Metal Structures II

Design project I

Vertical cylindrical tank

PROJECT OBJECTIVE’S

Simplified analysis of shell structure;
Analysis of wind action on cylinders and domes;
Comparison of resistance and stability;
Reminder of steel sub-grades impact of calculation;

DESIGN EXERCISES # 1

Student…………………………………………………………………………………………………

Topic:

Design of vertical cylindrical tank:

Volume: ……………………………………………………………………… m^3

Liquid: ………………………………………………………………………

Location: ……………………………………………………………………

Ground conditions: ………………………………………………………

EN 1990

Eurocode - Basis of structural design

EN 1991-1-1

Actions on structures - General actions - Densities, self-weight, imposed loads for buildings

EN 1991-1-3

Actions on structures - General actions - Snow loads

EN 1991-1-4

Actions on structures - General actions - Wind actions

EN 1991-1-5

Actions on structures - General actions - Thermal actions

EN 1993-1-10

Design of steel structure - material toughness and through-thickness properties

EN 1993-4-2

Design of steel structure - tanks

EN 14 015

Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above

PN B 3210

Zbiorniki walcowe pionowe na ciecze – Projektowanie i wykonawstwo

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.

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.

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

Proportions, dimensions

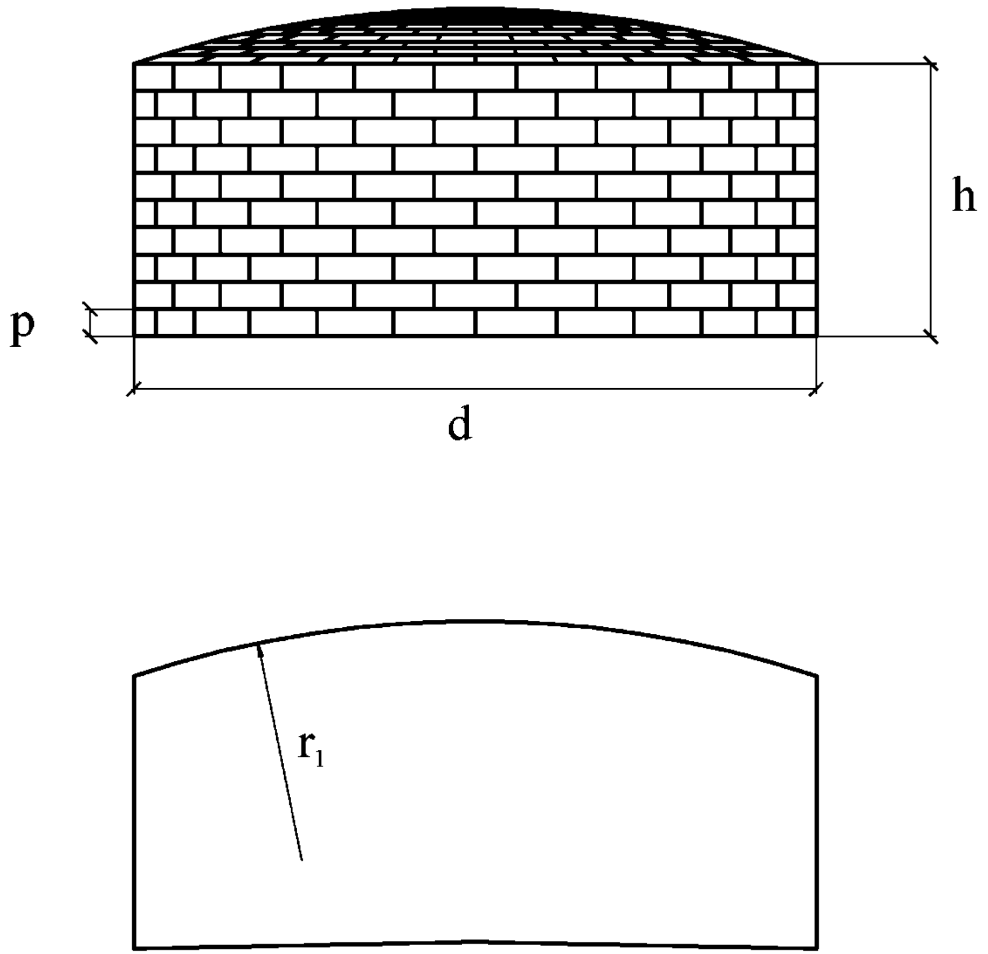


Photo: Author

r_1 = 1,0 - 1,5 d

p = 1,0 - 2,0 m

Tank volume, $[m^3]$ | Height, [m] | Height / Diameter

Pojemność zbiornika, v m^3			Wysokość płaszcza, h m	Stosunek wymiarów $\frac{h}{d}$
1	2	3	4	5
Zbiorniki naziemne (Above-ground)	dach pływający (Floating roof)	od 500 do 5 000	od 8,0 do 12,0	$\frac{1}{1{,}25}$ do $\frac{1}{2{,}0}$
		od 5 100 do 9 990	od 12,0 do 16,0	$\frac{1}{1{,}8}$ do $\frac{1}{2{,}0}$
		od 10 000 do 16 000	16,5	$\frac{1}{1{,}8}$ do $\frac{1}{2{,}3}$
		od 17 000 do 50 000	18,0	$\frac{1}{2{,}1}$ do $\frac{1}{3{,}6}$
		od 51 000 do 100 000	20,0	$\frac{1}{3{,}3}$ do $\frac{1}{4{,}3}$
		powyżej 100 000	22,0	$< \frac{1}{4{,}0}$
	dach stały (Fixed roof)	poniżej 1 000	od 6,0 do 11,0	$\frac{1}{1{,}0}$
		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	$< \frac{1}{2{,}8}$
Zbiorniki podziemne (Underground)		poniżej 500	4,5	$< \frac{1}{1{,}8}$
		od 500 do 1 000	6,0	$\frac{1}{1{,}8}$
		od 1 000 do 5 000	7,5	$\frac{1}{1{,}8}$ do $\frac{1}{1{,}4}$

PN B 3210 tab. 2

$\pi d^2 h / 4 \approx 1{,}05 V$

Reliability

There are few different ways of calculations of tanks, according to their consequences classes CC. Way presented on this design project is dedicated to CC2. More information had been presented on lecure #1.

Consequences calsses	Description	Examples
CC3	**High consequence** for loss of human life or economic, social or envirnomental ceonequences **very heavy**	Grandstands; public buildings where consequences of failure are high
CC2	**Medium** for loss of human life or economic, social or envirnomental ceonequences **considerable**	Residential; office buildings; public buildings where consequences of failure are medium
CC1	**Low** for loss of human life and economic, social or envirnomental ceonequences **small or neglegible**	Agricultural buildings where people do not normally enter; greenhouses

EN 1990 tab B1

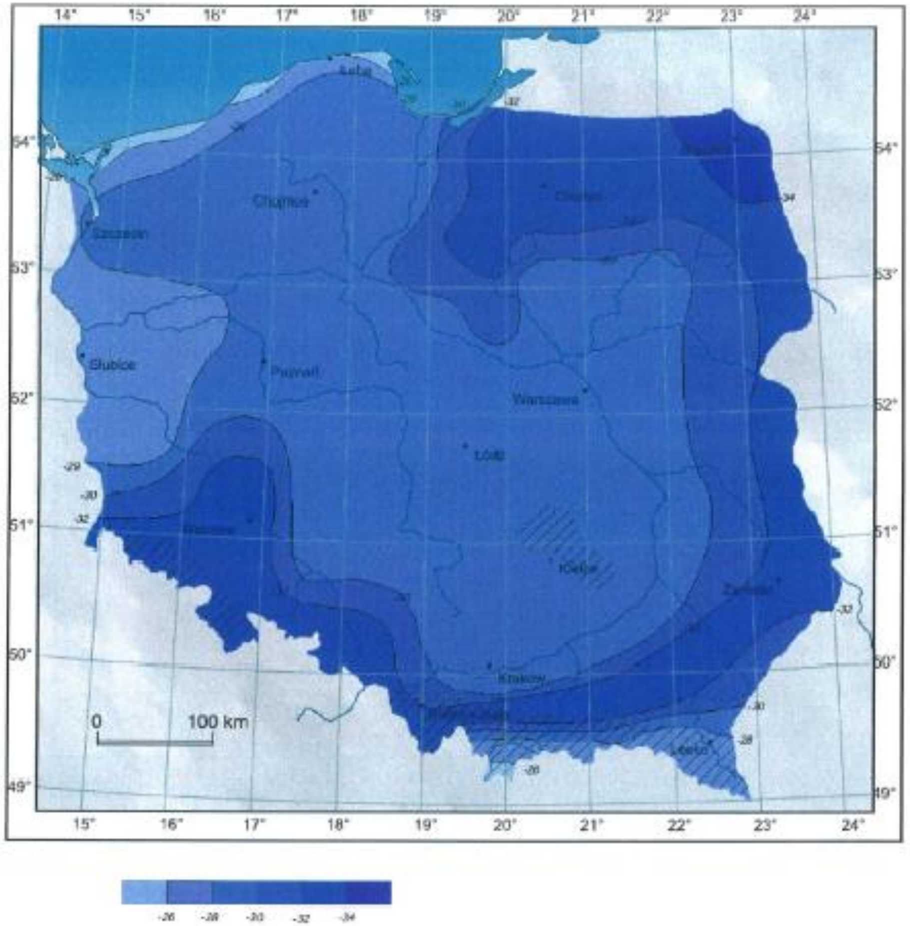
→ #1 / 19

Consequences calsses	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

EN 1993-4-2 2.2

„Medium size” = according ot unofficial definition, volume ≤ 10.000 m^3

Grade and subgrade of steel



EN 1991-1-5 fig NB.3 → min temperature in winter

Steel grade	Sub-grade	KV at T [°C]	J_{min}	Reference temperatu…											
				10	0	-10	-20	-30	-40	-50	10	0	-10	-20	-3
				$\sigma_{Ed} = 0{,}75\, f_y(t)$							$\sigma_{Ed} = 0{,}50\, f_y($				
S235	JR	20	27	60	50	40	35	30	25	20	90	75	65	55	4
	J0	0	27	90	75	60	50	40	35	30	125	105	90	75	6
	J2	-20	27	125	105	90	75	60	50	40	170	145	125	105	9
S275	JR	20	27	55	45	35	30	25	20	15	80	70	55	50	4
	J0	0	27	75	65	55	45	35	30	25	115	95	80	70	5
	J2	-20	27	110	95	75	65	55	45	35	155	130	115	95	8

