}500}{2.0} = 2{,}750 \text{ kN/m} \qquad [6.12\text{-a.}]$$

Resistance of web:

$$F_{t,R} = \frac{t_w \cdot f_y}{S_{F,2}} = \frac{12.5 \cdot 355}{1.5} = 2{,}958 \text{ kN/m} \qquad [6.12\text{-b.}]$$

Determining resistance: $F_{t,R} = 2{,}750$ kN/m

Junction pile:

r_m = cell radius = 9.93 m

r_a = connecting arc radius = 4.17 m

$$\beta_T = 0.9 \cdot \left(1.3 - 0.8 \frac{r_a}{r_m}\right) \cdot (1 - 0.3 \tan\varphi_k)$$

Note: Above formula from EN 1993-5 has been determined with characteristic values of the internal friction angle φ_k. In this particular case, φ_k can be determined with following formula (adapted from EAU 1990):

$$\tan(\varphi') = \frac{\tan\varphi_k}{1.1}$$

Hence:

$\varphi_k = \arctan(\tan(30°) \cdot 1.1) = 32.42°$

$$\beta_T = 0.9 \cdot \left(1.3 - 0.8 \cdot \frac{4.17}{9.93}\right) \cdot (1 - 0.3 \cdot \tan(32.42°))$$

$$= 0.7022$$

$F_{tm} = p_m \cdot r_m = 165.0 \cdot 9.93 = 1{,}638$ kN/m

$< \beta_T \cdot F_{t,R} = 0.702 \cdot 2{,}750 = 1{,}931 \text{ kN/m} \Rightarrow$ OK [6.5-bis.]

6.4.1.4. Durability

As the structure is only for temporary use (2 years), it is not necessary to take into account any loss of steel thickness during its service life.

Project:	Paraíso, Panama Canal
Sections:	AS 500 - 12.0
Quantity:	3 000 tonnes

7. Construction of cellular structures

7.1. Circular cells

Usual construction sequence for circular cell structures:

- pitch the main cells, using a template;
- drive the sheet piles in the main cells;
- fill the main cells;
- pitch the connecting arcs between two completed main cells, using a template;
- drive the connecting arcs;
- fill between the main cells.

7.1.1. Template

Straight web sheet piles have no inherent flexural stiffness. Therefore a template is necessary to stabilize the cell during assembly and backfill operations. The design of the template is governed by following considerations:

- installation on land;
- installation in water:
  - open sea conditions (waves, wind, current velocity, installation method,...),
  - river conditions (current velocity, installation method,...);
- number of cells to be constructed and reuse of the template;
- length of sheet piles;
- capacity of lifting equipment;
- safety considerations for work crew.

The template must have at least two guiding levels with sufficient distance from each other to assure proper sheet pile alignment. The lower guide shall be positioned as close to the ground as possible. It shall be movable to allow easy handling during installation and backfill. Similar conditions apply to the upper guide. Additionally, this upper guide shall provide a safe working platform for the crew.

The theoretical external diameter of the template is determined by following formula:

$$R_{ext} = \frac{N_{ssp} \cdot 503}{2\pi} - 55 \text{ (mm)} \qquad [7.1.]$$

with N_{ssp} : number of steel sheet piles of the cell

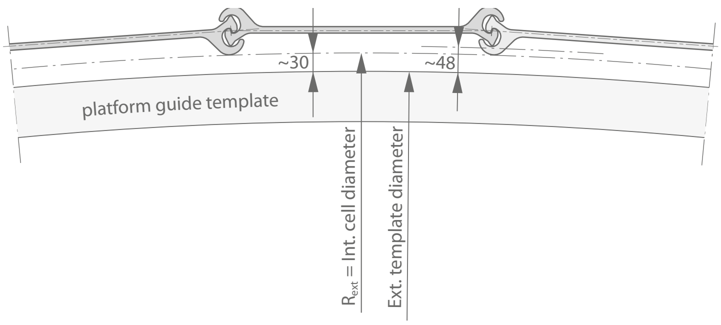


Fig. 7.1.: Recommended template diameter.

Additionally, to take into account rolling tolerances of the sheet piles and fabrication tolerances of the template, the radius R_{ext} should be reduced by further 30 mm.

The design shall follow local standards and be made by experienced design engineers.

7.1.2. Cell assembly

After installing the template at the correct position, the straight web sections shall be placed around the template, starting with the junction piles. The exact position of the junction piles has to be determined by a surveyor. Verticality of these piles has to be checked carefully. All piles shall be fixed temporarily to the template. The correct position of the sheet piles shall be checked constantly, for instance by measuring or using fixed marks on the template. Closing of the cell shall occur in the middle between two junction piles. This enables a maximum of flexibility taking into account all the tolerances mentioned above. To close the cell, the last piles can be pushed or pulled easily using standard construction equipment (ropes, chain pull) in order to widen or shorten the gap between the piles already in place.

