

# Metal Structures II

## Design project I

### Vertical cylindrical tank

### Example of calculation

## Algorithm

- ◆ Proportions, dimensions - initial assumptions
- ◆ Reliability
- ◆ Grade and subgrade of steel
- ◆ Loads
- ◆ Loadbearing of roof
- ◆ Stability of roof
- ◆ Edge ring
- ◆ Loadbearing of shell
- ◆ Stability of shell
- ◆ Shell man holes
- ◆ Shell nozzles
- ◆ Bottom
- ◆ Global stability
- ◆ Foundations
- ◆ Drawing and list of materials

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## Example: data

$$V = 35\,000 \text{ m}^3$$

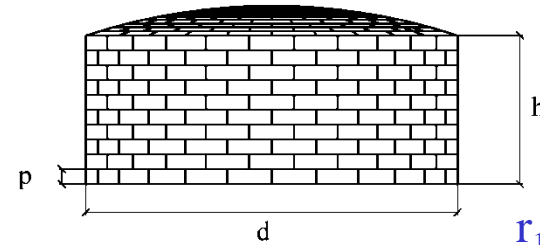
Location: Hel-seashore

Liquid: diesel

Ground : very good

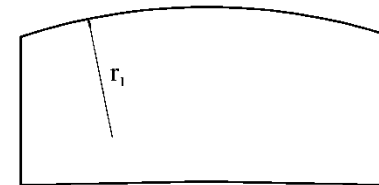
## Proportions, dimensions

dach stały	poniżej 1 000	od 6,0 do 11,0	4,0 $\frac{1}{1,0}$
	od 1 100 do 10 000	od 12,0 do 14,0	$\frac{1}{1,1}$ do $\frac{1}{2,3}$
	od 11 000 do 16 000	14,0	$\frac{1}{2,2}$ do $\frac{1}{2,8}$
	od 17 000 do 32 000	16,5	$\frac{1}{2,2}$ do $\frac{1}{3,2}$
	powyżej 32 000	18,0	$< \frac{1}{2,8}$
	poniżej 500	14,5	4,0



$$r_1 = 1,0 - 1,5 d$$

Photo: Author



$$p = 1,0 - 2,0 m$$

Photo: PN B 3210 tab. 2

$$V = 35\,000 \text{ m}^3$$

Initial assumption:

$$h = 18,0 \text{ m}$$

$$h / d = h / 2r < 1 / 2,8 \rightarrow d = 52,0 \text{ m}$$

$$r = 26,0 \text{ m}$$

$$r_1 = 78,0 \text{ m}$$

$$V = \pi d^2 h / 4 = 38\,227 \text{ m}^3$$

$$38\,227 / 35\,000 = 1,09 \text{ OK}$$

Total height: 22,461 m

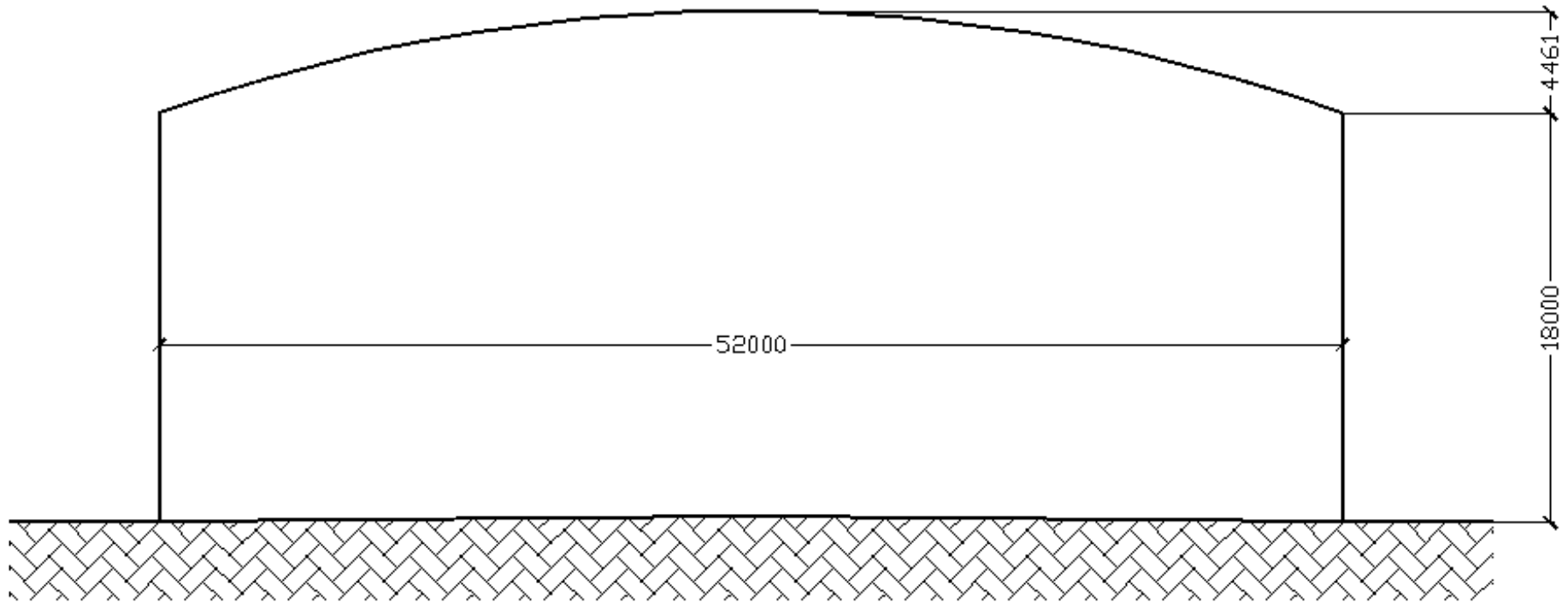


Photo: Author

# Reliability

„Reliability” in this context means values of safety factors for load.

EN 1993-4-2, 4.2.2.1:

## 4.2.2.1 General

- (1) The analysis of the tank shell should be carried out according to the requirements of EN 1993-1-6.
- (2) A higher class of analysis may always be used than that defined for the selected Consequence Class.
- (3) Irrespective of the Consequence Class chosen, the simplified design described in Section 11 may be used if the conditions listed there are met.

EN 1993-4-2 presents two ways of calculation:

According to EN 1993-1-6 (shell structure), where full analysis of CC impact on safety factors must be made ( $\rightarrow$  #t / 10-12);

Simplified method presented in EN 1993-4-2, 11, where values of safety factors are independent on CC ( $\rightarrow$  #t / 13-14);

In presented example, simplified way will be taken into consideration. But, unofficially, impact of CC will be taken the same.

Separated problem are values of safety factor, presented in recalled standard EN 14 015. There are safety factors common for loads and materials.

Basic standard for tanks in EN 1993-4-2. Standard EN 14 015 is recalled in EN 1993-4-2 as complementary standard. Old Polish Standard PN B 03211 can be treated as auxiliary standard for initial assumption of geometry. But these three standards based on different assumptions.

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Standard	Method	$f_k$	Safety factors
EN 1993-4-2	Limit States Method	5%	Two separated: for actions and for material, calculated for special values of quantiles
EN 14 015	Permissible Stress Design	5%	One for proportion between effects and resistance
PN B 03211	Limit States Method	2%	Two separated: for actions and for material, calculated for special values of quantiles

There are special standards for actions and for values of safety factors, dedicated for each method of calculations. Calculation according EN 14 015, based on actions and safety factors from Eurocodes, does not give correct results. It is inconsequence in Eurocode, when EN 14 015 is recalled.

Differences in formulas for shell resistance in EN 1993-4-2 and EN 14 015 comes from two completely various methods of calculation: Limit States Method and Permissible Stress Design. Both standards must be analysed in cooperation with other standards: values of external actions are various for both methods (safety factors, first of all). Crossing between actions according to Eurocodes and old standard for resistance can make overdesign of shell.

EN 14 015 is mentioned in EN 1993-4-2 only 4 times:

- Point 1.1.(2) (2) This Part 4.2 is concerned only with the requirements for resistance and stability of steel tanks. Other design requirements are covered by EN 14015 for ambient temperature tanks and by EN 14620 for cryogenic tanks, and by EN 1090 for fabrication and erection considerations. These other requirements include foundations and settlement, fabrication, erection and testing, functional performance, and details like man-holes, flanges, and filling devices.
- Point 1.2 (title of standard)  
EN 14015 *Specification for the design and manufacture of site built, vertical, cylindrical, flat bottomed, above ground, welded, metallic tanks for the storage of liquids at ambient temperatures*
- Point 11.4.(2) (2) Bottom plates should be lap welded or butt welded. For welding details see EN 14015 or EN 14620, as appropriate.
- Point 11.4.(7) (7) The radial seams connecting annular plates to each other should be full penetration butt welded. For welding details, see EN 14015 or EN14620, as appropriate.

Consequences calss	Description
CC3	Tanks storing liquids or liquefied gases with toxic or explosive potential and large size tanks with flammable or water-polluting liquids in urban areas
CC2	Medium size tanks with flammable or water-polluting liquids in urban areas
CC1	Agricultural tanks or tanks containing water

„Medium size” = according to unofficial definition, volume  $\leq 10.000 \text{ m}^3$

EN 1993-4-2 2.2

Consequences calss	Circular shell structure of a tank	Box structure of a rectangular tank
CC3	+ numerical analysis (finite element shell analysis)	An analysis based on nonlinear plate bending and stretching theory
CC2	+ membrane theory with bending theory or + numerical analysis (finite element shell analysis)	An analysis based on linear plate bending and stretching theory
CC1	+ membrane theory and + simplified formulas to describe local bending effects	Static equilibrium for membrane forces and beam theory for bending

EN 1993-4-2 4.2.2 4.3.3

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Partial factors for permanent and variable actions for tanks			
Type of effects	Reliability class	Permanent actions	Variable actions
Unfavourable	CC3	1.50 (1.35)	1,65
	CC2	1.35	1,50
	CC1	1.20 (1.35)	1,35
Favourable	CC1, CC2, CC3	1,0	0,0
Accidental situations		1,0	1,0

T. Michałowski, M. Piekarczyk, Selected Issues of Special Steel Structures, Cracow University of Technology 2019

## Simplified method

Design Situation	Liquid type	$\gamma_f$ , liquids	$\gamma_f$ , rest loads
Exploitation	Tyoxic, exploxive or dangerous liquids	1,40	1,35
	Flammable liquids	1,30	
	Other liquids	1,20	
Test	All liquids	1,00	
Accidental actions	All liquids	1,00	

EN 1993-4-2 tab. 2.1

### Unofficially:

- $\gamma_f$ , rest loads – according to CC of tank ( $\rightarrow \#t / 10$ );
- $\gamma_f$ , liquids – taken into consideration impact of CC, according to EN 1990, tab. B3

Design Situation	Liquid type	$\gamma_f$ , liquids			$\gamma_f$ , rest		
		CC1	CC2	CC3	CC1	CC2	CC3
CC							
Exploitation	Toxic, explosive or dangerous liquids	1,30	1,40	1,55	d-weight: 1,20	d-weight: 1,35	d-weight: 1,50
	Flammable liquids	1,20	1,30	1,45			
	Other liquids	1,10	1,20	1,35	l-load: 1,35	l-load: 1,50	l-load: 1,65
Test	All liquids	1,00					
Accidental actions	All liquids	1,00			1,00		

## Grade and subgrade of steel

Initially, the most popular steel S235 JR will be taken into consideration. Such assumption will be controlled and, maybe, changed during calculation.

Thickness of plates can't be too small, for ensure enough resistance.

On the other hand, thickness of plate can't be too big, to avoid cracking in low temperature (tank have not thermal insulation).

Is possible, than finally higher grade than S235 (strength bigger than 235 MPa) will be applicated, and subgrade higher than JR (smaller probability of cracking) will be applicated.

Dead weight of steel structure

## Loads

Snow

Wind

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Over- and underpressure

Liquid pressure

Corrosion

Thermal action (main part)

Actions during execution

Accidental actions

Rainfall

Seismic

Dynamic

Loads resulting from connected piping and attachments

Foundation settlement loads

## Dead weight of steel structure

Dead weight comes from thickness of plate and cross-section of bar members, applied in structure.