EN 1993-1-10 tab. 2.1

Standard	Designation	Options	Steel type as given in Figure 1	Maximum thickness[a)] mm
EN 10025 1993	S235 JRG2	1, 12	Type I	12
	S235 JO	1, 5, 12	Type II	30
	S235 J2G3	1, 5, 12	Type III	40

EN 14 015 tab. 5

Standard	Designation	Options	Steel type as given in Figure 1	Maximur
EN 10025 1993	S235 JRG2	1, 12	Type I	
	S235 JO	1, 5, 12	Type II	

EN 14 015 tab. 6

Resistance will be presented as condition:

$$t \geq t_{min} \text{ (geometry, grade of steel, loads} \rightarrow \text{resistance)}$$

On the other hand:

$$t \leq t_{max} \text{ (grade of steel, EN 1993-1-10, EN 14 015)}$$

This means, that you must make assuption about grade and subgrade of steel, and control this assumption on each step of calculations:

$$t_{min}\text{(geometry, grade of steel, loads)} \leq t \leq t_{max}\text{(grade of steel, EN 1993-1-10, EN 14 015)}$$

and change grade / subgrade steel, if it occurs necessary.

Of course, there is possibility to make thermal isulation. But this solution is user rather because of technological reasons (tanks for hot or very cold liquids), not for protection of structure.

Photo: zbiorniki-silosy.pl

Loads

Dead weight of steel structure

Snow

Wind

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

Snow - no information for dome, aproximation by cylindrical roof

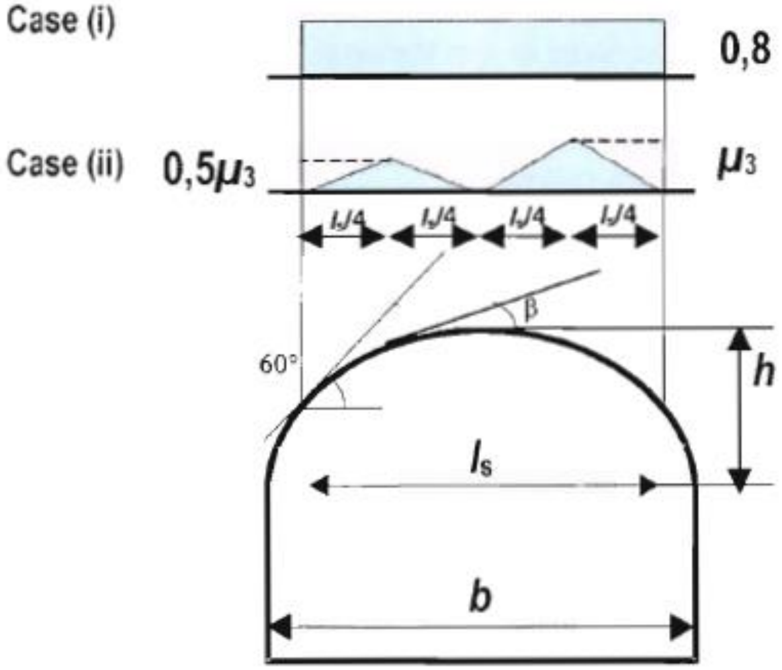
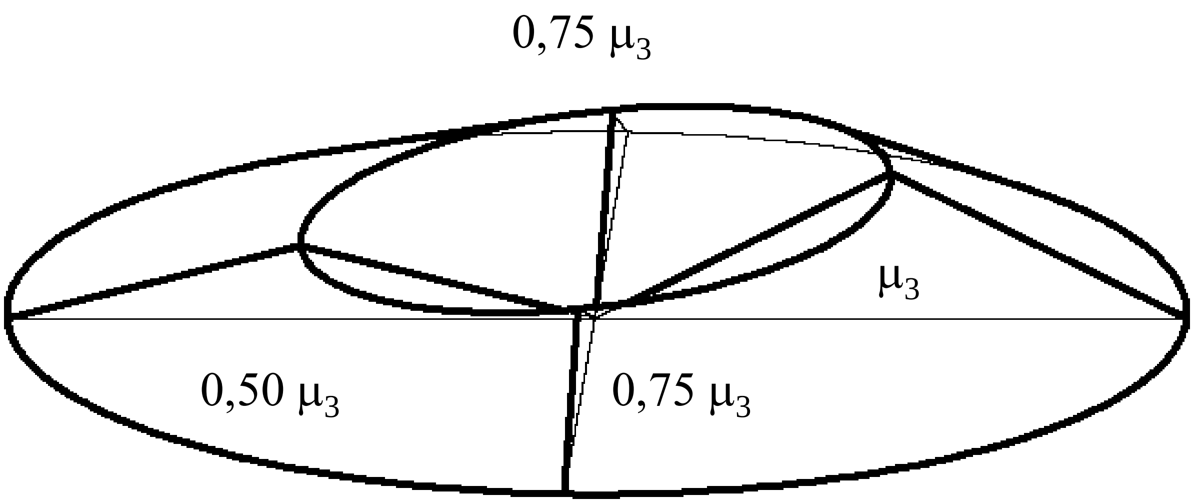


Photo: EN 1991-1-3 fig 5.6

Calculation of snow load on dome is rather complicated. Information in Eurocode is dedicated to cylindrical roof, not dome. Approximation of this information shows nonlinear shape of snow on roof; various values on each point.



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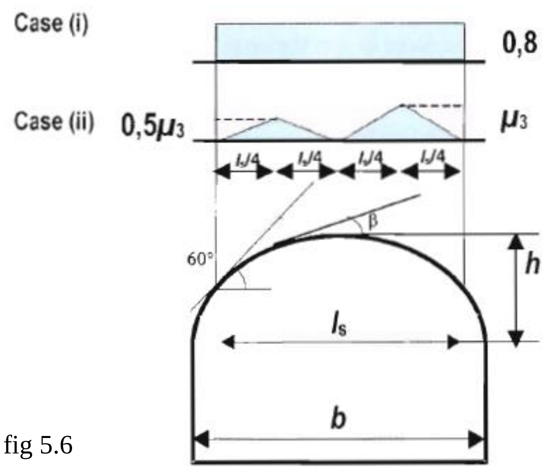


Photo: EN 1991-1-3 fig 5.6

Nonlinear shape can be linearised by division roof on few part and applying constant value on each part.

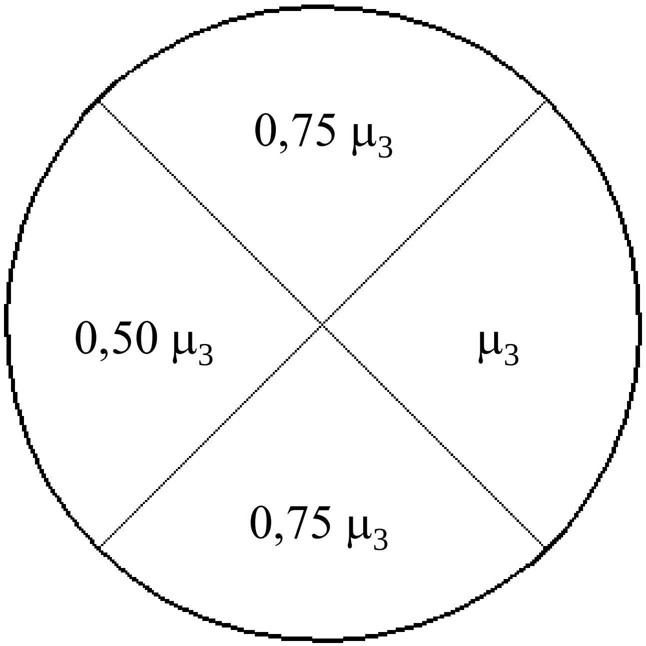


Photo: Author

For Your range of project, important is only max value of snow load. We assume in calculations, snow load of constant value = max value on entire roof.

$$\max \rightarrow \max(\mu_3 \quad ; \quad 0{,}8)$$

Wind acts on dome – the most complicated part of calculation.

There is only very short information in Eurocode about wind action on dome:

- Shape of wind pressure / suction is presented for cross-section parallel to wind direction;
- Values of wind action (A, B, C) are defined for windward point, top of dome and leeward point;
- Linear approximation is recommended for rest values;
- These values depend on geometrical proportion of cylinder and dome;
- There is constant value of wind action on each cross-section perpendicular to wind direction;
- Wind action is always perpendicular to dome.