To speed up the installation process previously paired double piles can be of advantage.

For load transfer reasons, it is generally not recommended to put grease in the interlocks.

7.1.3. Pile driving

After the cell is completed as described above, the temporary fixation of the first pile to be driven is removed. This must be one of the junction piles. Driving is done in stages of less than 2.0 m, depending on soil conditions. The driving shall proceed in one direction from this point on until one reaches the first junction pile again. Driving direction shall change to prevent leaning of the piles in one direction. This procedure is repeated until design depth is reached. To allow smooth working progress, the upper guide of the template should move stepwise with the piles. Alternatives are possible, for example using a special follower.

Before starting filling of the main cell, at least two piles of the intermediary arcs shall be pitched to minimize the impact of deformation during filling.

Intermediary arcs shall be installed only after filling of the adjacent cells is completed.

Preferred installation equipment is a vibratory hammer, selected according to the specific job-site conditions. If an impact hammer is used, the energy level shall be monitored closely to prevent damages to the sheet piles.

To speed up the installation process, driving of panels with double or triple piles is possible.

7.1.4. Filling of the cells

The main cells can be backfilled independently. It is essential that the template remains in place and guarantees the stability of the cell. Generally, backfill should reach 2/3 of the cell height at least before removing the template. The filling operation shall be carried out from the centre of the cell to avoid any unbalanced loadings. Conveyor belts or hydraulic fills are normally used.

During the filling the sheet piles develop tensile resistance which translates into a small increase of the diameter, and corresponds to the barrel effect.

Granular soils (well graded sands, gravels, quarry material) are recommended as fill material. This allows to choose correct design parameters, and helps the consolidation process.

If the cell fill is to be compacted additional earth pressure has to be taken into account in the design.

Vertical drains may reduce the consolidation time of the fill.

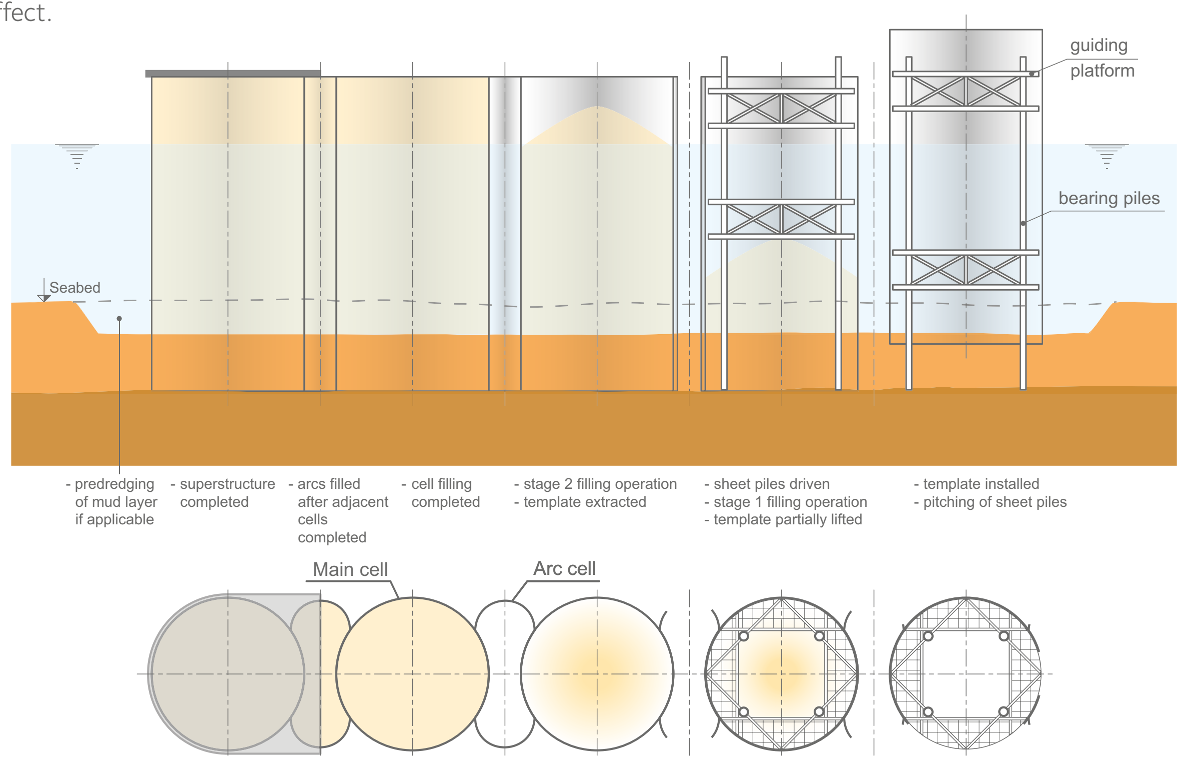


Fig. 7.2.: Installation phases of circular cell structures.