## Wind action

Hel, seashore → EN 1991-1-4 NA:

$$V_{b,0} = 26,0 \text{ m / s} \rightarrow q_{b,0} = 0,42 \text{ kPa}$$

$$\text{Terrain category 0} \rightarrow c_e(z) = 2,98 (z / 10)^{0,176}$$

$$c_{dir} = 1,0$$

$$c_{season} = 1,0$$

EN 1991-1-4:

$$z_{min} = 1,0 \text{ m}$$

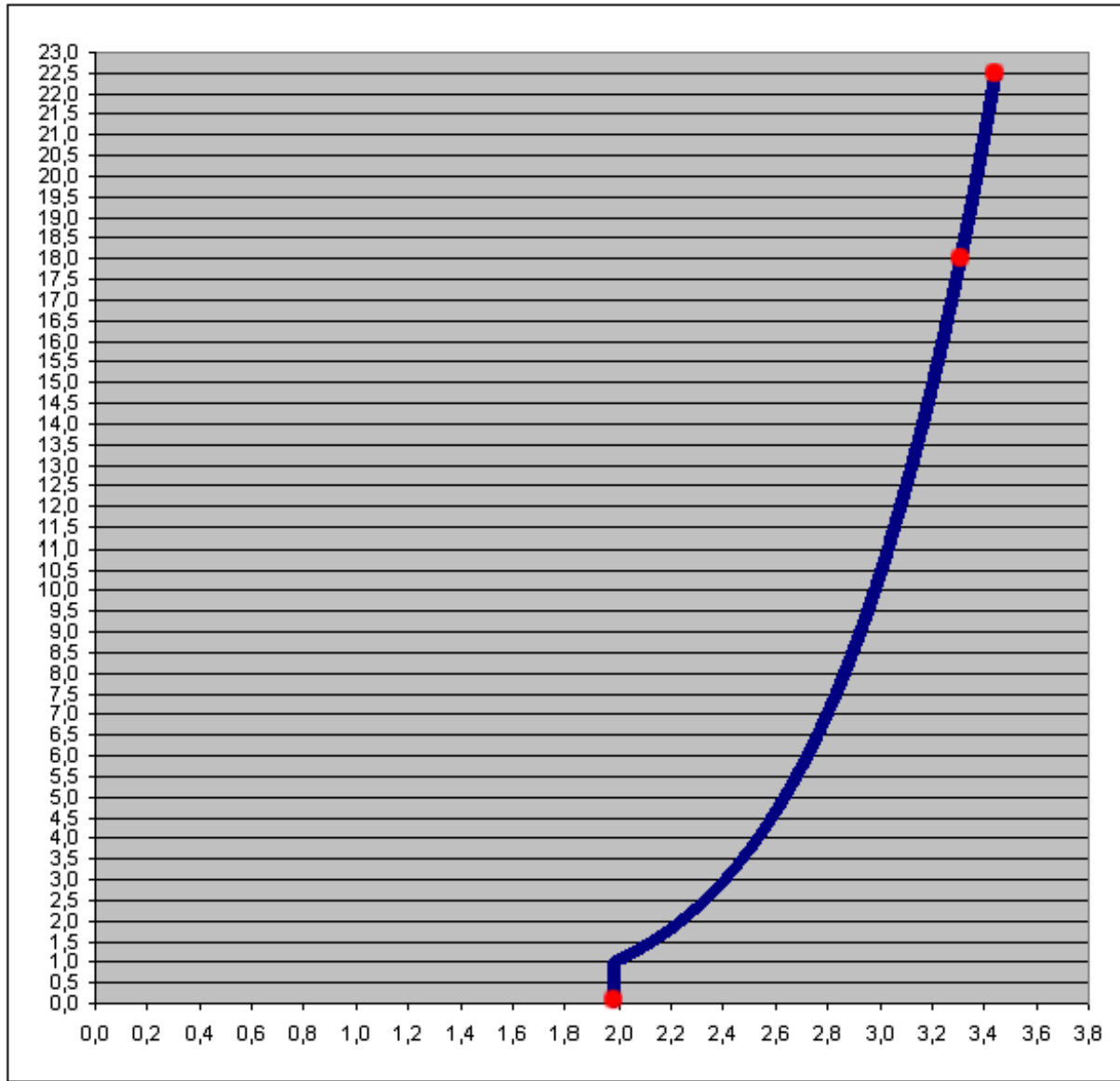
Tank → structure non-susceptible to dynamic action of wind →  $c_s c_d = 1,0$

$$q_p = q_{b,0} c_{dir} c_{season} c_e(z) =$$

$$= 0,42 \text{ kPa} \cdot 2,98 (z / 10)^{0,176} \text{ for } z > z_{min} (= 1,0 \text{ m})$$

$$= 0,42 \text{ kPa} \cdot 2,98 (z_{min} / 10)^{0,176} \text{ for } z \leq z_{min} (= 1,0 \text{ m})$$

$z$  [m]

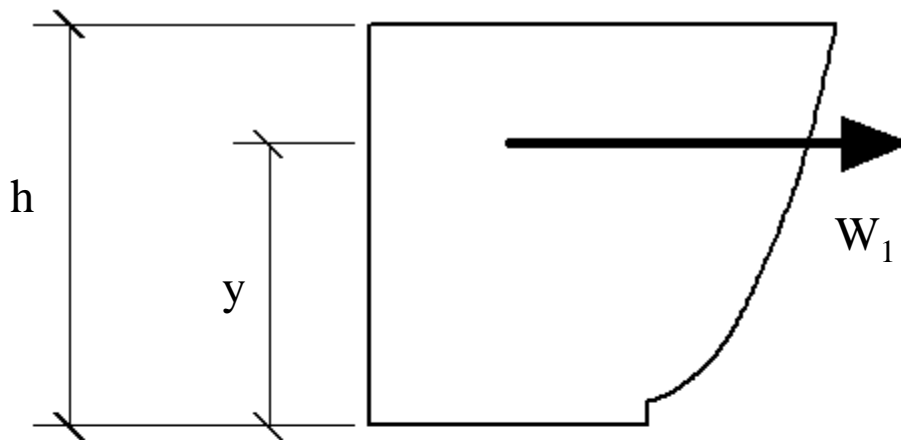


Vertical profile of wind velocity.

There are important three values of  $c_e$ : for bottom of cylinder, for connection cylinder-dome and fro top of dome.

Photo: Author

$c_e$



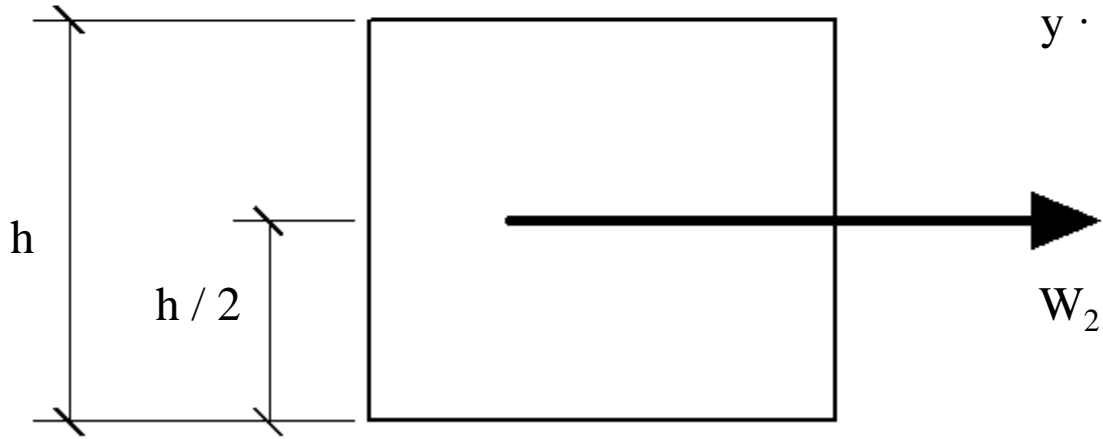
Precise description

One of conditions to be checked is value of wind load moment relative to tank base:

$$M = y \cdot W$$

$$W_1 < W_2$$

$$y > h / 2$$



Approximate description

$$y \cdot W_1 \rightarrow ?? < = > ?? \leftarrow h / 2 \cdot W_2$$

Example provides precise description.

Photo: Author

Cylinder:

$$c_e(h = 1,0) = 1,978$$

$$c_e(h = 18,0) = 3,309$$

Dome:

$$c_e(h = 18,0) = 3,309$$

$$c_e(h = 22,46) = 3,342$$

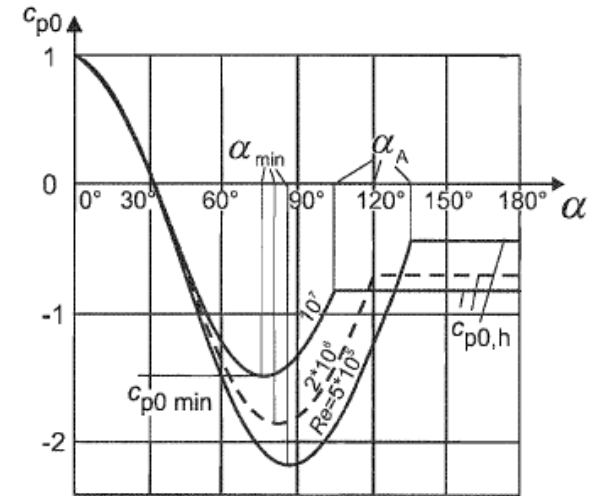
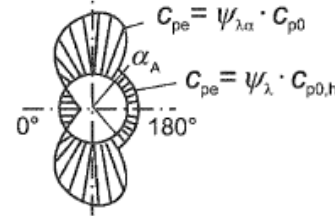
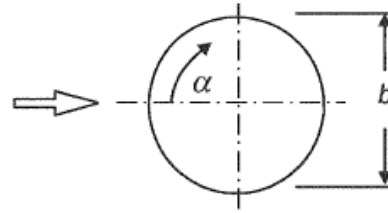


Photo: EN 1991-1-4 fig. 7.27

For cylindrical part, parameters presented on EN 1991-1-4 fig 7.27 are function of Reynolds number:

$$Re(d, V) = d V(z) / \nu = Re(d, z)$$

$$\text{Kinematic viscosity of air: } \nu = 15 \cdot 10^{-6} \text{ m}^2 / \text{s}$$

Wind pressure:

$$q_p = q_{b,0} c_{dir} c_{season} c_e(z) = [(V_{b,0})^2 \rho / 2] c_{dir} c_{season} c_e(z) = \{V_{b,0} \sqrt{[c_e(z)]}\}^2 \rho c_{dir} c_{season} / 2 = [V(z)]^2 \rho c_{dir} c_{season} / 2$$

$$V(z) = V_{b,0} \sqrt{[c_e(z)]}$$

$$V(0) = V_{b,0} \sqrt{[c_e(1,0)]} = 36,567 \text{ m/s}$$

$$V(18) = V_{b,0} \sqrt{[c_e(18,0)]} = 47,297 \text{ m/s}$$

Reynolds numer:

$$Re(d, V) = d V(z) / \nu$$

$$Re(0,0) = d v(1,0) / \nu = 126,7 \cdot 10^6$$

$$Re(18,0) = d v(18,0) / \nu = 163,9 \cdot 10^6$$

$$Re_{average} = 145,3 \cdot 10^6 = 1,45 \cdot 10^8$$

EN 1991-1-4, tab. 7.12

Re	$\alpha_{\min}$	$c_{p,0\min}$	$\alpha_A$	$c_{p,0h}$
$5 \cdot 10^5$	$85^\circ$	-2,2	$125^\circ$	-0,4
$2 \cdot 10^6$	$80^\circ$	-1,9	$120^\circ$	-0,7
$1 \cdot 10^7$	$75^\circ$	-1,5	$105^\circ$	-0,8

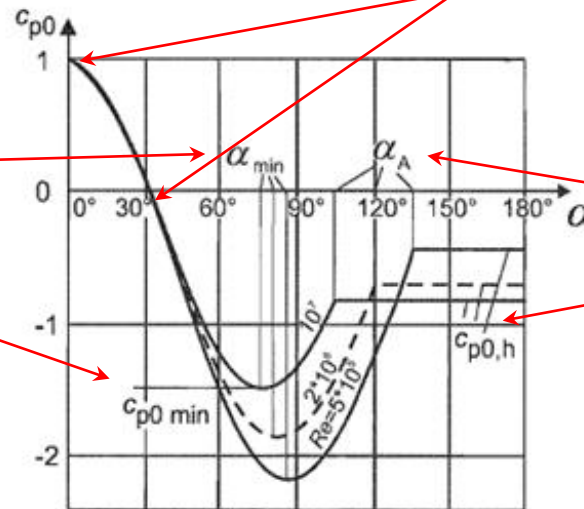
$Re_{\text{average}} = 1,45 \cdot 10^8 > 1,0 \cdot 10^7$

$Re_{\text{average}} > 1 \cdot 10^7$

$\alpha_{\min} = 85^\circ$

$c_{p,0\min} = -1,5$

constant



$Re_{\text{average}} > 1 \cdot 10^7$

$\alpha_A = 105^\circ$

$c_{p,0h} = -0,8$

Photo: EN 1991-1-4 fig. 7.27

End-effect factor  $\psi_\lambda(\alpha)$  – important for leeward part of cylinder; shows effects of moving of air around end of cylinder (quasi-laminar / turbulent). Factor changes its value around cylinder.

EN 1991-1-4 p.p. 7.9.1 and 7.13

For circular cylinders, EN 1991-1-4 p. 7.9.1.(4):

$$0^\circ \leq \alpha \leq \alpha_{\min} \rightarrow \psi_\lambda(\alpha) = 1,0$$

$$\alpha_{\min} \leq \alpha \leq \alpha_A \rightarrow \psi_\lambda(\alpha) = \psi_\lambda + (1 - \psi_\lambda) \cos [ (\pi / 2) (\alpha - \alpha_{\min}) / (\alpha_A - \alpha_{\min}) ]$$

$$\alpha_A \leq \alpha \leq 180^\circ \rightarrow \psi_\lambda(\alpha) = \psi_\lambda$$

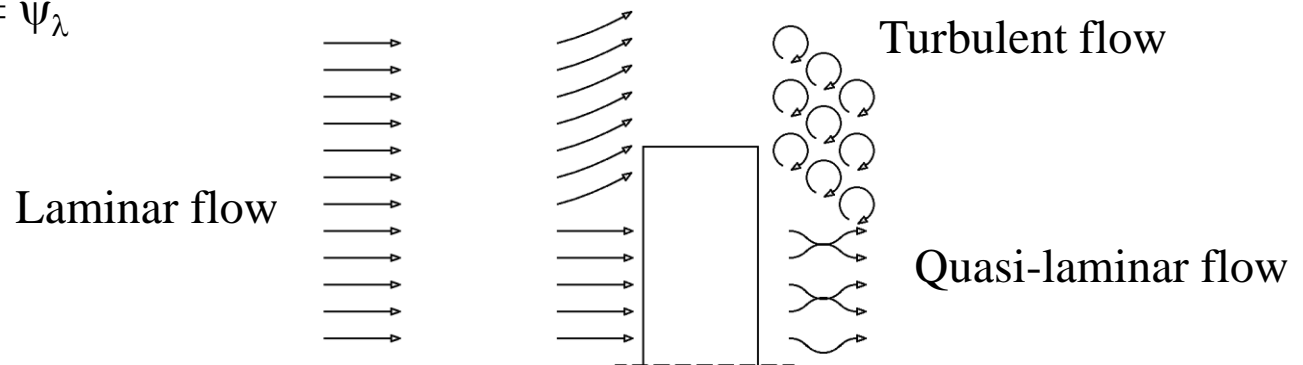


Photo: Author

End-effect factor  $\psi_\lambda(\alpha)$

EN 1993-1-4 p. 7.13

According to tab. 7.16:

$h < 15$  m:

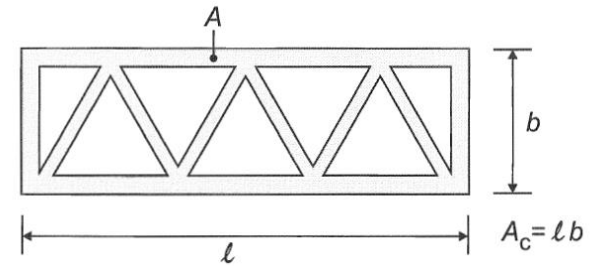
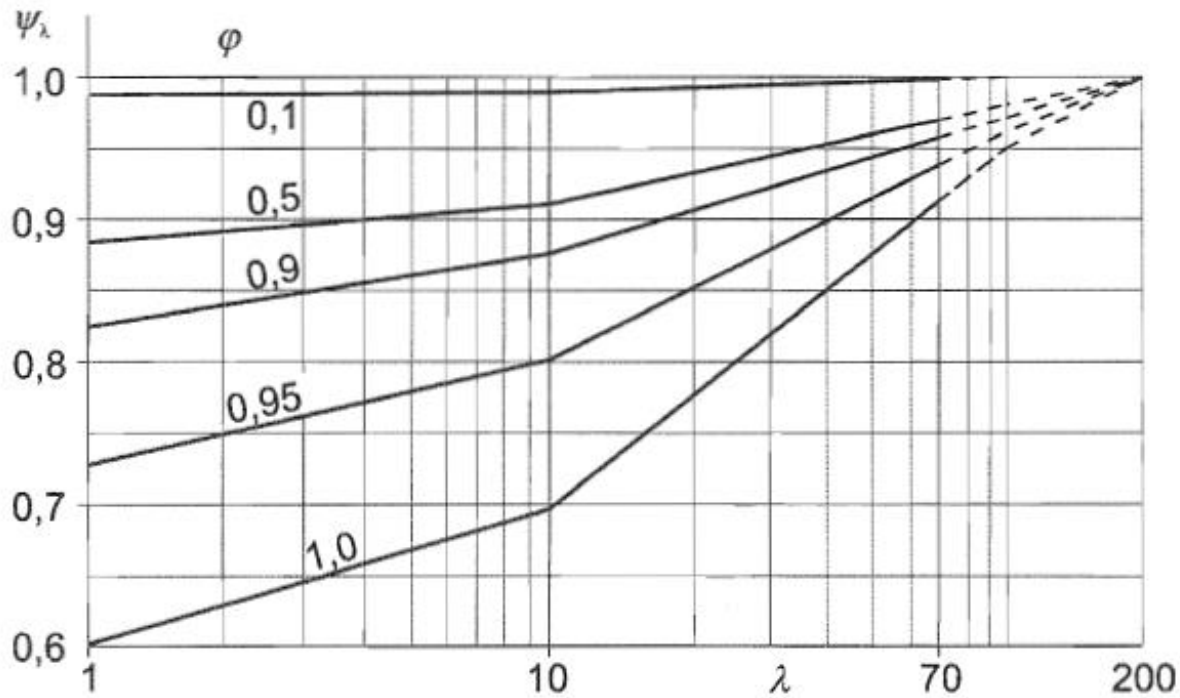
$$\lambda = \min(0,7 h / d ; 70) = 0,252$$

$h > 50$  m

$$\lambda = \min(h / d ; 70) = 0,360$$

$15 \text{ m} < h < 50 \text{ m} \rightarrow$  linear interpolation

Interpolation:  $h = 18 \text{ m} \rightarrow \lambda = 0,351$



Solidity ratio:

$$\phi = A / A_c = 1,0$$

$$\lambda = 0,351$$

But  $\lambda = 0,351 < 1,000 \rightarrow \lambda = 1,000$

$$\psi_\lambda = 0,60$$

$$\alpha_{\min} = 85^\circ, \alpha_A = 105^\circ (\rightarrow \#t / 23)$$

Approximation of  $c_{p,0}$  ( $\rightarrow \#t / 23$ ):

$$0^\circ \leq \alpha \leq 30^\circ \rightarrow c_{p,0} = \cos (3 \alpha)$$

$$30^\circ \leq \alpha \leq 85^\circ \rightarrow c_{p,0} = c_{p,0\min} \sin (\alpha_1) \quad ; \quad \alpha_1 = 90^\circ (\alpha - 30^\circ) / (85^\circ - 30^\circ) = 1,636 (\alpha - 30^\circ)$$

$$85^\circ \leq \alpha \leq 105^\circ \rightarrow c_{p,0} = c_{p,0h} + C \sin (\alpha_2) \quad ; \quad \alpha_2 = 90^\circ [1 - (\alpha - 85^\circ) / (105^\circ - 85^\circ)]$$

$$105^\circ \leq \alpha \leq 180^\circ \rightarrow c_{p,0} = c_{p,0h}$$

Additionally:

$$0^\circ \leq \alpha \leq 85^\circ \rightarrow \psi_\lambda(\alpha) = 1,0$$

$$85^\circ \leq \alpha \leq 105^\circ \rightarrow \psi_\lambda(\alpha) = \psi_\lambda + (1 - \psi_\lambda) \cos [ (\pi / 2) (\alpha - 85^\circ) / (105^\circ - 85^\circ) ]$$

$$105^\circ \leq \alpha \leq 180^\circ \rightarrow \psi_\lambda(\alpha) = \psi_\lambda$$

$$\psi_\lambda = 0,60$$

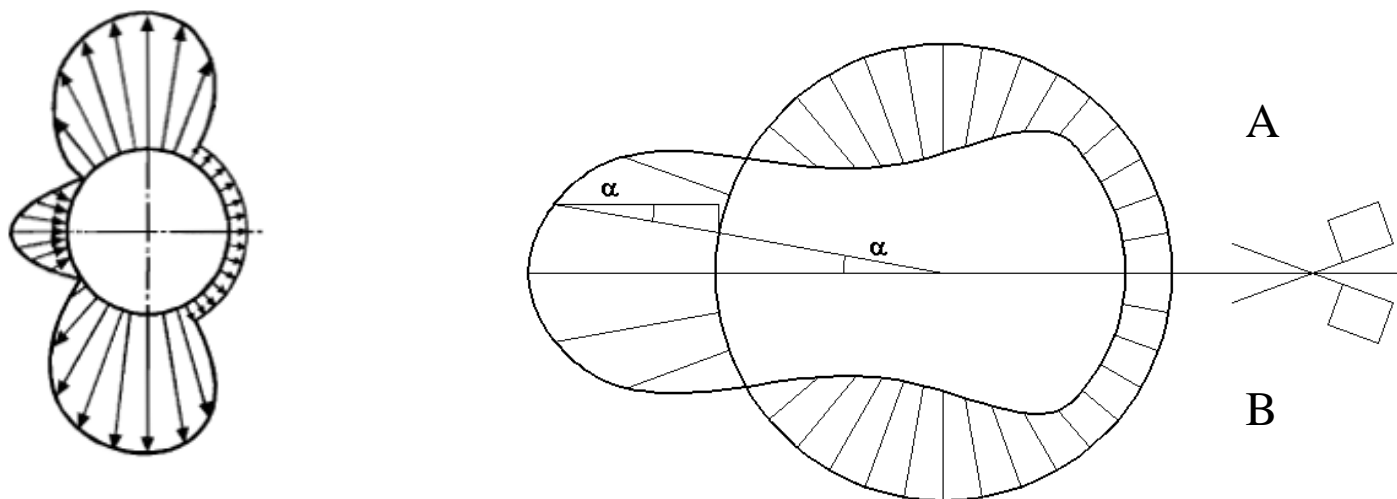


Photo: Author

Aerodynamical factor for radial loads:  $c_{\text{radial}} = c_{p,0}(\alpha) \psi_{\lambda}(\alpha)$

Aerodynamic factor for loads parallel to wind direction:

$$\begin{aligned}
 c &= c(A) + c(B) = |\text{symmetry}| = 2 c(A) = \\
 &= 2 \int_0^{180} [c_{\text{radial}}(\alpha) \cos \alpha] d\alpha = 2 \int_0^{180} [c_{p,0}(\alpha) \psi_{\lambda}(\alpha) \cos \alpha] d\alpha
 \end{aligned}$$

z [m]

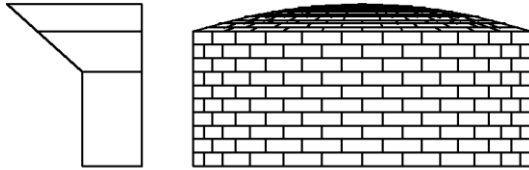


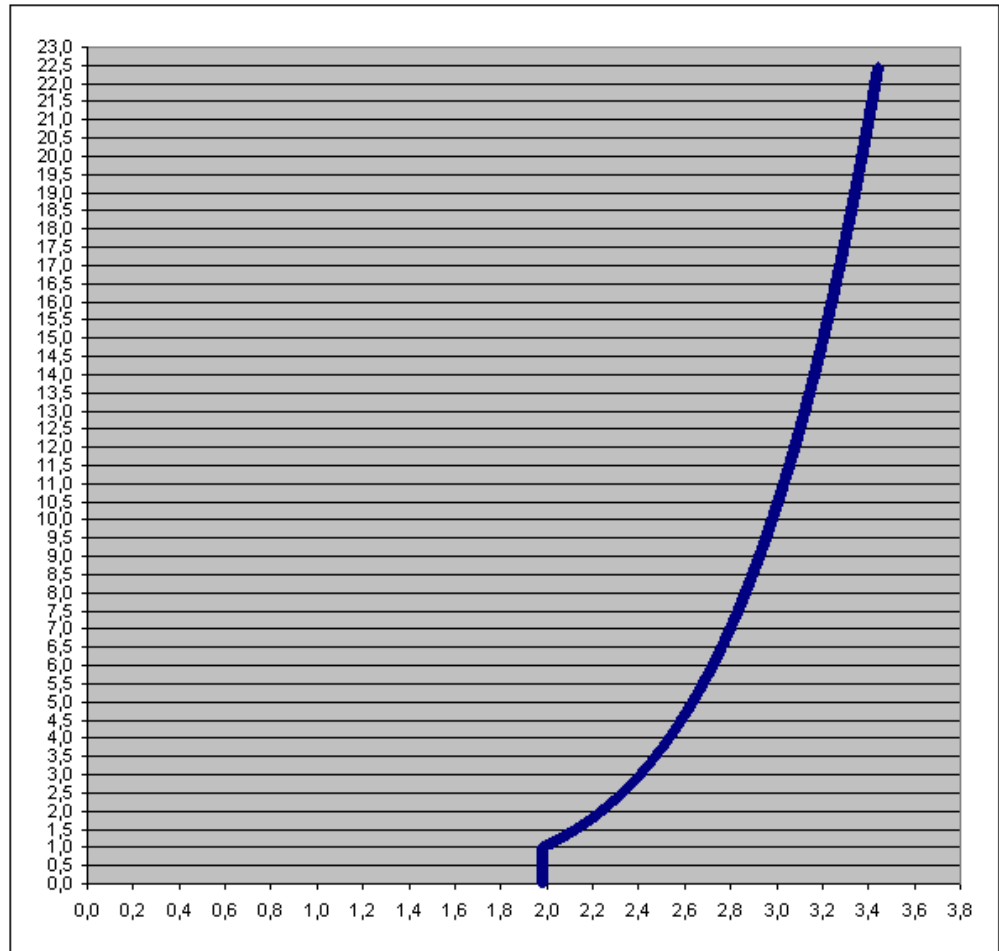
Photo: Author

Vertical profile:

$$q_p = q_{b,0} c_{dir} c_{season} c_e(z) =$$

$$= 0,42 \text{ kPa} \cdot 2,98 (z / 10)^{0,176} \text{ for } z > z_{\min} = 1,0 \text{ m}$$

$$= 0,42 \text{ kPa} \cdot 2,98 (1 / 10)^{0,176} \text{ for } z \leq z_{\min} = 1,0 \text{ m}$$



$c_e$

Products: horizontal force parallel to wind direction; integration of vertical profile and integration around cylinder:

$$W = 1,65 \int_0^h \left\{ 2 \int_0^{180} [c_{p,0}(\alpha) \psi_\lambda(\alpha) \cos \alpha] d\alpha \right\} q_{b,0} c_{dir} c_{season} c_e(z) dz$$

$$M(W, 0) = 1,65 \int_0^h \left\{ 2 \int_0^{180} [c_{p,0}(\alpha) \psi_\lambda(\alpha) \cos \alpha] d\alpha \right\} q_{b,0} c_{dir} c_{season} z c_e(z) dz$$