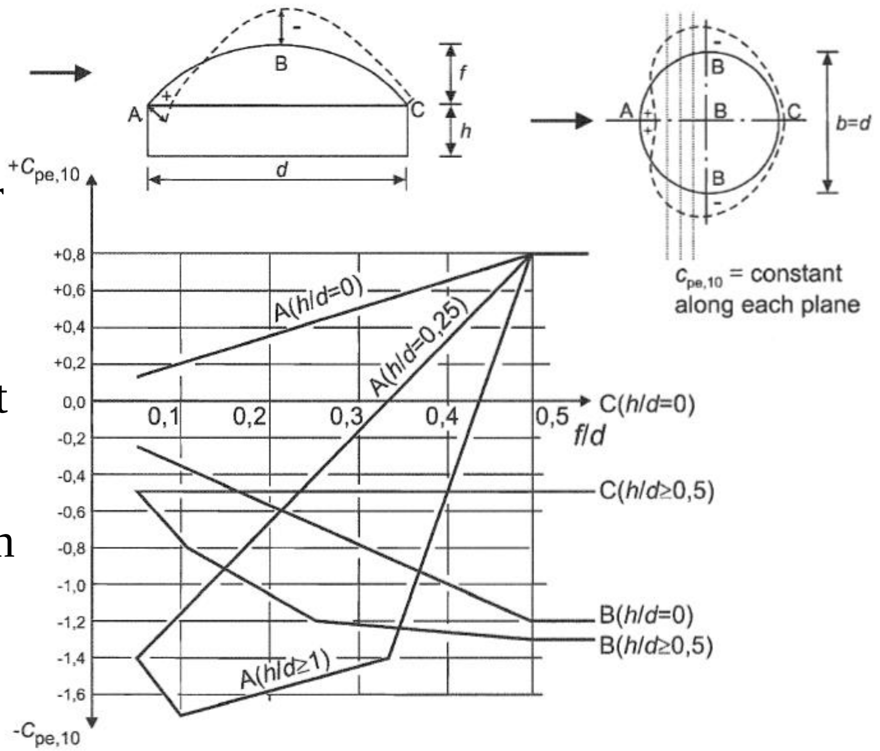
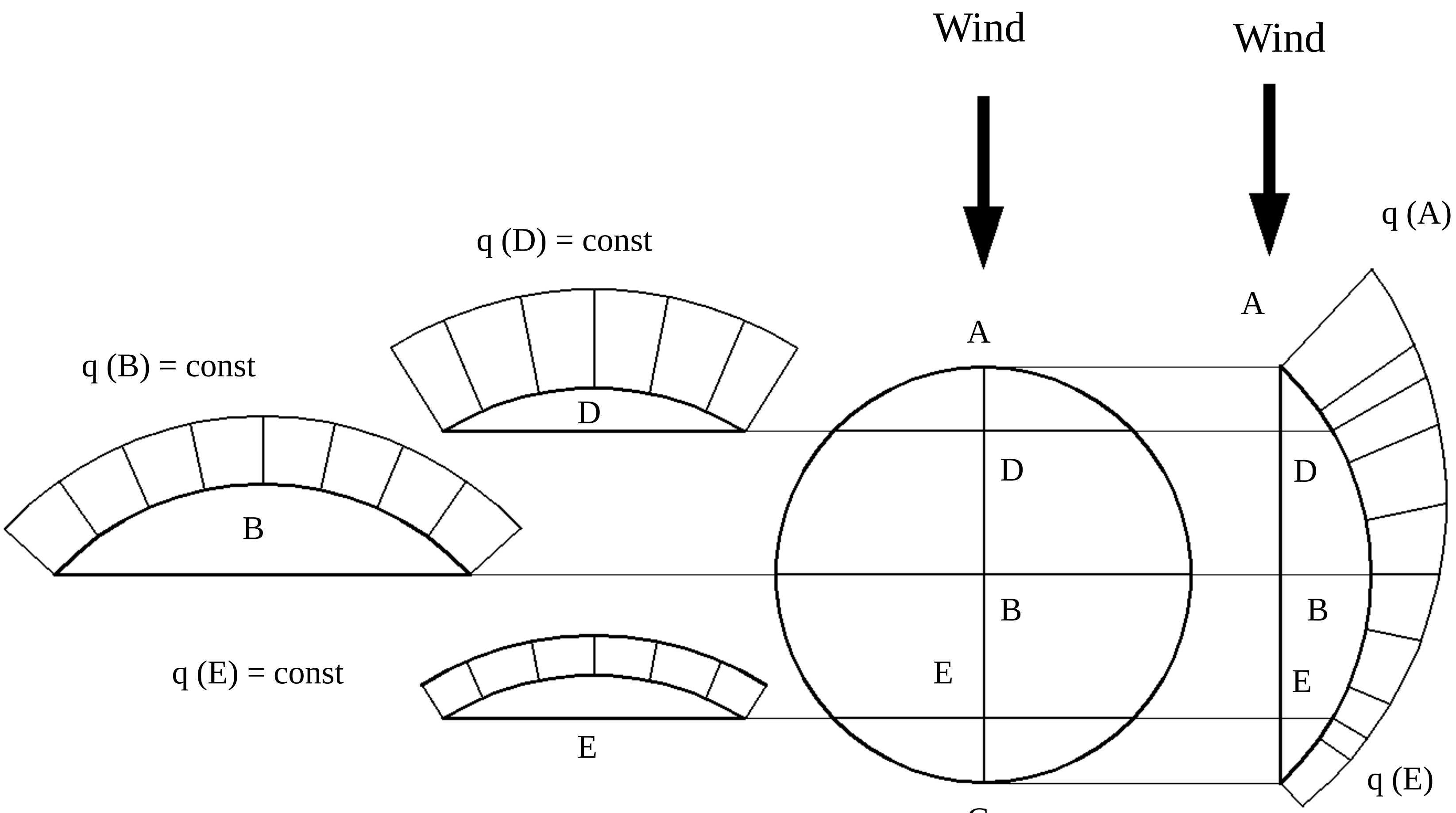


Photo: EN 1991-1-4 fig. 7.12



View from the top

Photo: Author

Wind action on dome is in each point prependicular to surface of dome – this means on each point there are three compounds:

- Horizontal parallel to wind direction;
- Horizontal perpenicular to wind direction;
- Vertical.

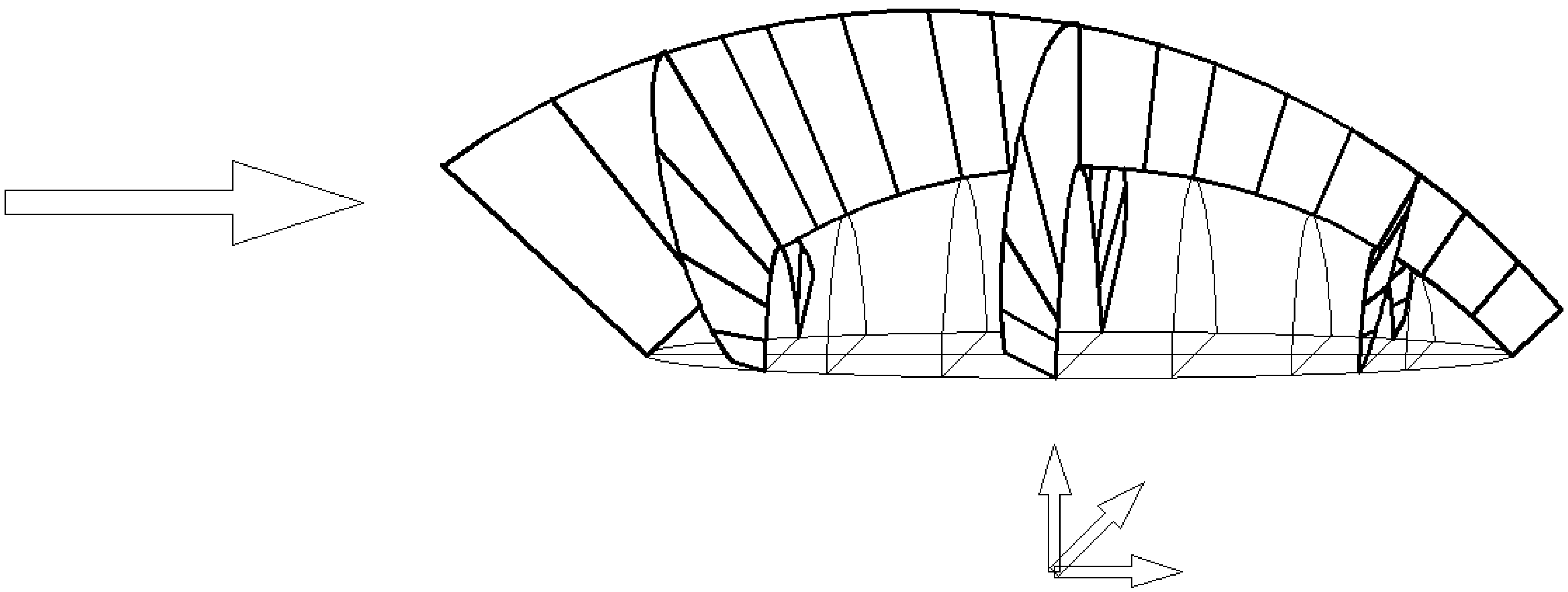
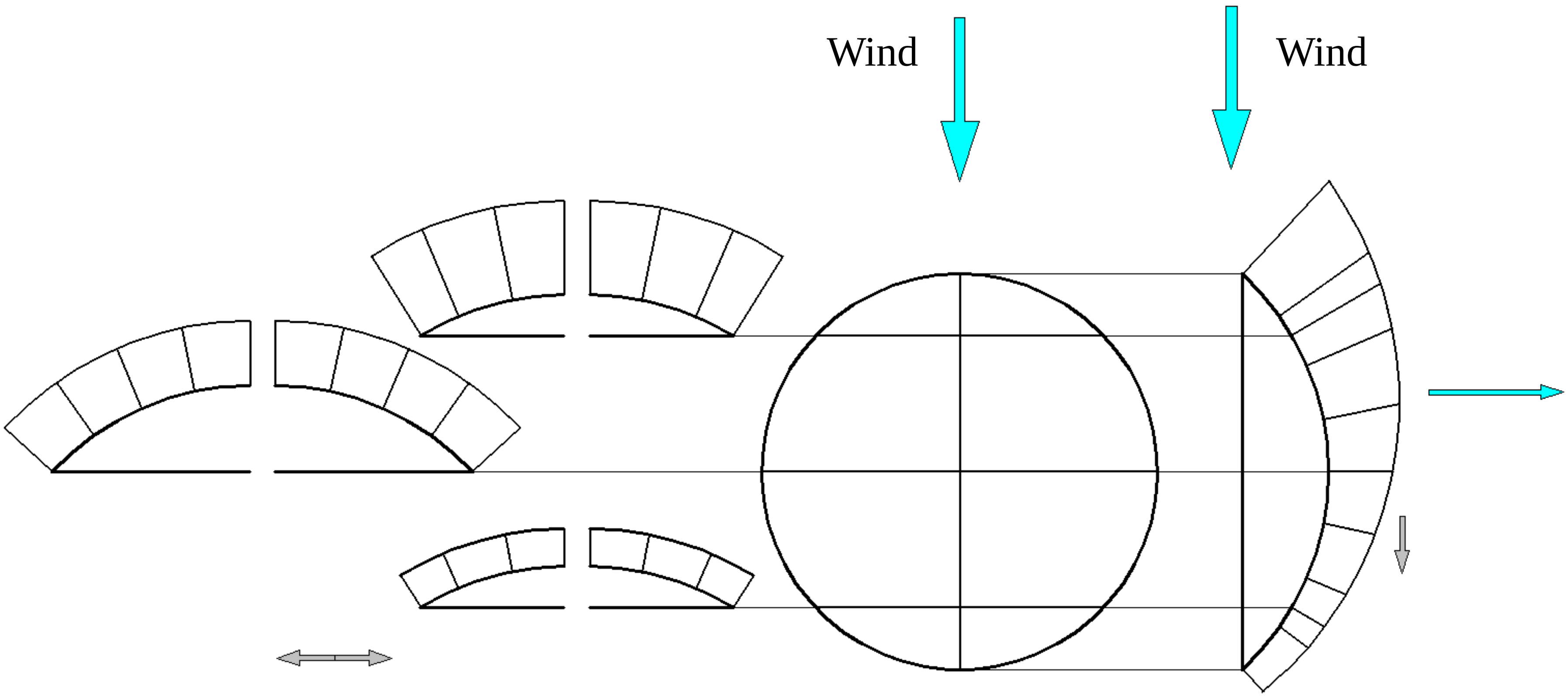
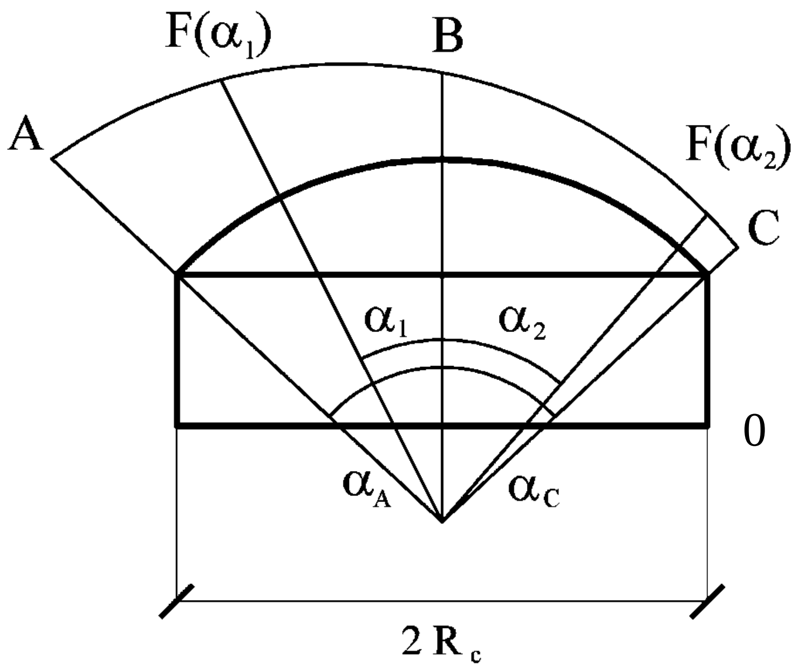