7.1.5. Superstructures and loadings

Fender, bollards, crane loads, surcharge loads, and permanent loads will be transferred either directly into the fill, or respectively introduced through bearing piles.

Any direct vertical loading of the straight web sheet piles shall be avoided. All permanent superstructure works shall be executed once the cofferdam has fully stabilized.

7.1.6. Construction time

Assuming appropriate job-site organization and equipment, it is possible to execute one cell system per seven working days. This can be subdivided into following construction stages for one cell:

- installation, positioning and fixing of template — 2 days
- pitching of sheet piles — 2 days
- driving — 1 day
- filling — 2 days
- execution of arcs (not on the critical path) — 2 days

Variations are possible and influenced by local experience and specific job-site conditions.

7.2. Diaphragm cells

The principal installation steps are similar to the ones for circular cells. The main differences consist in multi-staggering of sheet piles, the mandatory use of a second template and specific care of filling operations (if applicable).

Please contact our technical department for more details on installation procedures.

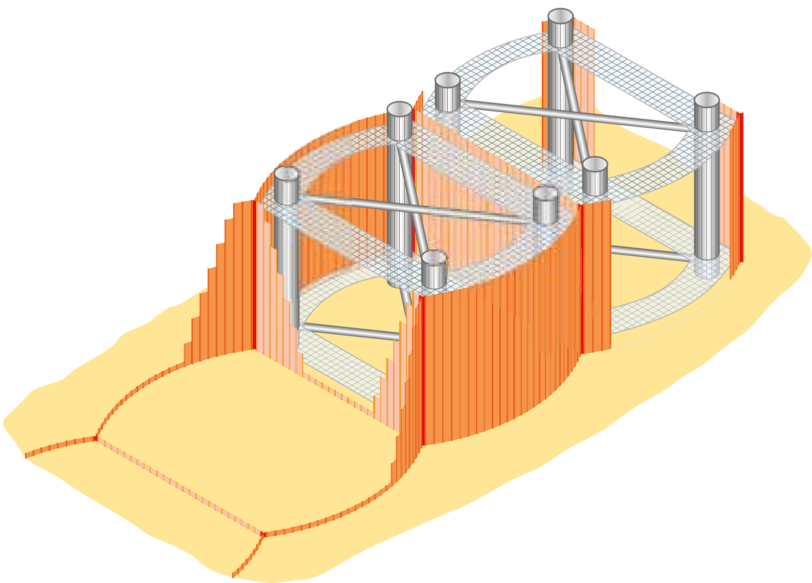


Fig. 7.3.: Typical installation steps for a diaphragm cell structure on land.

Project: Bal Haf, Yemen
Sections: AS 500 - 12.7
Quantity: 1 310 tonnes

8. Conventional symbols

Whenever possible, symbols and abbreviations are based on the documents that are referenced. Otherwise, they conform as far as possible to the rules and principles from Eurocode 1. However, some abbreviations, indexes and so on might be specific to this brochure either because they do not exist in the referenced documents or because the version of the documents / standards has changed. Symbols used only once in the document or which are defined each time they are used are not mentioned in this chapter.

8.1. Greek letters

Symbol	Definition	Units
β	pre-bent angle of a straight web steel sheet pile	°
β_{cor}	factor accounting for the corrosion of straight web steel sheet piles	
β_R	factor accounting for the interlock resistance of straight web steel sheet piles	
β_T	factor accounting for the behaviour of a welded junction pile at ultimate limit states	
δ	structure-ground interface friction angle	°
δ_a	deviation angle of the sheet piles in the arc cell	°
δ_m	deviation angle of the sheet piles in the main cell	°
γ	weight density of soil	kN/m³
γ'	effective weight density of soil (submerged)	kN/m³
γ_w	weight density of water	kN/m³
$\gamma_{c'}$	partial factor for the effective cohesion	
γ_{Ep}	partial factor for earth resistance	
γ_G	partial factor for a permanent action	
γ_Q	partial factor for a variable action	
γ_{GI}	partial factor for a permanent stabilising action	
φ'	angle of shearing resistance in terms of effective stress	°
θ	connecting angle of the junction piles	°
σ_v	vertical stress	kPa
σ_h	horizontal component of the vertical stress	kPa
$\sigma_{h,tot}$	horizontal stress at the governing level for cell structures	kPa