For analysed case:

$$W = 686,253 \text{ kN}$$

$$y = M(W, 0) / W = 12,099 \text{ m}$$

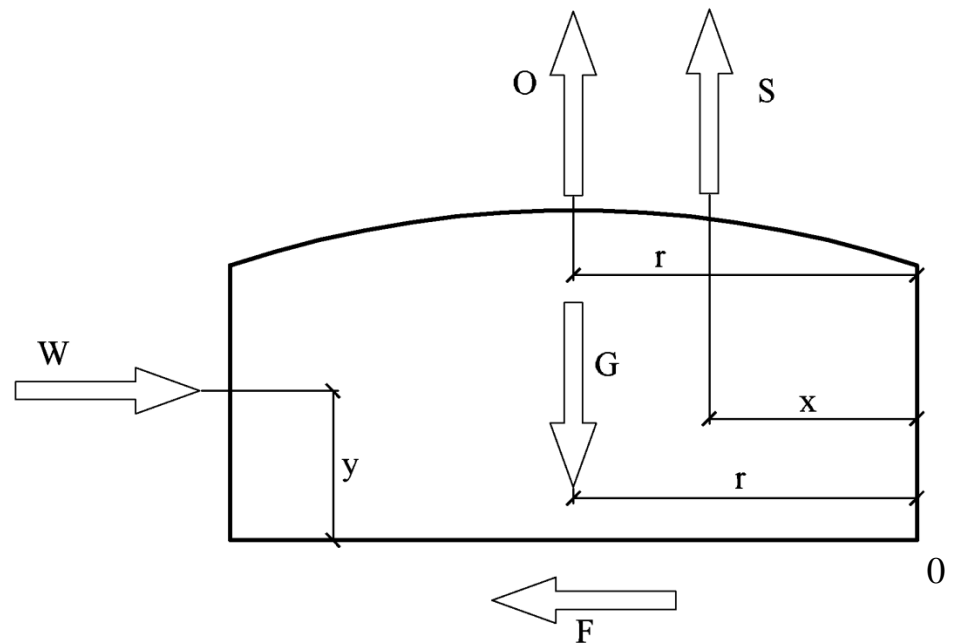


Photo: Author

# Dome

$$r = 26 \text{ m} \rightarrow d = 52 \text{ m}$$

$$h = 18 \text{ m}$$

$$r_1 = 78 \text{ m}$$

$$f = 4,461 \text{ m}$$

$$h / d = 0,346$$

$$f / d = 0,086$$

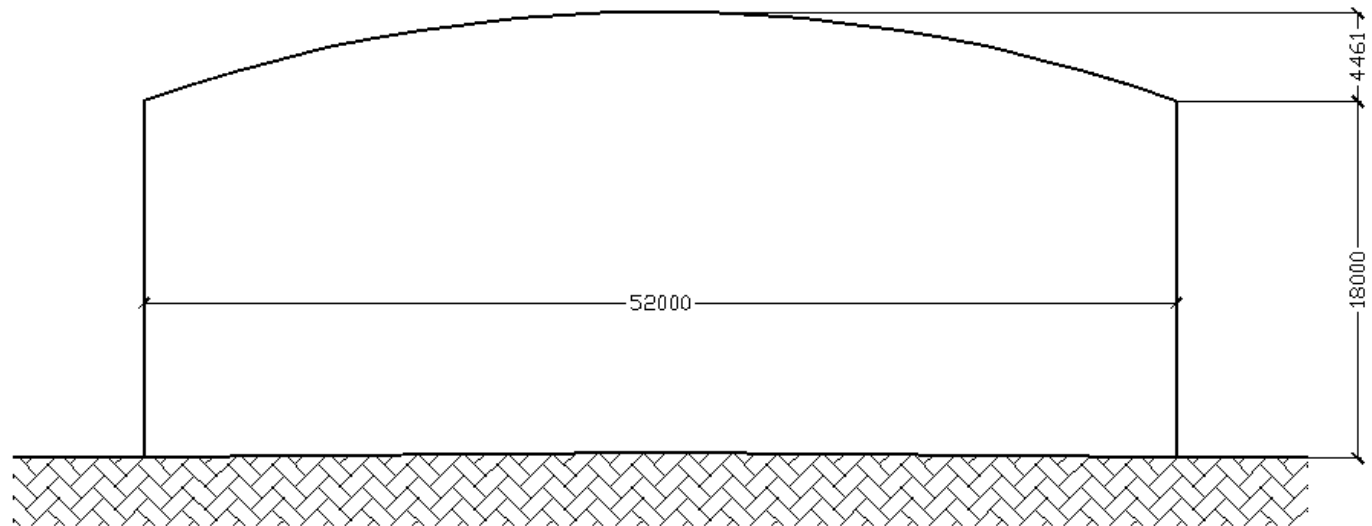


Photo: Author

Photo: EN 1991-1-4 fig. 7.12

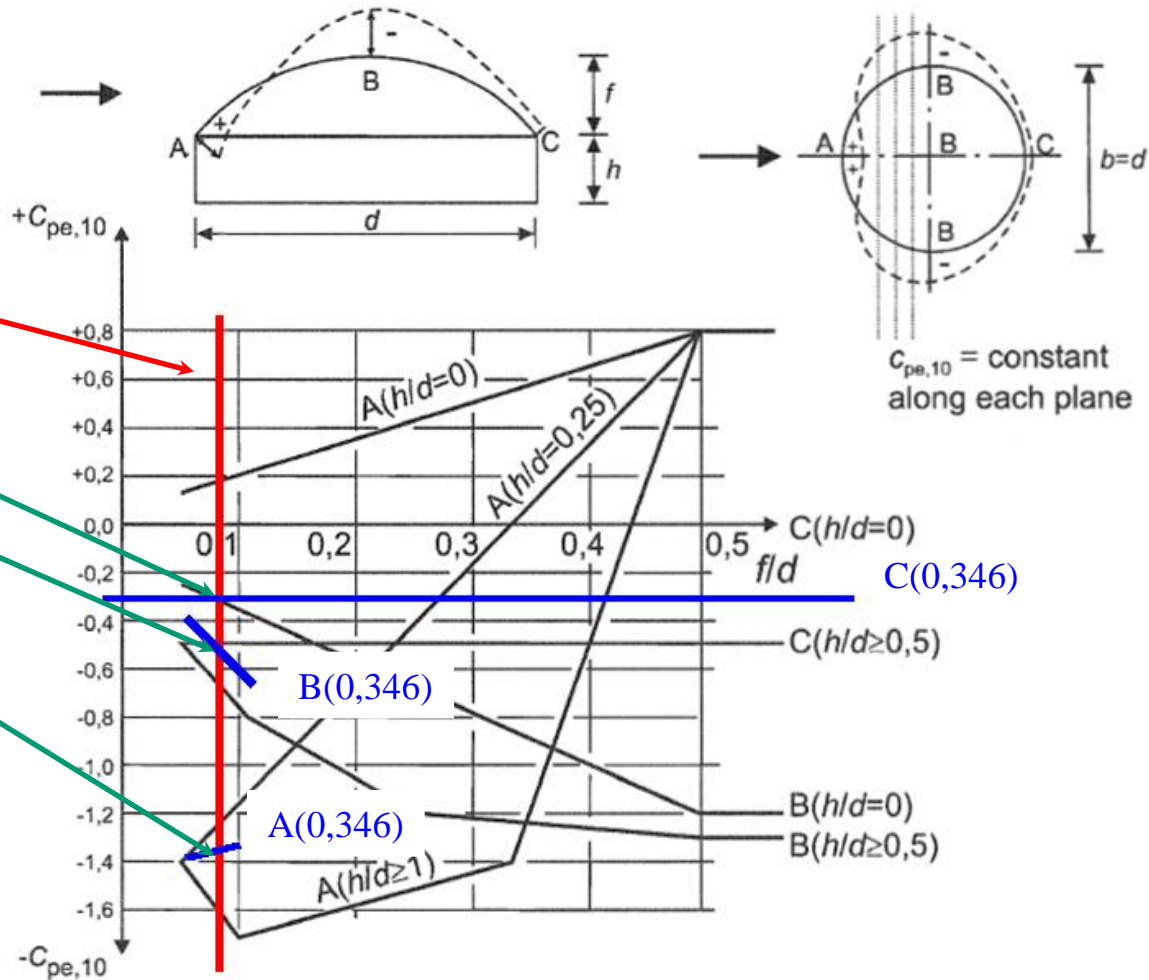
$h / d = 0,346$

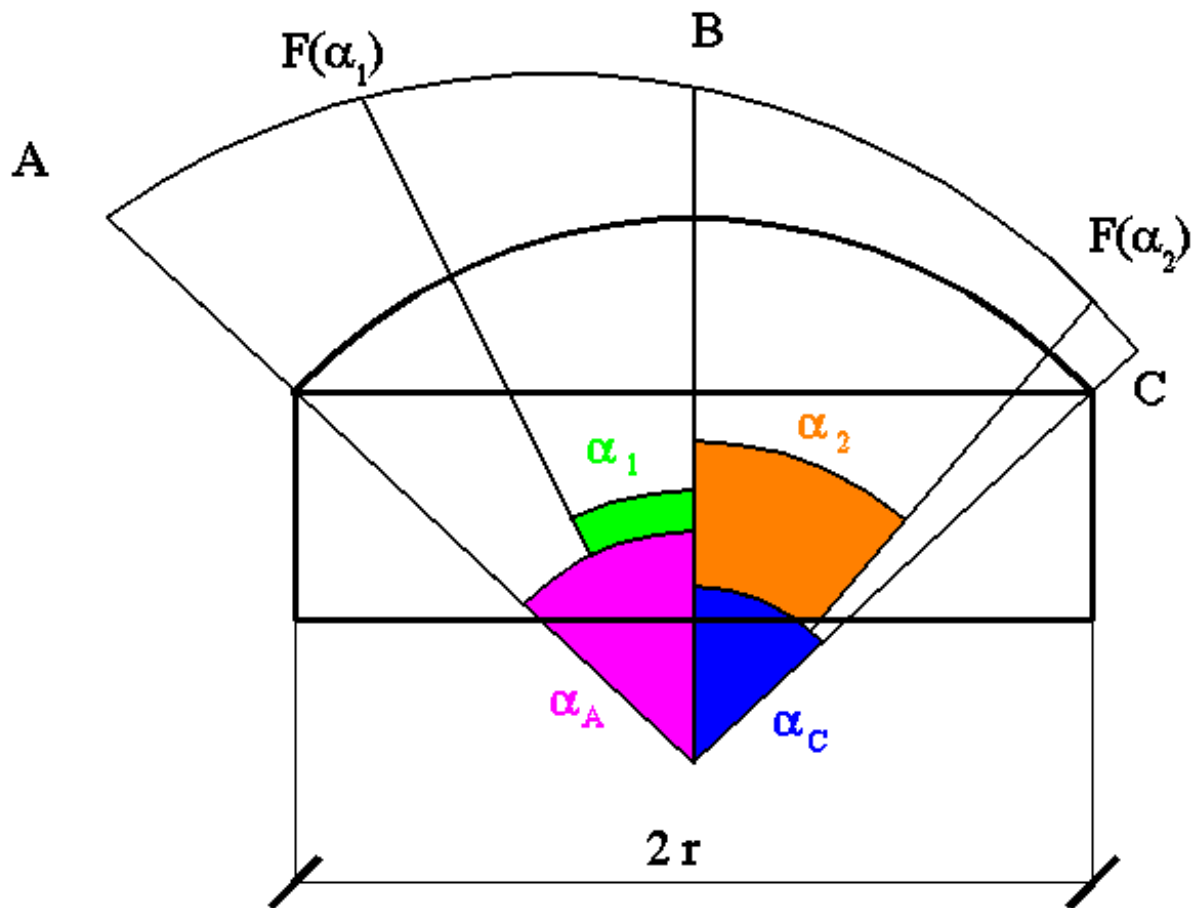
$f / d = 0,086$

$C \approx -0,3$

$B \approx -0,5$

$A \approx -1,3$





Symbols

Photo: Author

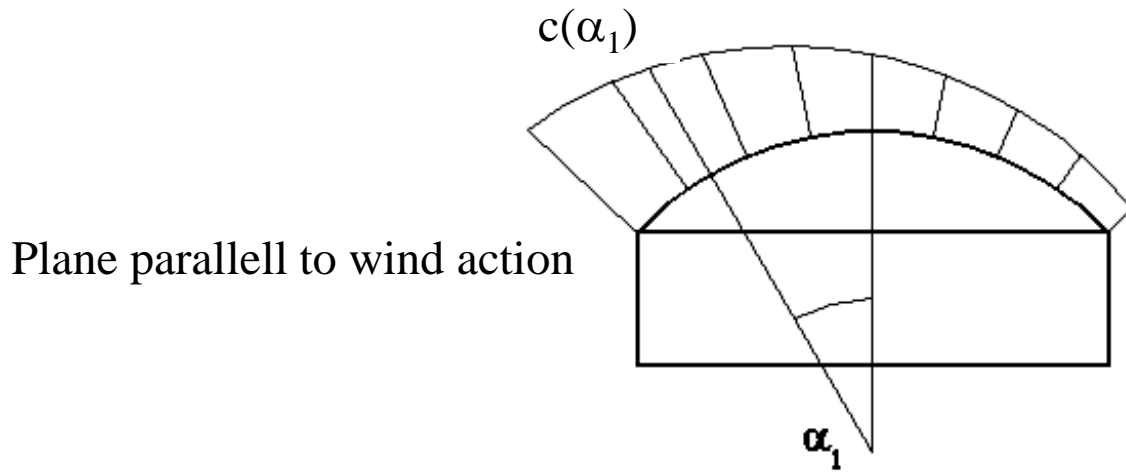
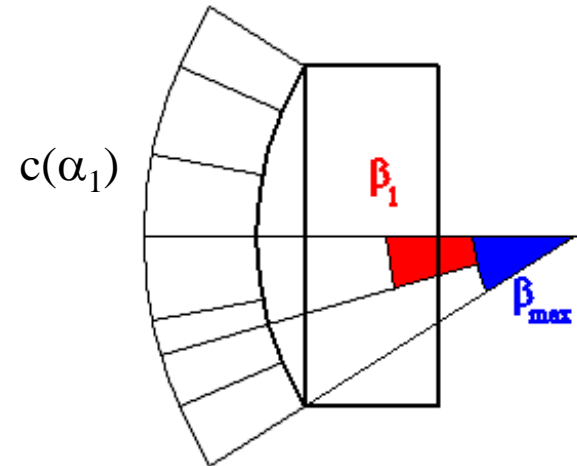