Photo: Author

Because of symmetry, force product of force horizontal perpendicular to wind direction is equal zero. Horizontal force parallel to wind direction has small value and – on this range of project – can be neglected. Important is only vertical force and its location on roof.



Approximation of wind pressure / suction on dome:



$F(\alpha_1) = a\alpha_1 + b$

$F(\alpha_1 = \alpha_A) = A$

$F(\alpha_1 = 0) = B$

Photo: Author

$F(\alpha_2) = c\alpha_2 + d$

$F(\alpha_2 = \alpha_A) = C$

$F(\alpha_2 = 0) = B$

Wind action on cylindrical part:

- Nonlinear shape of wind pressure / suction;
- Pressure on windward part, suction on the rest;
- Value defined for few characteristic points.

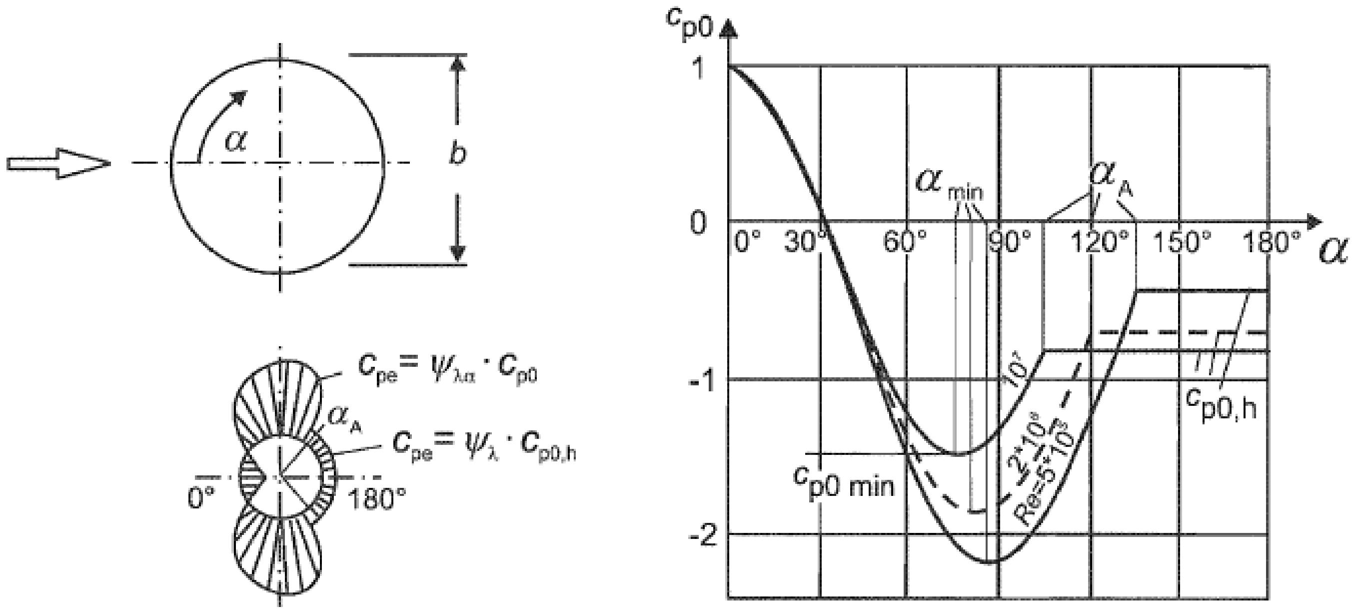


Photo: EN 1991-1-4 fig. 7.27

There are two compounds of wind action on both parts of cylinder: parallel and perpendicular. Because of symmetry, both perpendiculars have the same values and opposite directions. Result: only force parallel to wind direction.

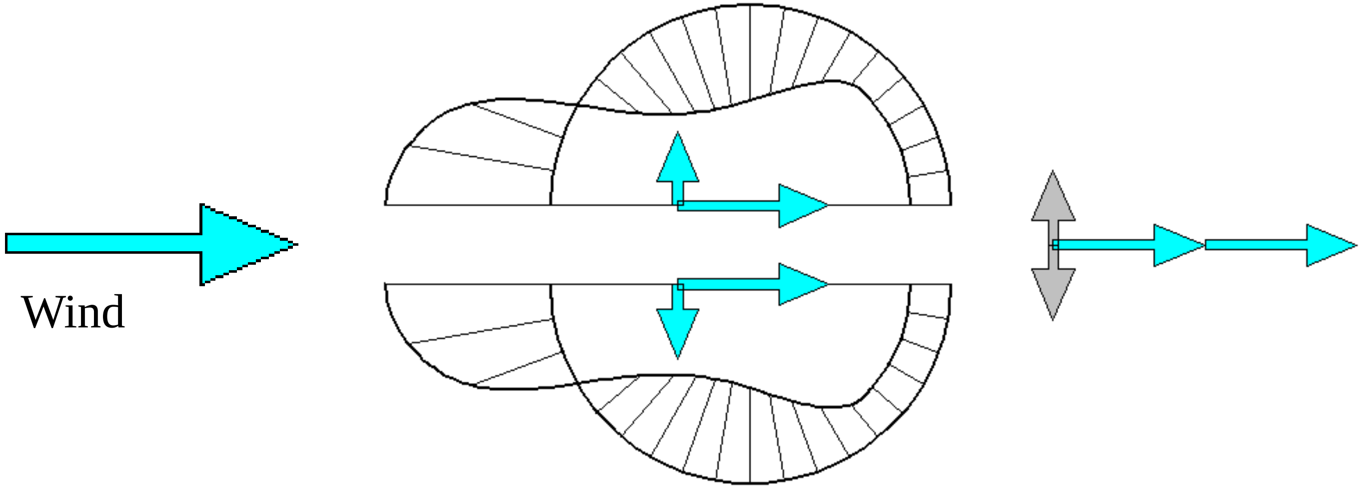


Photo: Author

Approximation of $c_{p,0}$:

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

$30^o \leq \alpha \leq \alpha_{min} \rightarrow c_{p,0} = c_{p,0min} \sin(\alpha_1)$; $\alpha_1 = 90^o (\alpha - 30^o) / (\alpha_{min} - 30^o)$

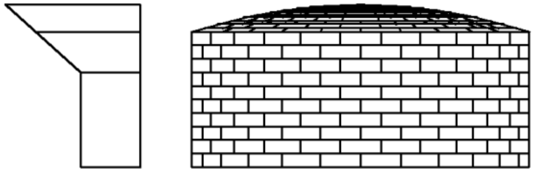
$\alpha_{min} \leq \alpha \leq \alpha_A \rightarrow c_{p,0} = c_{p,0h} + C \sin(\alpha_2)$; $\alpha_2 = 90^o [1 - (\alpha - \alpha_{min}) / (\alpha_A - \alpha_{min})]$

$C = c_{p,0min} - c_{p,0h}$

$\alpha_A \leq \alpha \leq 180^o \rightarrow c_{p,0} = c_{p,0h}$

Additionally, we must take into consideration end-effect factor $\psi_\lambda(\alpha)$, according to EN 1993-1-4 p. 7.15

Additionally, there is important vertical profile of wind - it is possible, that constant value is only on bottom part of cylinder.