8.2. Latin letters

Symbol	Definition	Units
c	cohesion intercept of soil	kPa
c'	cohesion intercept in terms of effective stress	kPa
c_u	undrained shear strength of soil	kPa
dl	length of the diaphragm wall	m
d_y	offset of the arc cell to the main cell; arc height	m
f_y	yield strength of straight web steel sheet piles	MPa
$p_{m,Ed}$	design value of the internal pressure acting in the main cell of a cellular cofferdam	kPa
p_w	water pressure	kPa
r	radius	m
r_a	initial radius of the arc cell in a cellular cofferdam	m
r_m	initial radius of the main cell in a cellular cofferdam	m
t_f	nominal flange thickness of a steel sheet pile	m
t_w	nominal web thickness of a steel sheet pile	m
w_e	equivalent width of a cellular / diaphragm cell system	m
x	system length of a cellular / diaphragm cell system	m
HWL	High Water Level	m
LWL	Low Water Level	m
K_a	coefficient of active earth pressure	
K_0	coefficient of at-rest earth pressure	
K_p	coefficient of passive earth pressure	
$F_{t,Ed}$	design value of the circumferential tensile force in a cellular cofferdam	kN/m
$F_{ta,Ed}$	design tensile force in the arc cell of a cellular cofferdam	kN/m
$F_{tm,Ed}$	design tensile force in the main cell of a cellular cofferdam	kN/m
$F_{ts,Rd}$	design tensile resistance of simple straight web steel sheet piles	kN/m

8.3. Subscripts

Symbol	Definition
cor	corroded
d	design value
k	characteristic value
red	reduced

Note: Subscripts may have different meanings.

9. References

Standards

[1] EN 1991 Eurocode 1: Actions on structures. CEN
[2] EN 1993 Eurocode 3: Design of steel structures. Part 5: Piling. Version 2007. CEN
[3] EN 1997 Eurocode 7: Geotechnical design. CEN
[4] EN 1998 Eurocode 8: Earthquake resistant design of structures. CEN
[5] EN 10248 Hot rolled sheet piling of non alloy steels. CEN
[6] EN 10249 Cold formed sheet piling of non alloy steels. CEN
[7] EN 12063 Execution of special geotechnical work - Sheet-pile walls. CEN

Books

[8] EAU 2004. Recommendations of the Committee for Waterfront Structures. Ernst & Sohn. Berlin
[9] EAU 1990. Recommendations of the Committee for Waterfront Structures. Ernst & Sohn. Berlin

Software

[10] Coffdam 4.0. Software by Marco Mascarin (2001)

2nd Incheon Bridge, South Korea

Ohio River, USA

CERTIFICATE

The ESCEM asbl Certification Body hereby certifies that the company

ArcelorMittal Belval & Differdange S.A.

Site de Belval	**Site de Differdange**	**Site de Rodange**
L-4008 Esch-sur-Alzette	**L-4503 Differdange**	**L-4823 Rodange**

has established and applies a quality, environmental and occupational health and safety management system for the scope

Design and manufacture of steel semi and finished products (beams, sheet piles, merchant bars, rails, special sections, special round bars as well as completed structural elements)

An audit was performed, report No 112
Proof has been furnished that the requirements according to

ISO 9001:2008, ISO 14001:2004 and BS OHSAS 18001:2007

are fulfilled.

The certificates are valid from 28.10.2016 until 14.09.2018

The due date for all future audits is 21.10 of each year

Certificates Registration No
900 112, 1400 112 et 1800 112

the 21 10 2016

ESCEM Asbl, 1 Avenue des Terres Rouges
L-4004 Esch-sur-Alzette

Disclaimer

The data and commentary contained within this steel sheet piling document is for general information purposes only. It is provided without warranty of any kind. ArcelorMittal Commercial RPS S.à r.l. shall not be held responsible for any errors, omissions or misuse of any of the enclosed information and hereby disclaims any and all liability resulting from the ability or inability to use the information contained within. Anyone making use of this material does so at his/her own risk. In no event will ArcelorMittal Commercial RPS S.à r.l. be held liable for any damages including lost profits, lost savings or other incidental or consequential damages arising from use of or inability to use the information contained within. Our sheet pile range is liable to change without notice.

Printed on FSC paper. The FSC label certifies that the wood comes from forests or plantations that are managed in a responsible and sustainable way (the FSC principles promote the social, economical, environmental and cultural needs of today's and the next generations). www.fsc.org

ArcelorMittal Commercial RPS S.à r.l.
Sheet Piling

66, rue de Luxembourg
L-4221 Esch-sur-Alzette (Luxembourg)

E sheetpiling@arcelormittal.com
sheetpiling.arcelormittal.com

Hotline: (+352) 5313 3105

ArcelorMittalSP

ArcelorMittal Sheet Piling (group)

1-31-17-1-GB