Photo: Author

Plane perpendicular to wind action in  $\alpha = \alpha_1$



Vertical component:

$$c_v(\alpha, \beta) = \sum c(\alpha_1) \cos \alpha_1 \cos \beta_1 = \int_{\alpha} \int_{\beta} [c(\alpha, \beta)] d\alpha d\beta$$

$$c_v = \int_0^{\alpha-A} [2 r_1 c_{A1} (\alpha_1) \sin (\beta_{\max})] d\alpha_1 + \int_0^{\alpha-C} [2 r_1 c_{A2} (\alpha_2) \sin (\beta_{\max})] d\alpha_2$$

$$\sin \beta_{\max} = \sqrt{[(\sin \alpha_A)^2 - (\cos \alpha_A \sin \alpha_1)^2]} = \sqrt{[(\sin \alpha_A)^2 - (\cos \alpha_A \sin \alpha_2)^2]}$$

$$c_{A1} (\alpha_1) = c (\alpha_1) \cos \alpha_1$$

$$c_{A2} (\alpha_2) = c (\alpha_2) \cos \alpha_2$$

$$c(\alpha_1) = -2,352 \alpha_1 - 0,500$$

$$c(\alpha_2) = 0,588 \alpha_2 - 0,500$$

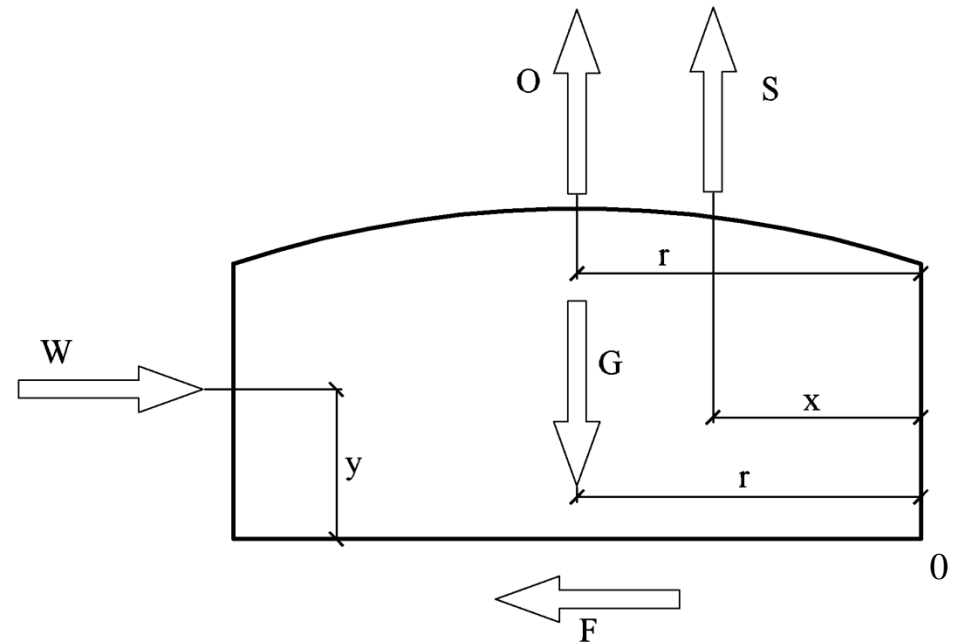


Photo: Author

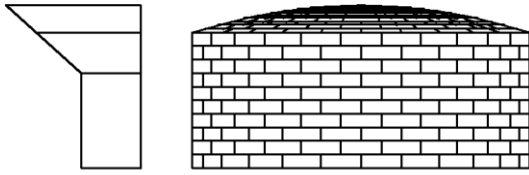


Photo: Author

Vertical profile:

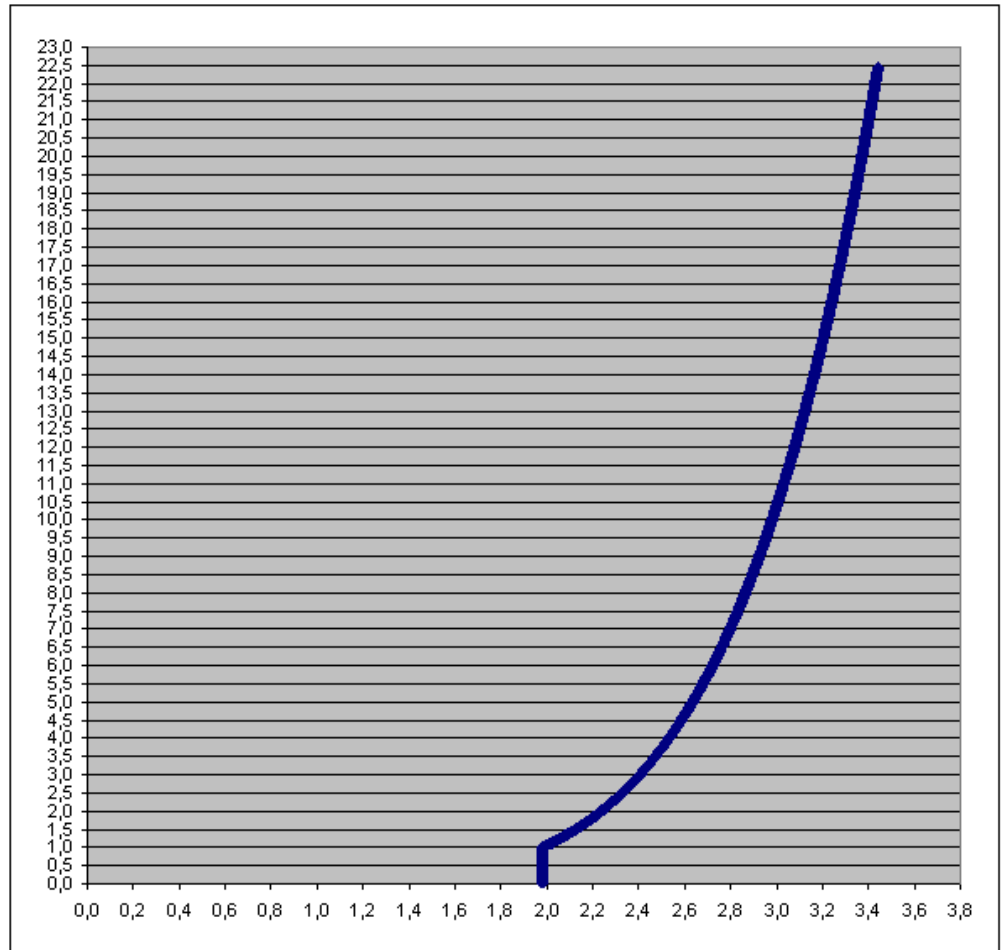
$$c_e(18,0) = 3,309$$

$$c_e(22,46) = 3,342$$

Small difference, linearisation to average value:

$$c_{e\text{-average}} = 3,326$$

$$q_p = q_{b,0} c_{dir} c_{season} = 0,42 \text{ kPa}$$



$$S = 1,65 c_v c_{e\text{-average}} q_p$$

$$c_v = \int_0^{\alpha-A} [2 r_1 c_{A1} (\alpha_1) \sin (\beta_{\max})] d\alpha_1 + \int_0^{\alpha-C} [2 r_1 c_{A2} (\alpha_2) \sin (\beta_{\max})] d\alpha_2$$

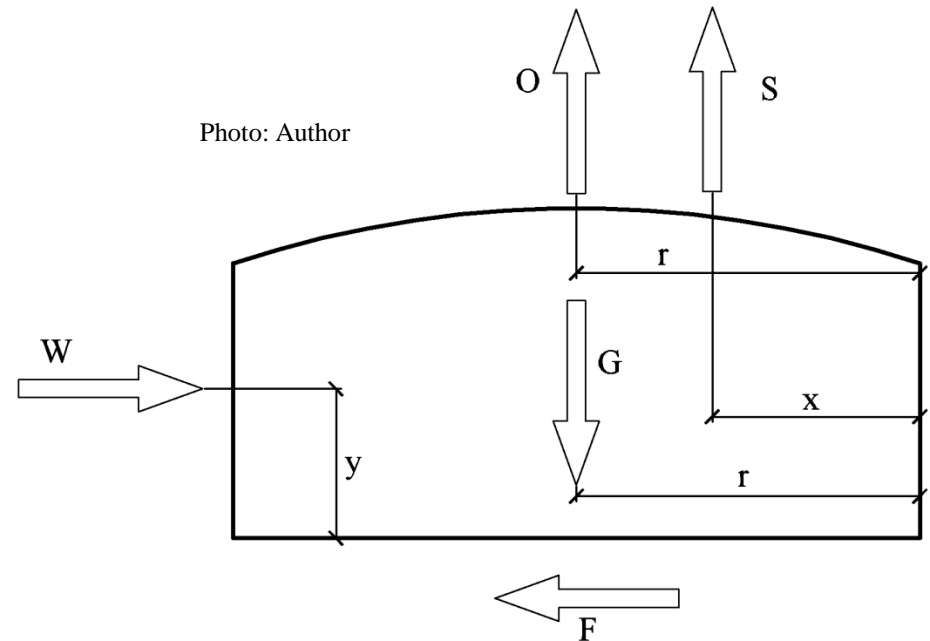
$$\sin \beta_{\max} = \sqrt{[(\sin \alpha_A)^2 - (\cos \alpha_A \sin \alpha_1)^2]} = \sqrt{[(\sin \alpha_A)^2 - (\cos \alpha_A \sin \alpha_2)^2]}$$

$$x = \left\{ \int_0^{\alpha-A} [2 r_1 c_{A1} (\alpha_1) \sin (\beta_{\max}) z_1] d\alpha_1 + \int_0^{\alpha-C} [2 r_1 c_{A2} (\alpha_2) \sin (\beta_{\max}) z_2] d\alpha_2 \right\} / c_v$$

For analysed case:

$$S = 2\,208,788 \text{ kN}$$

$$x = 31,597 \text{ m}$$



## Snow load

Hel, seashore → EN 1991-1-3 NA:

$$c_e = 0,8$$

$$s_k = \max ( 0,006 A - 0,6 \ ; \ 1,2 \text{ kPa} ) = 1,2 \text{ kPa}$$

Roof shape:  $f / d = 0,086 \rightarrow$  EN 1991-1-3 fig. 5.5:

$$\mu_3 = 1,2$$

$$\mu = \max ( 0,8 \ ; \ \mu_3 ) = 1,2$$

$$s_d = 1,65 \mu s_k c_e = 1,901 \text{ kPa}$$

## Rest loads

Overpressure:  $p_{\text{over, k}} = 1,0 \text{ kPa}$

$$p_{\text{over, d}} = 1,65 \cdot 1,0 \text{ kPa} = 1,650 \text{ kPa}$$

Underpressure:  $p_{\text{under, k}} = 0,5 \text{ kPa}$

$$p_{\text{under, d}} = 1,65 \cdot 0,5 \text{ kPa} = 0,825 \text{ kPa}$$

Liquid density → EN 1991-1-1 tab. A.10:

$$\rho_{\text{d, k}} = 8,3 \text{ kN} / \text{m}^3 \quad \rho_{\text{H}_2\text{O, k}} = 10 \text{ kN} / \text{m}^3$$

$$\rho_{\text{d, d}} = 1,45 \cdot 8,3 \text{ kN} / \text{m}^3 = 12,035 \text{ kN} / \text{m}^3 \quad \rho_{\text{H}_2\text{O, d}} = 1,00 \cdot 10 \text{ kN} / \text{m}^3 = 10,0 \text{ kN} / \text{m}^3$$

Temperture (Hel, seashore) → EN 1991-1-5 fig. NB.3:

$$T_{\text{min}} = -26 \text{ }^\circ\text{C}$$

$$\text{Corrosion} = 0,1 \text{ mm} \cdot 50 \text{ years} = 5 \text{ mm}$$

## Loadbearing of roof

$$p_{0,Ed} = \text{max wind suction on roof} + \text{overpressure} = \text{wind suction in point A} + \text{overpressure} = \\ = 2,006 \text{ kPa} + 1,650 \text{ kPa} = 3,656 \text{ kPa}$$

$$p_{0,Ed} r_1 / (2 j f_{y,d}) \leq t$$

**Steel S235 (initial assumption)**

j – butt welds : 1,0:

$$t \geq 5 \text{ mm}$$

$$p_{0,Ed} r_1 / (2 j f_{y,d}) = 0,6 \text{ mm}$$

Roof thickness > 5 mm

## Stability of roof

Unstiffened roof shell

$$4 r_1 \sqrt{(p_{i,Ed} / E)} \leq t$$

$p_{i,Ed}$  = dead weight of roof (10 mm taken into consideration) + snow load +  
underpressure + max wind pressure on roof =

$$= 1,35 \cdot 0,785 \text{ kN/m}^2 + 1,905 \text{ kN/m}^2 + 0,825 \text{ kN/m}^2 + 0,000 \text{ kN/m}^2 = 4,320 \text{ kPa}$$

$$4 r_1 \sqrt{(p_{i,Ed} / E)} = 0,043 = 43 \text{ mm}$$

Roof thickness should be non less than 43 mm.

**If roof thickness should be bigger than 10-15 mm → recommended solution is applying complex of rafters inside tank and thickness comes from loadbearing (10 mm)**



Photo: artson.net

This solution (sometimes with complex of columns inside tank) is adopted in case of very large tanks.