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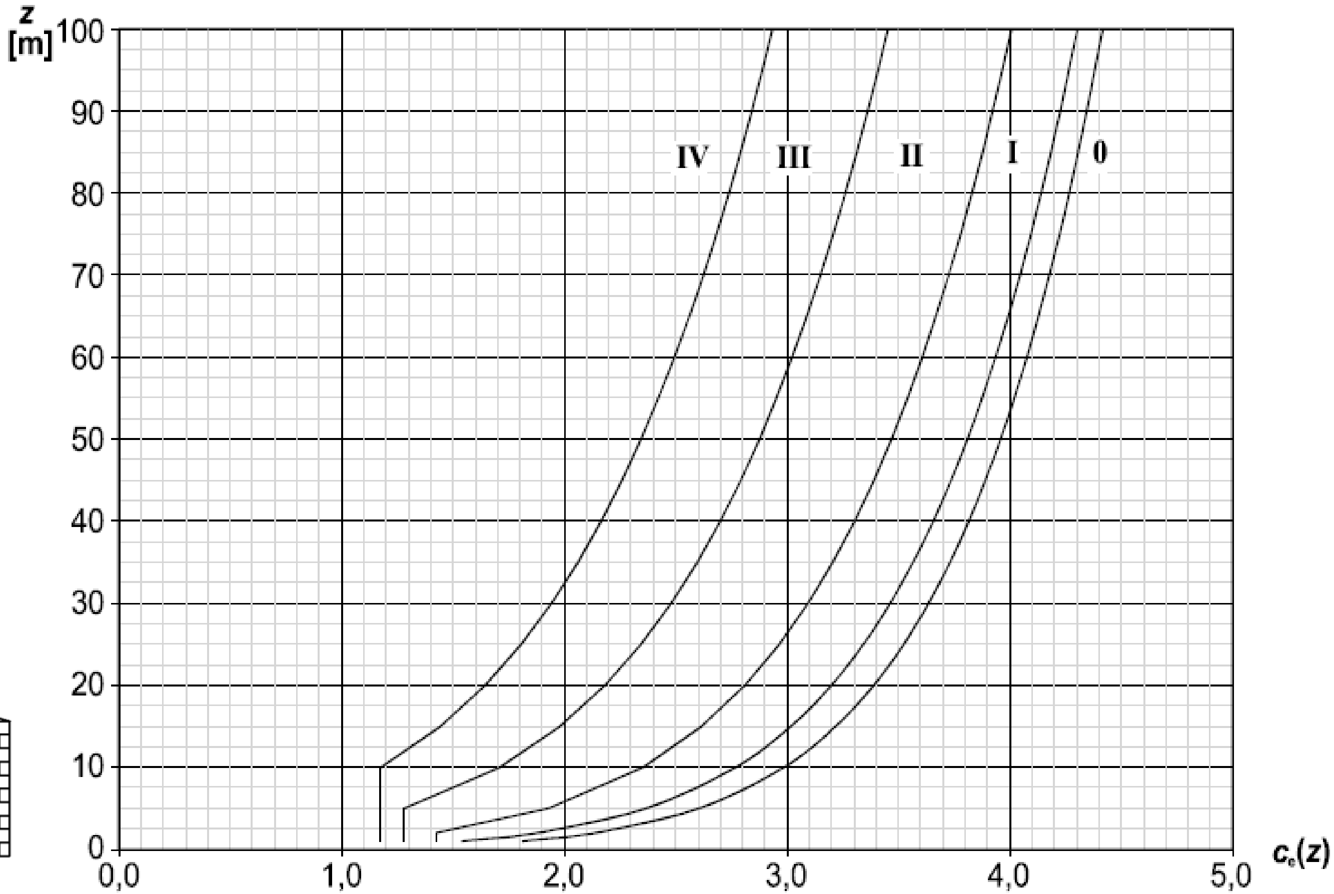

Photo: EN 1991-1-4 fig. 4.2

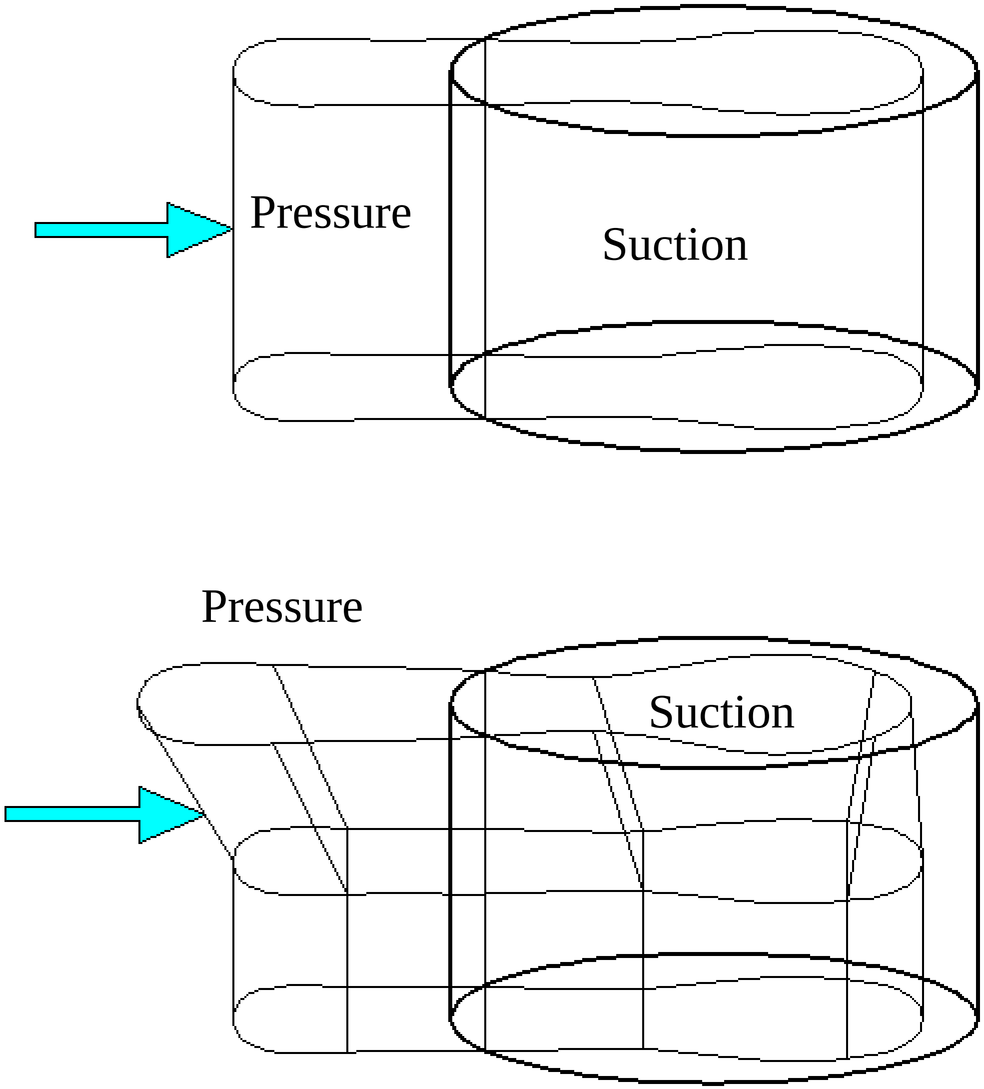

Photo: Author

Vertical profile changes position of product on find action on cylindrical part.

Of course, vertical profile is important for dome, too.

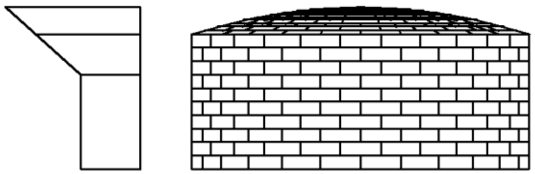

Photo: Author

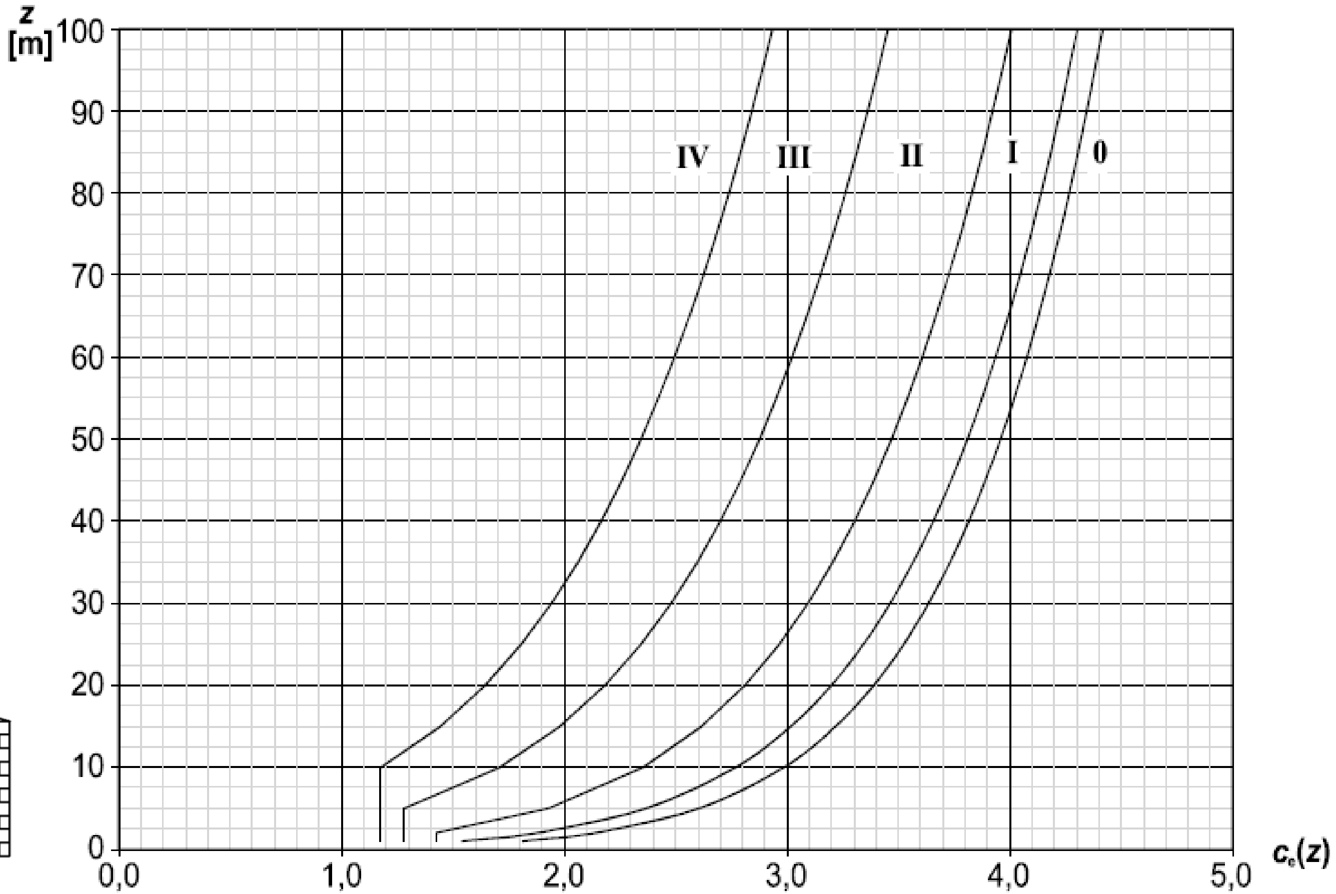

Photo: EN 1991-1-4 fig. 4.2

Resistance and stability could be calculated according to two standards, EN 1993-4-2 and EN 14 015. EN 1993-4-2 bases on Limit States Method, EN 14 015 bases on Permissible Stress Design. Impact of safety factors in both methods is different. In Limit States Method, complex of factors for loads and for material enables make very accuratre calculations. In Permissible Stress Design only one safety factor makes calculation rought and inaccurate. Elements in Permissible Stress Design are overdesigned in comparison to Limit States Method. So, in your range of project:

- resistance will be calculated only according to EN 1993-4-2 (Limit States Method);
- stability will be taken into consideration as bigger value from two results: according to EN 1993-4-2 (Limit States Method) and according to EN 14 015 (Permissible Stress Design).

Overpressure, underpressure: investor guidelines

EN 14 015 tab 3

$p_{over} = 1{,}0$ kPa ; $p_{under} = 0{,}5$ kPa

Liquid: water- and fuel-density

EN 1991-1-1 table A10

Corrosion: investor guidelines

$t_c = 0{,}1$ mm / year · 50 years = 5 mm

Unstiffened roof shell

<u>Loadbearing of roof</u>

Photo: boerger.com

$p_{0,Ed}\ r_1 / (2\ j\ f_{y,d}) \leq t$ EN 1993-4-2 (11.2)

EN 14 015 (12)

$t \geq 5$ mm EN 1993-4-2 11.2.2.(1)

EN 14 015 10.3.3, 10.3.4

$p_{0,Ed}$ = max wind suction on roof + overpressure

j - joint efficency factor:

	Butt welds	Lapped joints with filled welds in both sides	Lapped joints with filled welds in one side only
EN 1993-4-2 11.2.1	1,0	0,5	
EN 14 015 10.3.6	1,0	0,5	0,35

Stability of roof

Unstiffened roof shell

$4\, r_1 \sqrt{(p_{i,,Ed} / E)} \leq t$ EN 1993-4-2 (11.4)

EN 14 015 (14)

$p_{i,Ed}$ = dead weight of roof + snow load + underpressure + max wind pressure on roof

Edge ring - loadbearing

Effective area of edge ring A_{eff}

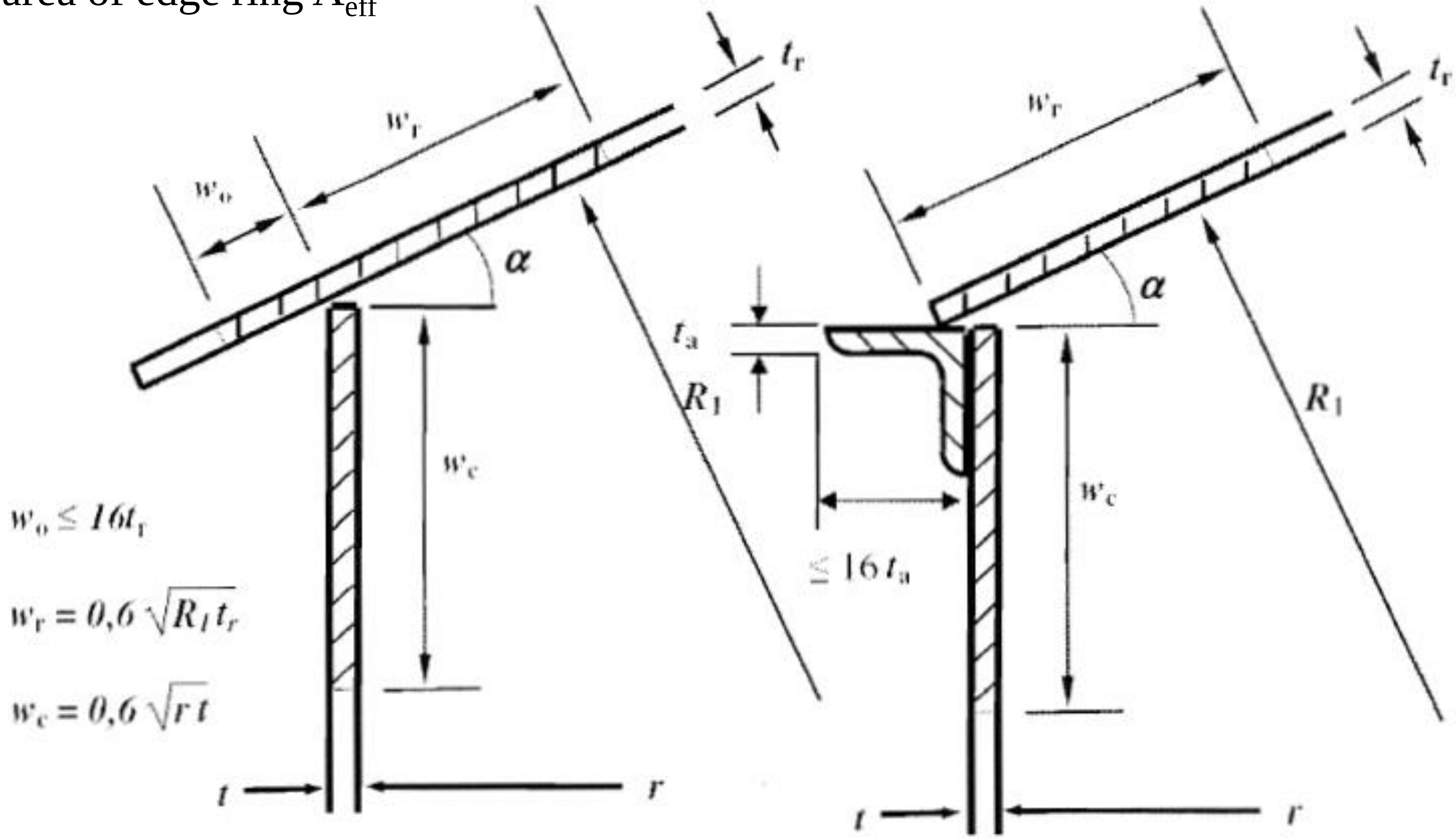

Photo: EN 1993-4-2 fig. 11.4, EN 14 015 fig. 8

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

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

$p_{v,Ed}$ = max (dead weight of roof + snow + underpressure + max wind pressure on roof ;

max wind suction on roof + overpressure)

Recommended additional L-section:

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

Stability of edge ring

Resistance: tensile or compressive forces

Stability: compressive force only (stability factor)

Non obligatory on this range of student's design project

Loadbearing of shell

Tank diameter [m]	Recommended minimum shell tickness 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

→ #1 / 52

I stage: water test (tested of leaks; sometimes the need to seal)

Loads: water pressure

Duration: 1 week - 1 month

II stage: exploatation

Loads: fuel pressure, overpressure, corrosion

Duration: many many years (in this design project: 50 years)

There is possible, than tank is not completely hermetic after erection. Hermeticity must be tested before start of exploatation. Water is used for test - economic and environmental losses in case of leaks are much much less than in case of, for example, gasoline leak.

Photo: photo.tepco.co.jp

→ #1 / 53

Photo: photo.tepco.co.jp

Density of water is different than density of liquid during operation (other loads). Time of test is too short to start corrosion. There is no need to analyse overpressure during test.