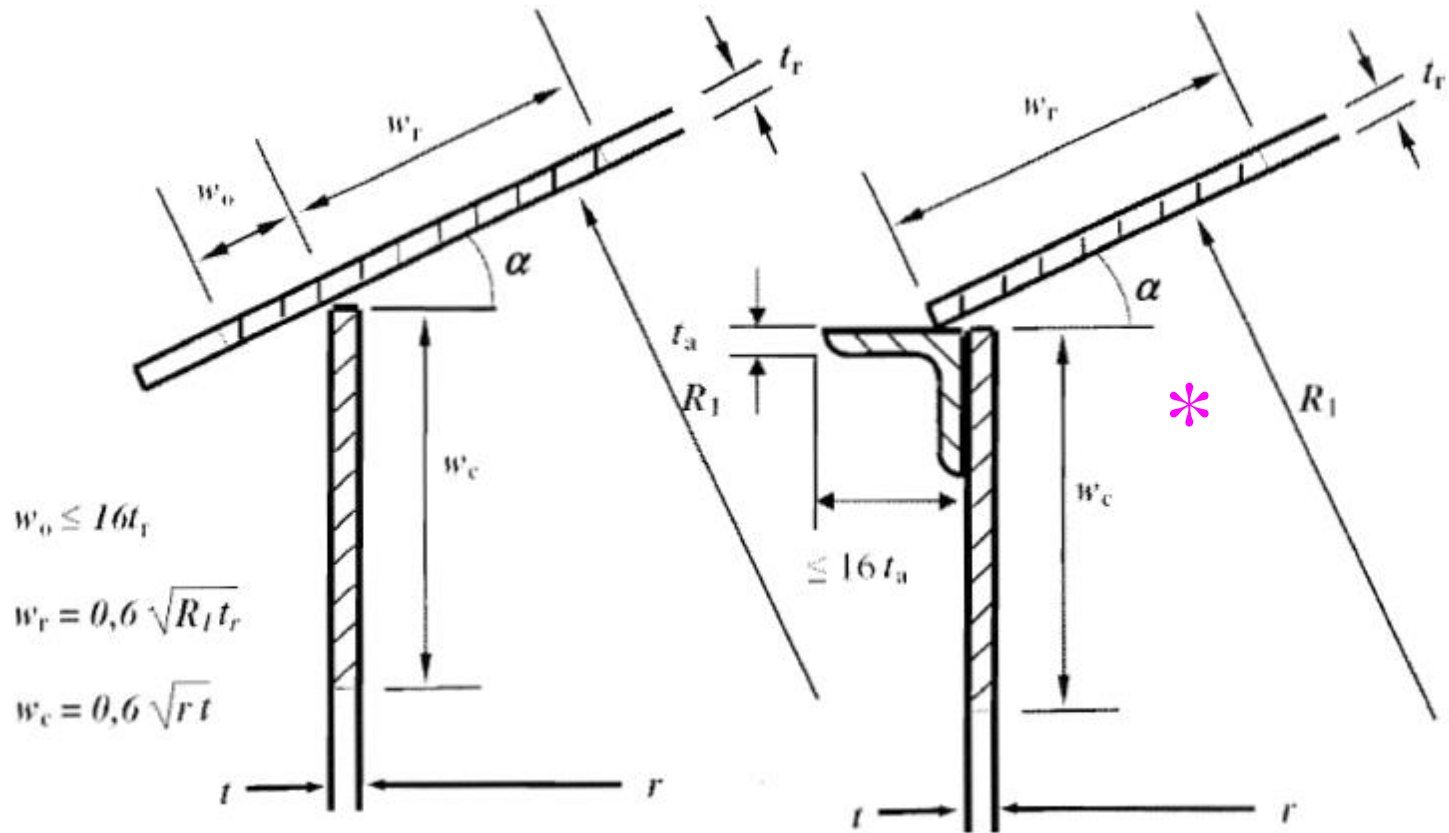
Photo: tiwsteelplatework.ca



Analised case: roof thickness 10 mm with rafters (rafters are out of range of project)

## Edge ring - loadbearing

Effective area of edge ring  $A_{\text{eff}}$



$t_r = 10 \text{ mm}$

Photo: EN 1993-4-2 fig. 11.4, EN 14 015 fig. 8

$t$  = thickness of the highest shell ring.

Tank diameter [m]	Recommended minimum shell thickness $t_{\min}$ [mm]	
	Carbon and carbon- manganese steels	Stainless steels
$D < 4$	5	2
$4 \leq D < 10$	5	3
$10 \leq D < 15$	5	4
$15 \leq D < 30$	6	5
$30 \leq D < 45$	8	6
$45 \leq D < 60$	8	-
$60 \leq D < 90$	10	-
$90 \leq D$	12	-

EN 14 015 tab. 16

Recommended additional L-section:

→ Des #1 / 38

Tank diameter [m]	Minimum L-section
$D \leq 10$	60 x 60 x 6
$10 < D \leq 20$	60 x 60 x 8
$20 < D \leq 36$	80 x 80 x 10
$36 < D \leq 48$	100 x 100 x 12
$48 < D$	150 x 150 x 12

EN 14 015 tab. 18

$$t_r = 10 \text{ mm}$$

$$t = 8 \text{ mm}$$

$$R_1 = 78 \text{ m}$$

$$R = 26 \text{ m}$$

$$A_{L200 \times 200 \times 20} = 76,4 \text{ cm}^2$$

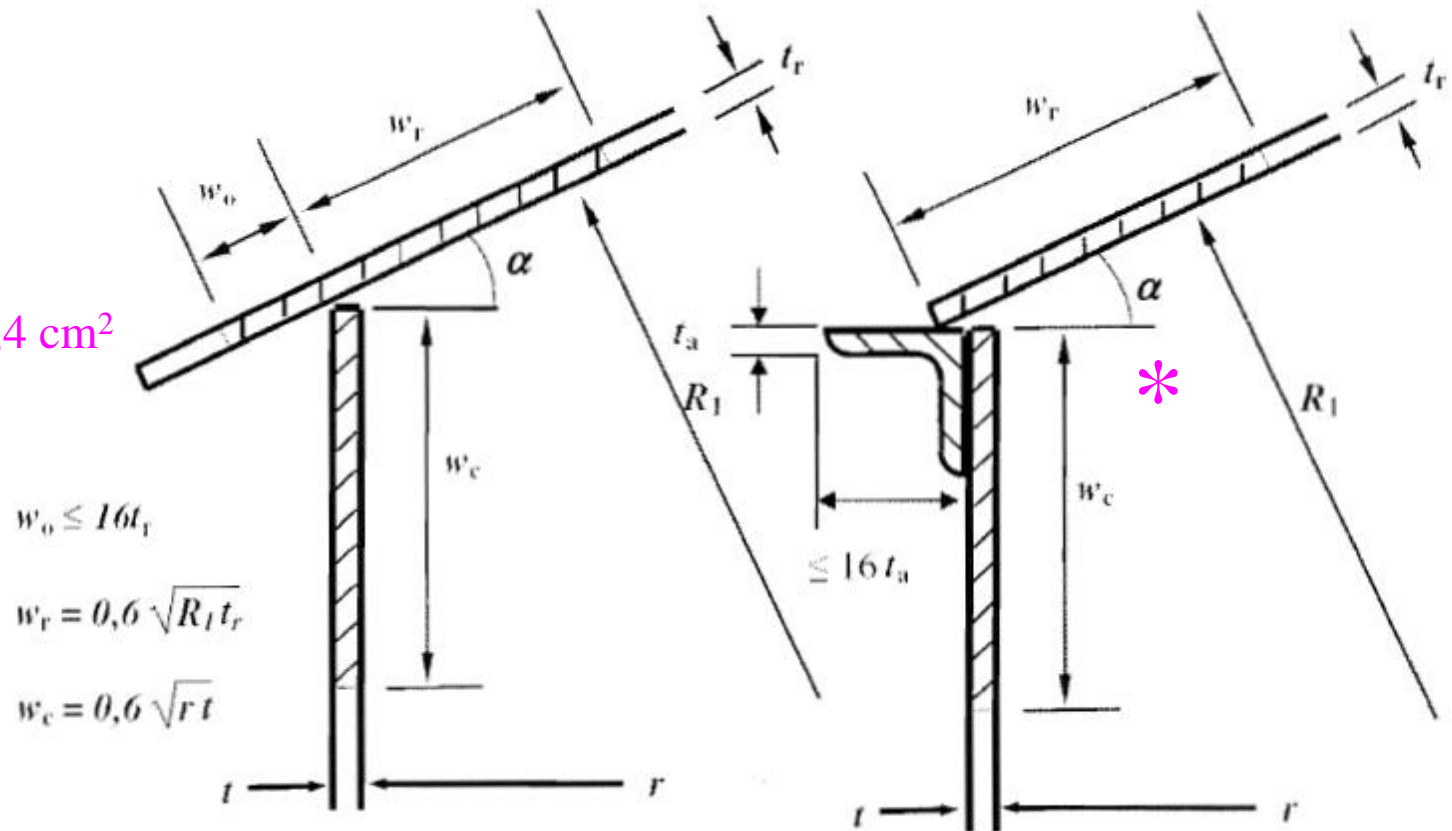


Photo: EN 1993-4-2 fig. 11.4, EN 14 015 fig. 8

$$w_r = 0,6 \cdot \sqrt{(78 \cdot 0,010)} = 530 \text{ mm}$$

$$w_c = 0,6 \cdot \sqrt{(26 \cdot 0,008)} = 274 \text{ mm}$$

$$N_{Ed} / (A_{eff} f_{y,d}) \leq 1,0 \quad (\text{is additional L-section needed or not}) \quad \text{EN 1993-4-2 (11.17)}$$

$$N_{Ed} = p_{v,Ed} r^2 / (2 \operatorname{tg} \alpha) \quad \text{EN 1993-4-2 (11.18)}$$

$$p_{v,Ed} = \max (\text{dead weight of roof} + \text{snow} + \text{underpressure} + \text{max wind pressure on roof} ; \\ \text{max wind suction on roof} + \text{overpressure}) = \max (4,320 ; 3,656) = 4,320 \text{ kPa}$$

$$A_{eff} = 1 \cdot 53 + 0,8 \cdot 27,4 + 76,4 = 151,32 \text{ cm}^2$$

$$N_{Ed} = 2\,920,320 \text{ kN}$$

Steel S235:

$$N_{Ed} / A_{eff} f_{y,d} = 2\,920,320 / 3\,556,020 = 0,821 < 1,0$$

## Loadbearing of shell

	Water test	Exploitation
EN 1993-4-2 (11.21)	$\gamma_{f1} r \rho_{H_2O,k} (H_j - \Delta) / f_{y,d}$	corr.+ $r [\gamma_{f2} \rho_{d,k} (H_j - \Delta) + \gamma_{f3} p_{over,k}] / f_{y,d}$
Safety factors	$\gamma_{f1} = 1,0$ (for CC2 and CC3)	$\gamma_{f2} = 1,40$ (for CC2) ; $1,55$ (for CC3) $\gamma_{f1} = 1,50$ (for CC2) ; $1,65$ (for CC3)
EN 14 015 (3), (4)	$4 r \rho_{H_2O} (H_j - \Delta) / (3 f_{y,d})$	corr.+ $3 r [\rho_d (H_j - \Delta) + p_{over}] / (2 f_{y,d})$
Safety factors	1,33	1,50
Conclusions	Safety factor for EN 14 015 is 33% bigger than safety factor for EN 1993-4-2. Taking into account EN 14 015 leads to oversizing of tank and may be omitted.	Safety factor for EN 14 015 is similar to safety factors for EN 1993-4-2 for CC2 and CC3. EN 14 015 will be taken into consideration.

$$\Delta = 0,3 \text{ m}$$

H [m]	$t_{min}$ [mm]	t (EN 1993, water) [mm]	t (EN 14015, water) [mm]	t (EN 1993, diesel) [mm]	t (EN 14015, diesel) [mm]	Final value [mm]
0	8,0	0,0	0,0	5,2	5,2	8,0
2	8,0	1,9	2,5	7,9	7,8	8,0
4	8,0	4,1	5,5	11,4	11,1	12,0
6	8,0	6,3	8,4	14,8	14,5	15,0
8	8,0	8,5	11,4	18,2	17,8	18,0
10	8,0	10,7	14,3	21,6	21,1	22,0
12	8,0	12,9	17,3	25,1	24,4	26,0
14	8,0	15,2	20,2	28,5	27,7	29,0
16	8,0	17,4	23,2	31,9	31,1	32,0
18	8,0	19,6	26,1	35,4	34,4	36,0