I stage:

$t_I \geq r\ \gamma_F\ \rho_{H2O}\ g\ (H_j - \Delta) / f_{y,d}$

EN 1993-4-2 (11.21)

II stage:

$t_{II} \geq r\ [\gamma_F\ \rho_{fuel}\ g\ (H_j - \Delta) + p_{over}] / f_{y,d} + t_{corrosion}$

$\Delta = 0{,}30$ m

I stage:

$t_I \geq r\, \gamma_F\, \rho_{H2O}\, g\, (H_j - \Delta) / (\gamma_I\, f_{y,d})$

EN 14 015 (3), (4)

II stage:

$t_{II} \geq r\, [\gamma_F\, \rho_{fuel}\, g\, (H_j - \Delta) + p_{over}] / (\gamma_{II}\, f_{y,d}) + t_{corrosion}$

$\Delta = 0,30$ m

$\gamma_I = 3/4$

$\gamma_{II} = 2/3$

→ #1 / 54

$t = \max(t_{min}\ ;\ t_{I}\ ;\ t_{II})$

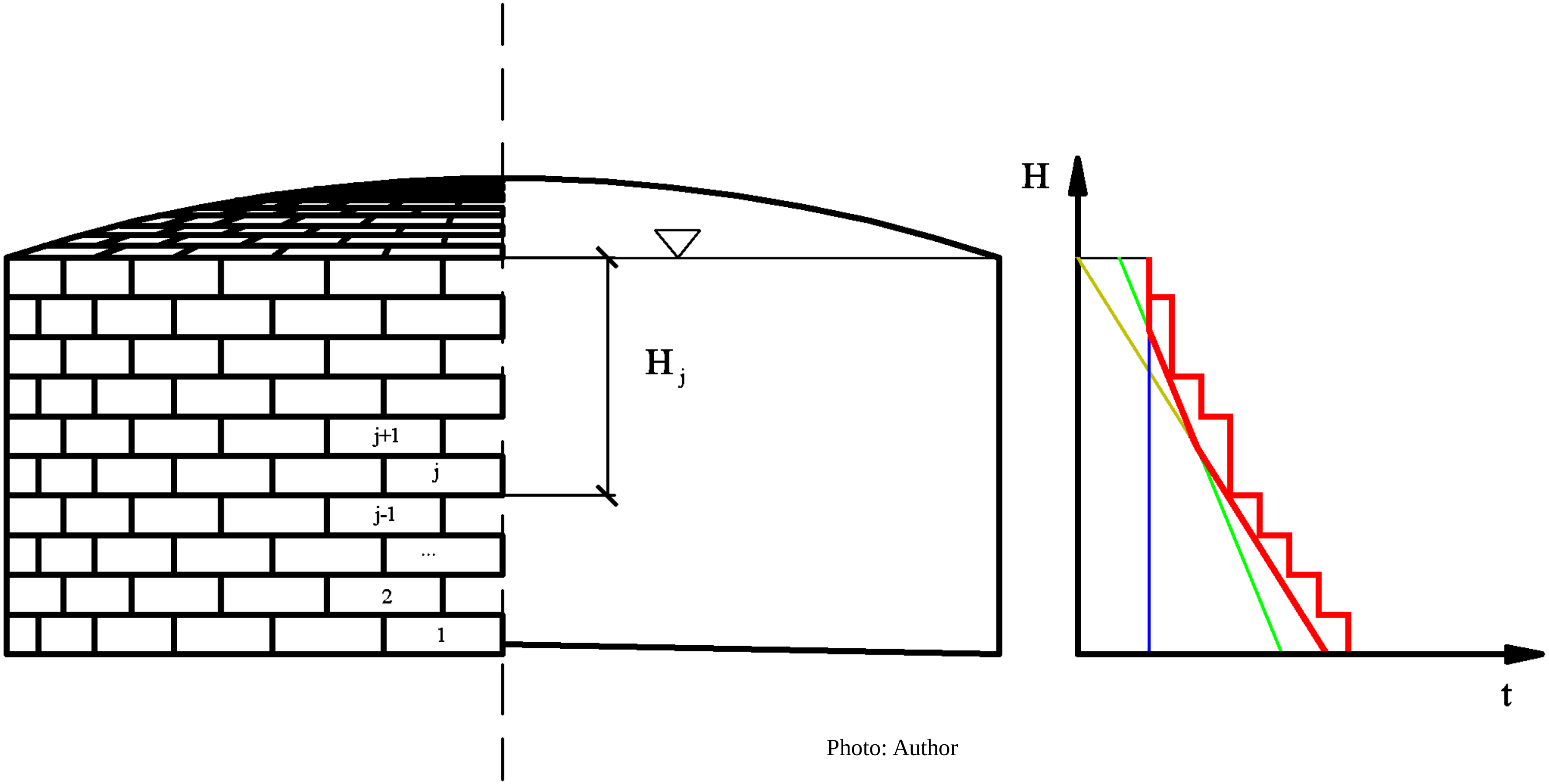

Photo: Author

$t_I = \max [t_I(\text{EN 1993-4-2}) \; ; \; t_I(\text{EN 14 015})]$

$t_{II} = \max [t_{II}(\text{EN 1993-4-2}) \; ; \; t_{II}(\text{EN 14 015})]$

Of course, it can’t be greater than max value in 1993-1-10 and EN 14 015 (→ #t / 14).

If is greater, you must change grade or subgrade of steel.

Stability of shell

Checking conditions for this type of calculations: EN 1993-4-2 11.3.2 (10)

H_E - part of shell in danger of buckling

H_P - self-stability high of shell

$H_E = \Sigma\, h_i\, (t_{min} / t_i)^{2,5}$ EN 1993-4-2 (11.24)

EN 14 015 (8), (9)

$t_{min} = \min\,(t_i)$

$H_E > H_P \rightarrow$ there are needed few secondary stiffening rings, equally spaced at separations H_P

H_P = min (EN 1993-4-2 ; EN 14 015)

$H_P = [A / (5{,}70\, q_{wind} + 5{,}80\, p_{under})]\, \sqrt{[t_{min}^5 / (2\, r)^3]}$ EN 14 015 (10), (11)

$A = 3\,004$ GPa

$q_{wind} = \rho_{air}\, V_b^2 / 2$

$H_P = 0{,}46\, (E / p_{Ed})\, (t_{min} / r)^{2{,}5}\, r\, K$ EN 1993-4-2 (11.25)

K, p_{Ed} → next slide

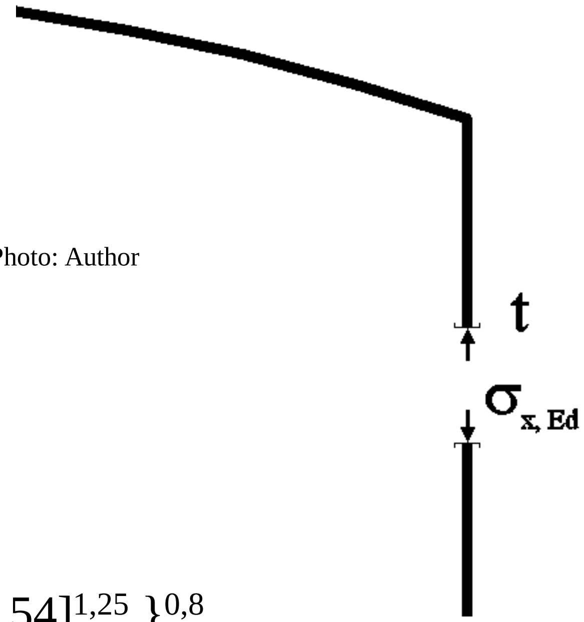

Photo: Author

$p_{Ed} = p_{under} + q_{Ed}$

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

EN 1993-4-2 (11.27)

$\sigma_{x,Ed}$ = dead weigth of steel structure + snow + underpressure + max wind pressure on roof

$q_{Ed} \rightarrow$ next slide

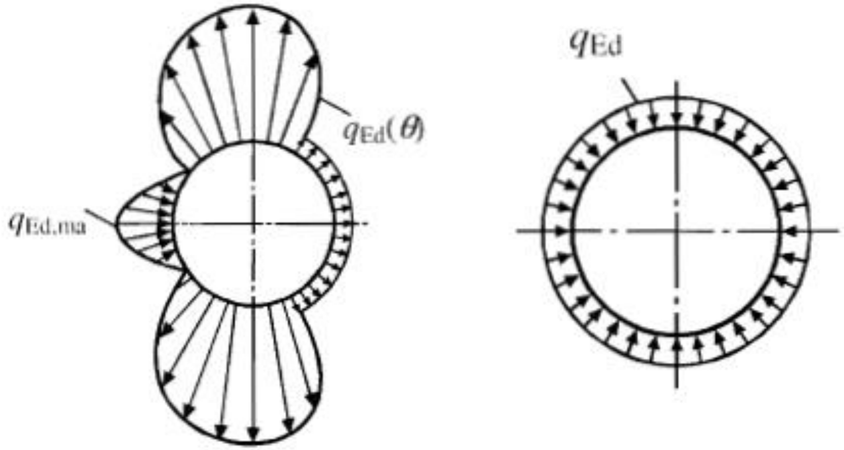

Photo: EN 1993-4-2 fig. 11.5

$$q_{Ed} = q_{Ed\,max} / C_w$$

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

$H_E > H_P \rightarrow$ there are needed few secondary stiffening rings, equally spaced at separations H_P

Stiffness and distance between secondary stiffening rings EN 1993-4-2 11.3.2 (13), (15)

Recommendation for this design project: better way is increase value of t_{min}

Of course, t can't be greater than max value in 1993-1-10 and EN 14 015 (→ #t / 14).

If is greater, you must change grade or subgrade of steel.

Man holes, nozzles

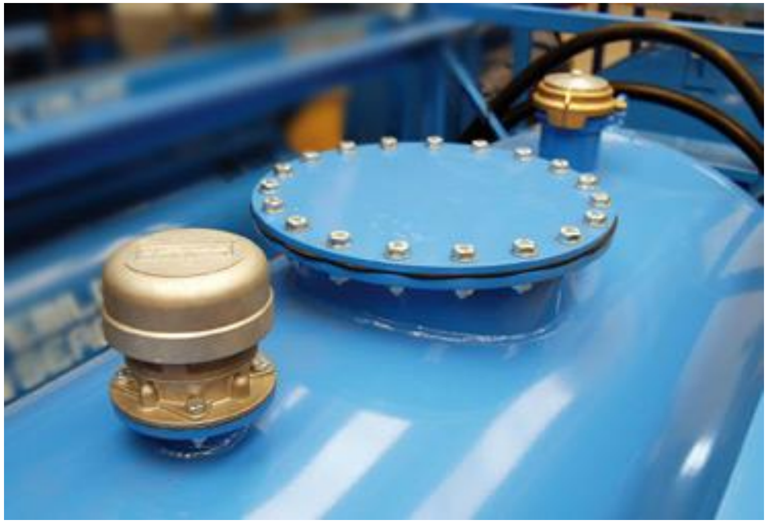

Photo: dystrybutory-paliw.pl

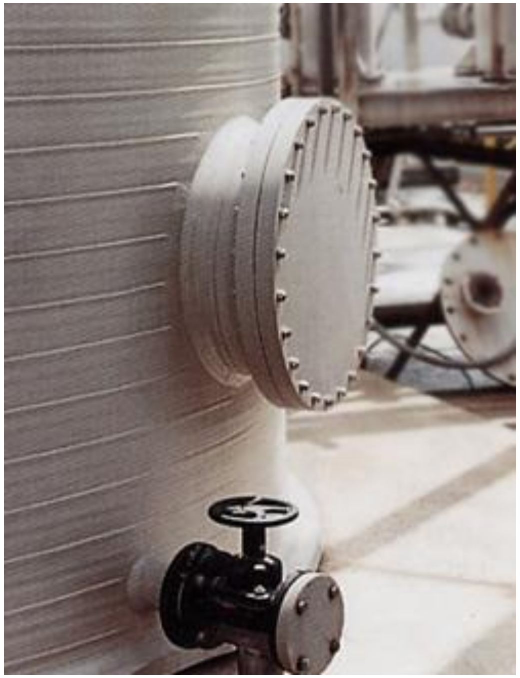

Photo: formoplast.com

Bottom

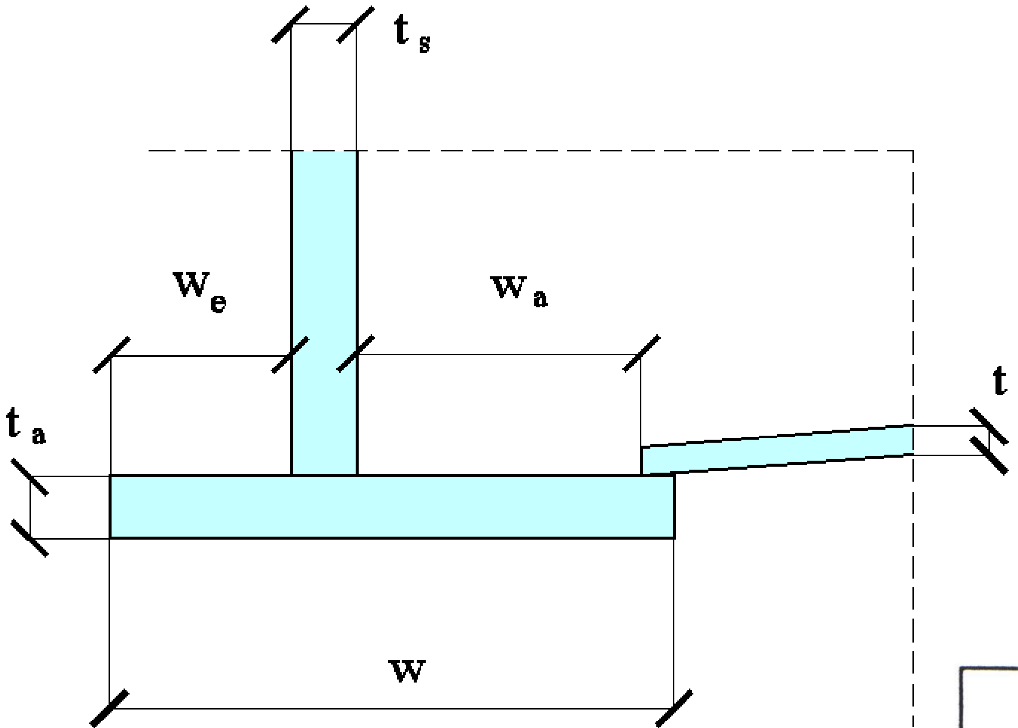

Photo: Author

PN B 3210 tab. 7

Tank diameter w

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

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

Internal tank diameter	t
Średnica wewnętrzna zbiornika m	Minimalna grubość blach środkowej części dna[1)] 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

1) Bez naddatku na korozję.

PN B 3210 tab. 5

$t_a = \max (t_c / 3 + 3 \text{ mm} + t_{corrosion} \quad ; \quad 6 \text{ mm})$ EN 1993-4-2 (11.37)

EN 14 015 (1)

$t_c = t_s - t_{corrosion}$

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

$\rho = \max (\rho_{H2O} \quad ; \quad \rho_{fuel})$

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

A = 57 600 m

$w_a \geq$ max (EN 1993-4-2 ; EN 14 015)

$50 \text{ mm} \leq w_e \leq 100 \text{ mm}$ EN 14 015 8.3.2

Global stability

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EN 1993-4-2 11.5

Tank can't be lifted up, pushed, rotated. Wind action and overpressure must be smaller than dead weight of tank. There is important position of wind action on cylinder (y) and dome (x). This is EQU LS.

W - wind pressure on cylindrical shell (design value)

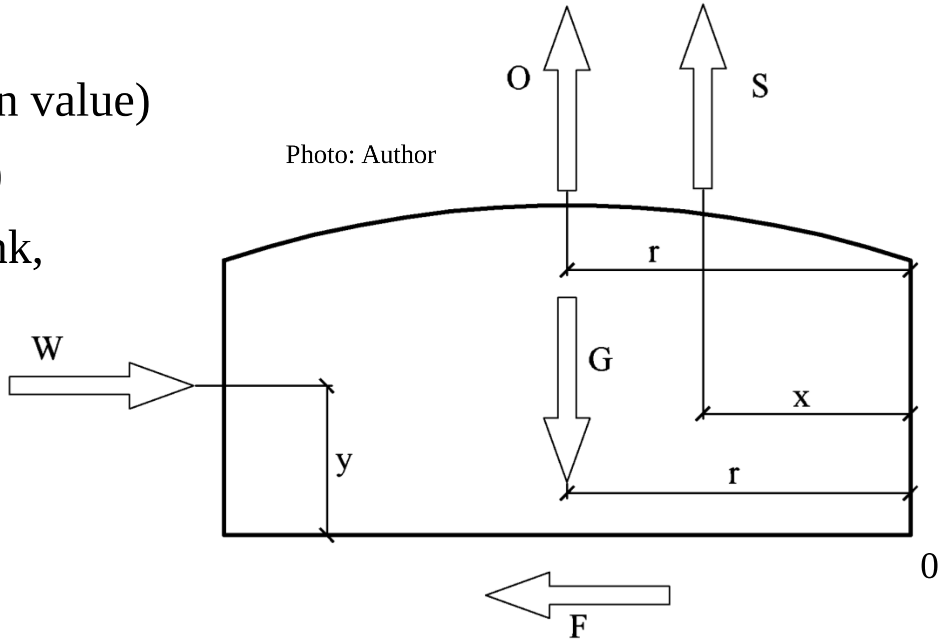
S - wind suction on dome roof (design value)

G_k - dead weight of steel structure (empty tank, characteristic value)

O – overpressure (design value)

F_k - friction (characteristic value)

Photo: Author



Requirements for global stability:

No lifting up: $O + S < 0{,}9\ G_k$

No pushing: $W < 0{,}9\ F_k$

No rotation around point 0: $W\ y + S\ x + O\ r < 0{,}9\ G_k\ r$

$O = \pi\ r^2\ p_{over}$

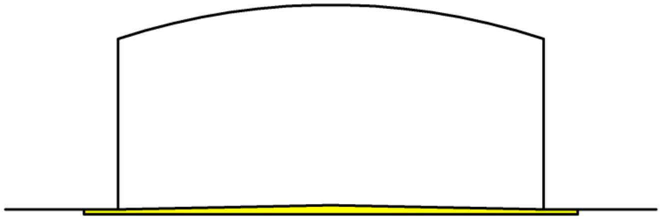
$F_k = (G_k - S - O)\ \mu$

$\mu = 0{,}3$

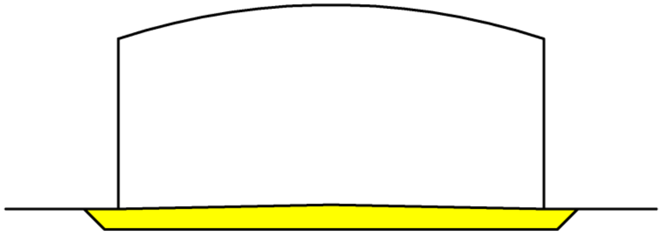
Foundations - ground conditions

→ #1 / 83

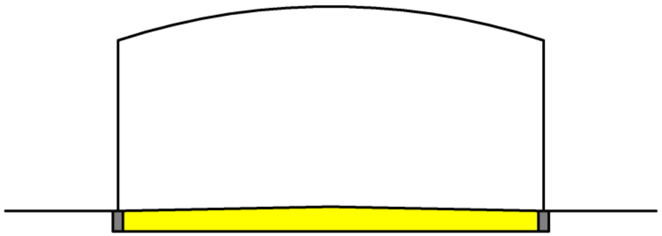
Photo: Author



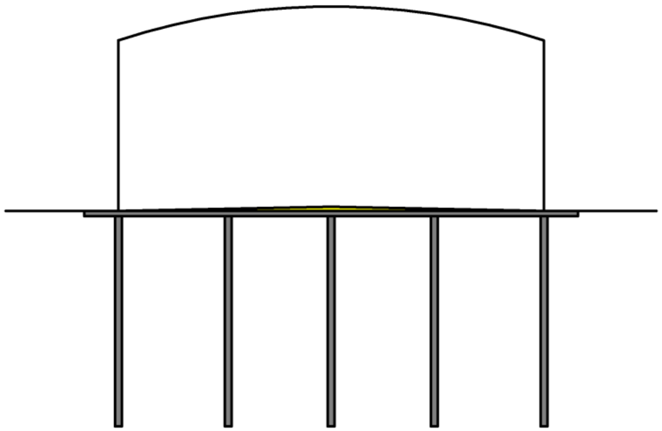
Very good (cohesionless bearing); sand bed to a depth of humus (about 30 cm)



Good (cohesive bearing); sand bed to a depth of frost penetration (about 120 cm)



Bad (cohesive non-bearing or cohesionless non-bearing); reinforced concrete ring under the shell + sand bed to a depth of frost penetration (about 120 cm)



Very bad (peat, made ground) sand bed, reinforced concrete slab, piles

→ #1 / 84

Ground conditions	Foundations	
	Conditions for global stability satisfied	Conditions for global stability not satisfied
Very good	Sand bed ~ 30 cm	Concrete ring
Good	Sand bed ~ 120 cm	
Bad	Concrete ring	
Very bad	Concrete slab and piles	

Drawing and list of materials

Thank you for attention

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