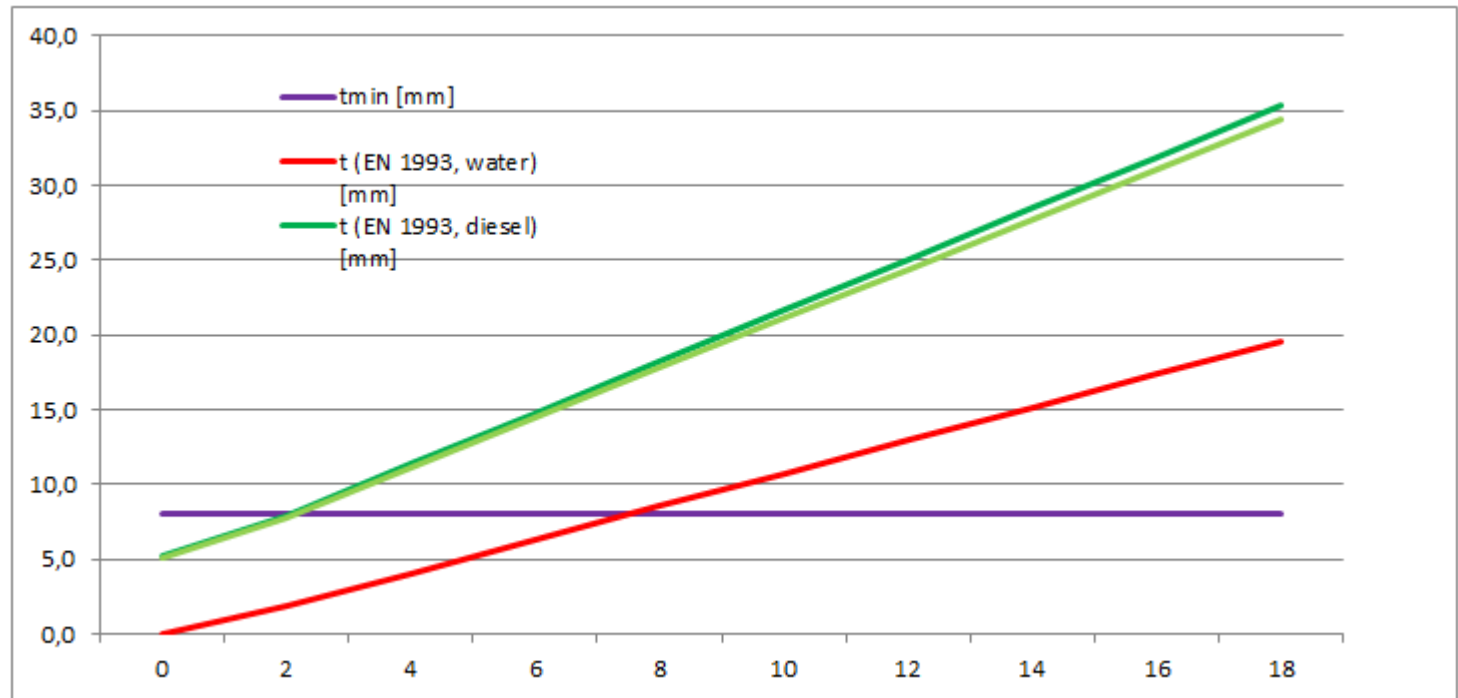


Photo: Autor

## Stability of shell

$H_E$  - part of shell in danger of buckling

$H_p$  - self-stability high of shell

Stability is satisfied, when

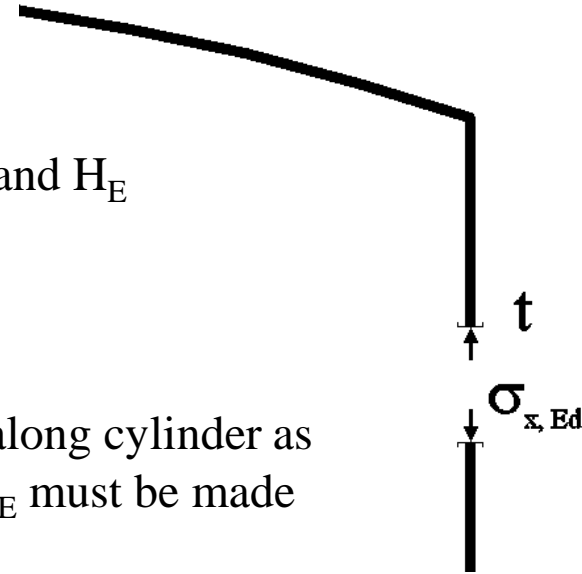
$$H_p > H_E$$

	$H_E$	$H_p$
EN 1993-4-2	$H_E = \sum h_i (t_{\min} / t_i)^{2,5}$	$0,46 (E / p_{Ed}) (t_{\min} / r)^{2,5} r K$
EN 14 015		$[A / (5,70 q_{\text{wind}} + 5,80 p_{\text{under}})] \sqrt{[t_{\min}^5 / (2 r)^3]}$

$$K = 1 - \{2,67 [\sigma_{x,Ed} / E] [r / t] [1 + (r / t)^{0,72} / 54]^{1,25} \}^{0,8}$$

EN 14 015 – one global comparison between  $H_P$  and  $H_E$

EN 1993-4-2 – parameter K depends on position along cylinder as function of  $\sigma_{x,Ed}$ . Comparison between  $H_P$  and  $H_E$  must be made for bottom edge of each cylindrical rings.



H [m]	t_max	t_real
0-2	8,0	8,0
2-4	11,4	12,0
4-6	14,8	15,0
6-8	18,2	18,0
8-10	21,6	22,0
10-12	25,1	26,0
12-14	28,5	29,0
14-16	31,9	32,0
16-18	35,4	36,0

Photo: Author

## EN 14 015 – rough analysis

$$A = 3\,004 \text{ GPa}$$

$$p_{\text{under, d}} = 0,825 \text{ kPa}$$

$$q_{\text{wind, d}} = 2,290 \text{ kPa}$$

$$r = 26,000 \text{ m}$$

$$t_{\text{min}} = 8 \text{ mm}$$

$$H_P = [A / (5,70 q_{\text{wind, d}} + 5,80 p_{\text{under}})] \sqrt{[t_{\text{min}}^5 / (2 r)^3]} = 2,572 \text{ m}$$

$$H_E = 3,858 \text{ m}$$

$$H_P = 2,572 \text{ m} < H_E = 3,858 \text{ m} \quad \text{WRONG, instability}$$

Calculations according to EN 14 015 are rough checking of stability condition. Because of problems, new values of shell thicknes will be adopted.

H [m]	t_max	t_real
0-2	8,0	15,0
2-4	11,4	15,0
4-6	14,8	15,0
6-8	18,2	18,0
8-10	21,6	22,0
10-12	25,1	26,0
12-14	28,5	29,0
14-16	31,9	32,0
16-18	35,4	36,0

8,0

12,0

$$H_E = 9,451 \text{ m}$$

$$H_P = 12,380 \text{ m}$$

$$H_P = 12,380 \text{ m} > H_E = 9,451 \text{ m} \text{ OK}$$

## Accurate calculation according to EN 1993-4-2

Total snow load on roof<sub>d</sub> :  $26 \cdot 26 \cdot \pi \cdot 1,901 = 4\,037,185 \text{ kN}$

Total underpressure on roof<sub>d</sub> :  $26 \cdot 26 \cdot \pi \cdot 0,825 = 1\,752,066 \text{ kN}$

Roof weight (only panels  $t = 10 \text{ mm}$ )<sub>k</sub> =  $2 \pi r_1 f t \cdot 1,35 \cdot 78,5 = 2\,548,382 \text{ kN}$

$q_{x,Ed}$  = dead weight of steel structure + snow + underpressure + max wind pressure on roof =  
=  $(1,5 \cdot 2\,548,382 \text{ kN} + 4\,037,185 \text{ kN} + 1\,752,066 \text{ kN} + 0,000) = 9\,611,824 \text{ kN}$

$C_w = \max (1,0 ; 2,2 / \{1 + 0,1 \sqrt{[0,6 r / h \sqrt{(r / t_{\min})}]}\}) = \max (1,0 ; 1,292) = 1,0$

$q_{Ed} = q_{Ed \max} / C_w = q_{Ed \max} = 1,387 \text{ kPa}$

$p_{Ed} = p_{\text{under}} + q_{Ed} = 2,212 \text{ kPa}$

H [m]	t_max	t_real
0-2	8,0	15,0
2-4	11,4	15,0
4-6	14,8	15,0
6-8	18,2	18,0
8-10	21,6	22,0
10-12	25,1	26,0
12-14	28,5	29,0
14-16	31,9	32,0
16-18	35,4	36,0

H [m]	H_E	H_p
0-2	2,000	2,704
2-4	4,000	2,400
4-6	6,000	2,099
6-8	7,268	4,177
8-10	8,036	5,740
10-12	8,541	6,609
12-14	8,926	6,998
14-16	9,227	7,280
16-18	9,451	7,582

$H_p > H_E$  OK one time only

## Recalculation

H [m]	t_max	t_real	
0-2	8,0	20,0	15,0
2-4	11,4	20,0	15,0
4-6	14,8	20,0	15,0
6-8	18,2	20,0	18,0
8-10	21,6	22,0	
10-12	25,1	26,0	
12-14	28,5	29,0	
14-16	31,9	32,0	
16-18	35,4	36,0	

H [m]	H_E	H_p
0-2	2,000	11,612
2-4	4,000	11,165
4-6	6,000	10,726
6-8	8,000	10,292
8-10	9,576	11,486
10-12	10,614	13,363
12-14	11,404	14,206
14-16	12,022	14,816
16-18	12,482	15,465

$$H_p > H_E \quad \text{OK}$$

## Summation: tension vs. compression

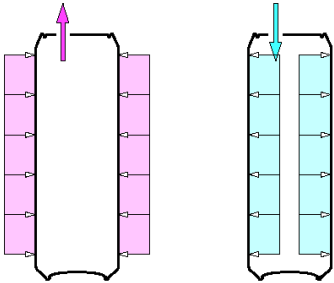


Photo: T. Michałowski, M. Piekarczyk, Selected Issues of Special Steel Structures, Cracow University of Technology 2019

### Tension:

Max internal pressure (liquid pressure + overpressure) = 218,280 kPa; thickness 8-36 mm

### Compression:

Max external pressure (wind pressure + underpressure) = 3,661 kPa, 60 times smaller

Walls must be thickened

# Bottom

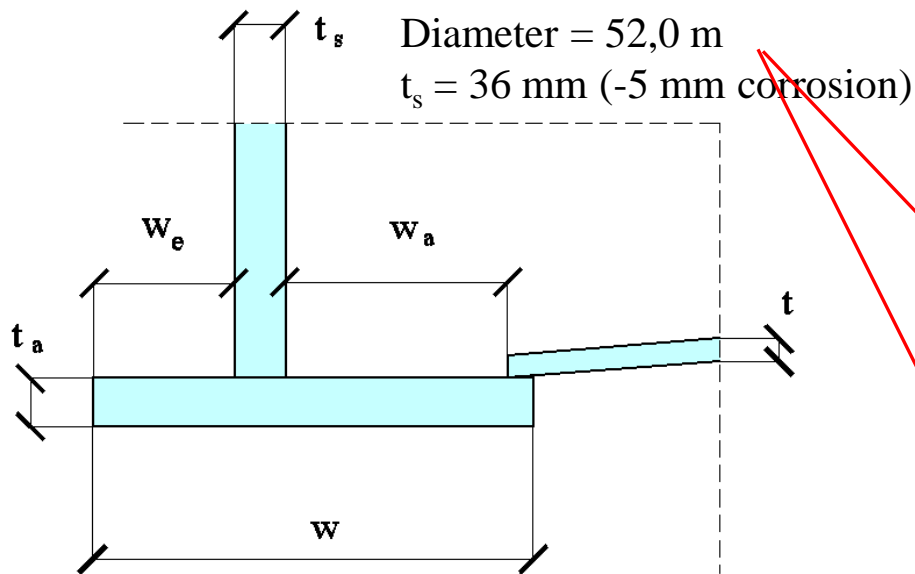


Photo: Author

Tank diameter [m]

w [mm]

Średnica zbiornika m	Szerokość blach pierścienia obrzeżnego mm
$d < 12,5$	500
$12,5 < d < 30$	650
$30 < d < 50$	750
$50 < d < 70$	1 000
$70 < d$	1 300

PN B 3210 tab. 7

w = 1 000 mm

$t \geq t_{\min} + t_{\text{corrosion}}$

EN 1993-4-2 tab. 11.1, EN 14 015 tab. 13

## Minimum nominal bottom plate thickness

Material	Lap welded bottoms	Butt welded bottoms
Carbon steels	6 mm	5 mm
Stainless steels	5 mm	3 mm

Tank diameter [m]

t [mm]

Średnica wewnętrzna zbiornika m	Minimalna grubość blach środkowej części dna <sup>1)</sup> $t_{b2}$ mm
$d \leq 12,5$	5
$12,5 < d \leq 30$	6
$30 < d \leq 50$	7
$50 < d \leq 90$	8
$90 < d$	9

<sup>1)</sup> Bez nadatku na korozję.

$t = \max(6 \text{ mm} ; 8 \text{ mm}) + \text{corrosion} = 13 \text{ mm}$

PN B 3210 tab. 5

$$t_a = \max ( t_c / 3 + 3 \text{ mm} + t_{\text{corrosion}} \quad ; \quad 6 \text{ mm} )$$

$$t_c = t_s - t_{\text{corrosion}}$$

$$t_a = \max [ (36 - 5) / 3 + 3 + 5 \quad ; \quad 6 ] = 18 \text{ mm} \quad ; \quad \text{will be taken } 20 \text{ mm}$$

$$w_a \geq \max \{ 1,5 \sqrt{ [f_y t_a^2 / (\rho g H_{\text{max}})] \quad ; \quad 500 \text{ mm} } \quad \text{EN 1993-4-2 (11.38)}$$

$$\rho = \max (\rho_{\text{H}_2\text{O}} \quad ; \quad \rho_{\text{fuel}})$$

$$w_a \geq \max \{ 0,938 \quad ; \quad 0,500 \} = 938 \text{ mm} \quad ; \quad \text{will be taken } 950 \text{ mm}$$

$$w_a > \max [ t_a \sqrt{ (A / H_{\text{max}}) \quad ; \quad 500 \text{ mm} ] \quad \text{EN 14 015 (2)}$$

$$A = 57\,600 \text{ m}$$

$$w_a \geq \max \{ 0,905 \quad ; \quad 0,500 \} = 905 \text{ mm} \quad ; \quad \text{will be taken } 910 \text{ mm}$$

$$w_a \geq \max (\text{EN 1993-4-2} \quad ; \quad \text{EN 14 015}) \rightarrow w_a = 950 \text{ mm}$$

$$50 \text{ mm} \leq w_e = w - w_a - t_s \leq 100 \text{ mm} \rightarrow w_e = 50 \text{ mm} \quad ; \quad w \text{ must be increased to } 1\,050 \text{ mm}$$

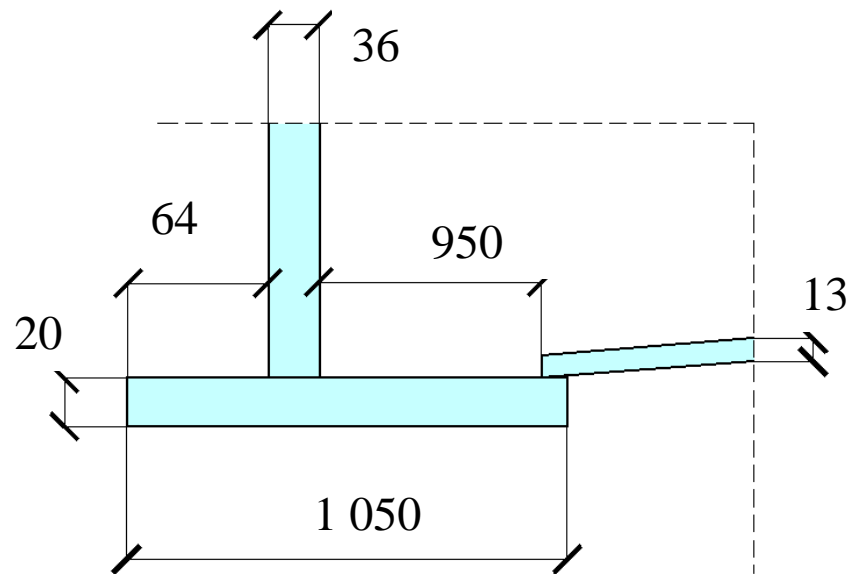


Photo: Author

## Global stability

Dead-weight of tank (approximation):

Roof: 2 548,382 kN ( $\rightarrow$  # t / 55)

Shell: 7 924,987 kN

Bottom ring:

$26 \cdot 2 \cdot \pi \cdot 1,05 \cdot 0,020 \cdot 78,5 \cdot 1,50 = 403,955$  kN

Bottom – central part:

$26^2 \cdot \pi \cdot 0,013 \cdot 78,5 \cdot 1,50 = 3 250,879$  kN

Total G: 14 128,203 kN

$G_k = G / 1,50 = 9 418,802$  kN

H [m]	t_real	G [kN]
0-2	20,0	769,416
2-4	20,0	769,416
4-6	20,0	769,416
6-8	20,0	769,416
8-10	22,0	769,416
10-12	26,0	846,358
12-14	29,0	1 000,241
14-16	32,0	1 115,653
16-18	36,0	1 115,653

7 924,987

Values:

Wind suction on roof ( $\rightarrow$  # t / 38)

$$S_d = 2\,208,788 \text{ kN}$$

$$x = 31,597 \text{ m}$$

Wind pressure on cylinder ( $\rightarrow$  # t / 31)

$$W_d = 686,253 \text{ kN}$$

$$y = 12,099 \text{ m}$$

Dead-weight

$$G_k = 9\,418,802 \text{ kN}$$

$$r = 26,000 \text{ m}$$

Overpressure ( $\rightarrow$  # t / 40)

$$O_d = 1,650 \cdot 26^2 \cdot \pi = 3\,504,132 \text{ kN}$$

$$r = 26,000 \text{ m}$$

Friction

$$\mu = 0,3$$

$$F_d = (G_k - S_d - O_d) \mu = 1\,111.765 \text{ kN}$$

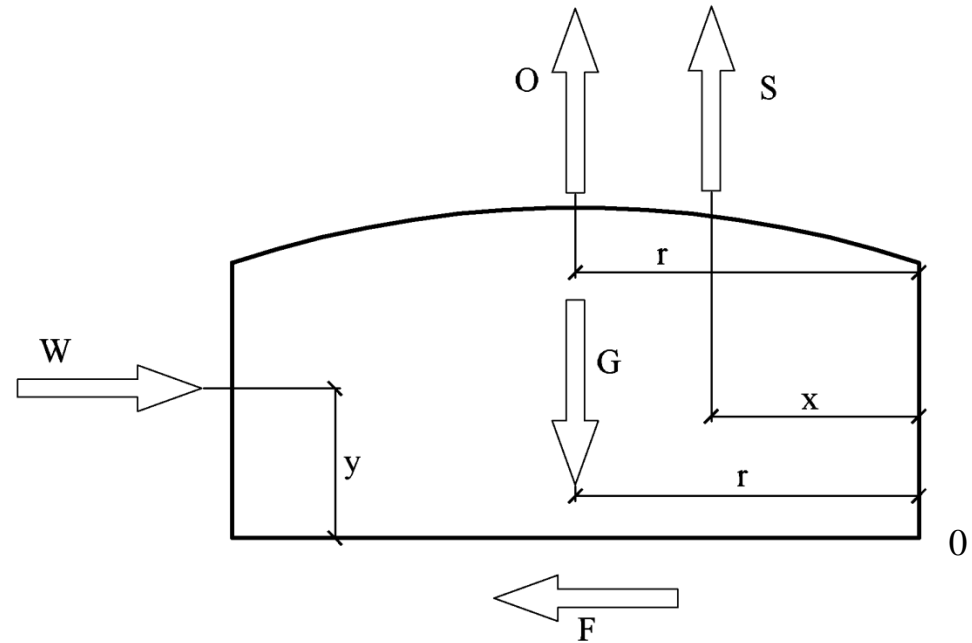


Photo: Author

$$O_d + S_d < 0,9 G_k$$

$$O_d + S_d = 5\,712,920 \text{ kN}$$

$$G_k = 9\,418,802 \text{ kN}$$

OK

$$W_d < 0,9 F_d$$

$$W_d = 686,253 \text{ kN}$$

$$F_d = 1\,111,765 \text{ kN}$$

OK

$$W_d y + S_d x + O_d r < 0,9 G_k r$$

$$\begin{aligned} W_d y + S_d x + O_d r &= 686,253 \cdot 12,099 + 2\,208,788 \cdot 31,597 + 3\,504,132 \cdot 26,000 = \\ &= 169\,201,482 \text{ kNm} \end{aligned}$$

$$G_k r = 9\,418,802 \cdot 26,000 = 244\,888,852 \text{ kNm}$$

OK

## Grade and subgrade of steel - verification

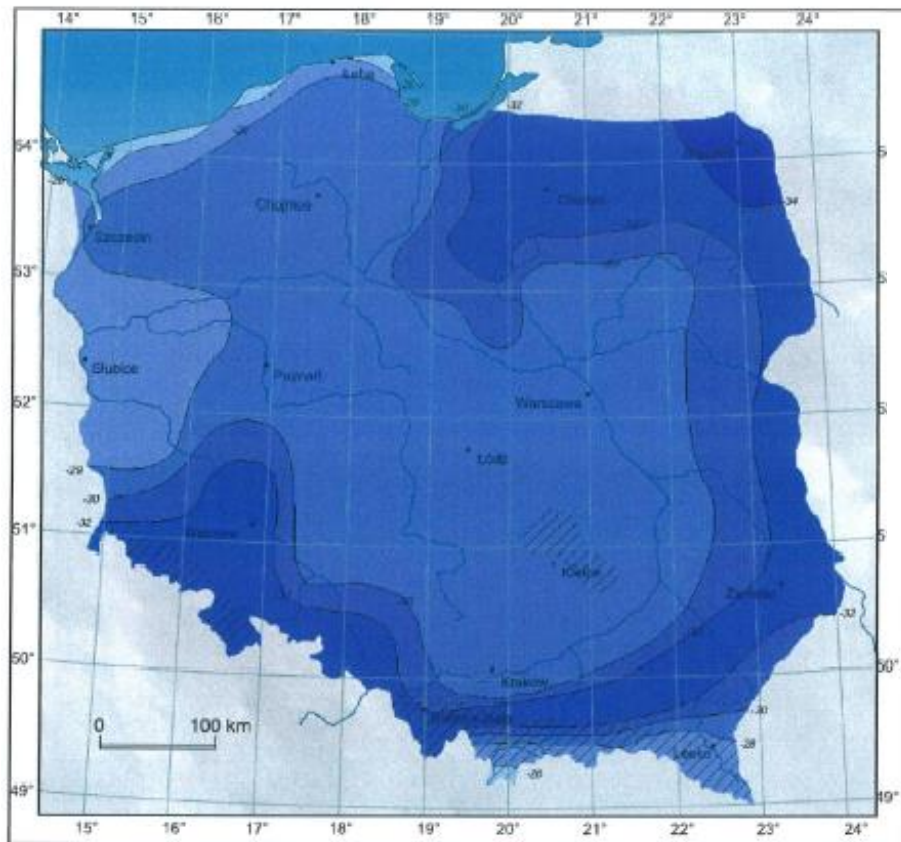


Photo: EN 1991-1-5 fig NB.3

Hel seashore:  $T = -26^{\circ}\text{C}$

H [m]	$t_{\text{max}} - \text{corr}$	$t_{\text{real}}$	$t_{\text{max}} - \text{corr} / t_{\text{real}}$
0-2	0,0	20,0	0,000
2-4	6,4	20,0	0,318
4-6	9,8	20,0	0,489
6-8	13,2	20,0	0,661
8-10	16,6	22,0	0,756
10-12	20,1	26,0	0,772
12-14	23,5	29,0	0,810
14-16	26,9	32,0	0,842
16-18	30,4	36,0	0,843

Steel S235. The fattest part of tank: 36 mm. Result from calculation: 30,4 mm. Effort could be taken into consideration as

$$\max[(t_{\text{max}} - \text{corr.}) / t_{\text{real}}] f_y = 0,843 f_y$$

Temperature between  $-20^{\circ}\text{C}$  and  $-30^{\circ}\text{C}$

Steel grade	Sub-grade	KV		Reference temperature $T_{Ed}$ [°C]														
		at T [°C]	$J_{min}$	10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-30	-40	-50	10
				$\sigma_{Ed} = 0,75 f_y(t)$							$\sigma_{Ed} = 0,50 f_y(t)$							
S235	JR	20	27	60	50	40	35	30	25	20	90	75	65	55	45	40	35	13
	J0	0	27	90	75	60	50	40	35	30	125	105	90	75	65	55	45	17
	J2	-20	27	125	105	90	75	60	50	40	170	145	125	105	90	75	65	20
S275	JR	20	27	55	45	35	30	25	20	15	80	70	55	50	40	35	30	12
	J0	0	27	75	65	55	45	35	30	25	115	95	80	70	55	50	40	16

Photo: EN 1993-1-10 tab. 2.1

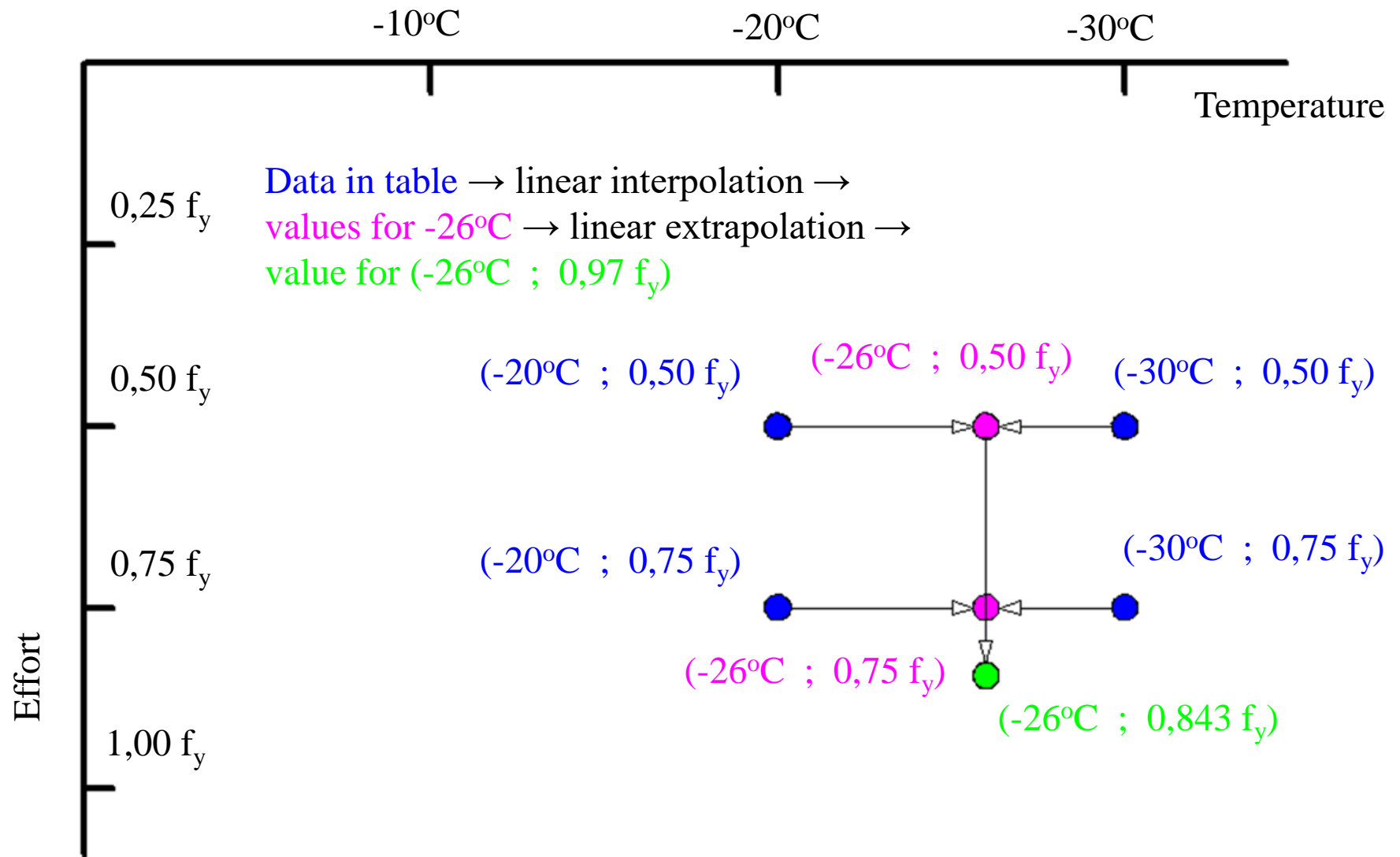


Photo: Author

Linear interpolation for temperature  $-26\text{ }^{\circ}\text{C}$ :

Subgrade	$0,75 f_y$			$0,50 f_y$		
	$-20\text{ }^{\circ}\text{C}$	$-26\text{ }^{\circ}\text{C}$	$-30\text{ }^{\circ}\text{C}$	$-20\text{ }^{\circ}\text{C}$	$-26\text{ }^{\circ}\text{C}$	$-30\text{ }^{\circ}\text{C}$
JR	35	<b>32</b>	30	55	<b>49</b>	45
J0	50	<b>44</b>	40	75	<b>69</b>	65
J2	75	<b>66</b>	60	105	<b>96</b>	90

Linear extrapolation for stress  $0,998 f_y$  :

Subgrade	$0,50 f_y (-26\text{ }^\circ\text{C})$	$0,75 f_y (-26\text{ }^\circ\text{C})$	$0,843 f_y (-26\text{ }^\circ\text{C})$
JR	49	32	25
J0	69	44	34
J2	96	66	54

**Permissible** thickness must be non smaller than 36 mm.

Final grade of steel:

S235

Final subgrade:

J2

Thank you for attention

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