WIND LOAD ON SILOS

The aim of this technical note is to make an introduction to the effect of the wind on a silo by identifying the forces that appear on weighing assemblies in addition to the silo weight. The following calculations are approximations and cannot substitute the necessary calculations and safety considerations that should be performed by a qualified technician.

First of all, we should identify the involved forces in the system; analyse how these forces affect to the selection of the load cell capacity and accessories, and consider if it will be necessary to implement some additional restraint methods.

The following figure shows a 4-legged silo and the involved forces in presence of wind:

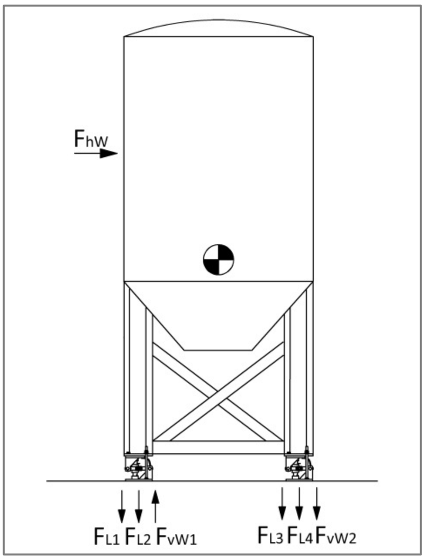

Fig. 1: Forces that appears in a silo weighing system

F_{hW} : Horizontal wind force against the silo
F_{L1}: Product weight against the load cell
F_{L2}: Structure weight against the load cell
F_{vW1}: Vertical wind force (lifting force)
F_{L3}: Product weight against the load cell
F_{L4}: Structure weight against the load cell
F_{vW2}: Vertical wind force (against the load cell)

To calculate the forces involved in a silo, it's necessary to decompose those forces in horizontal and vertical forces to obtain the maximum force applied on each load cell and accessory.

Horizontal wind force will be the same independently that the silo is full of product or empty; this is not the case for vertical forces applied to load cells and mounting accessories. For this reason two scenarios will be calculated: when the silo is full of product, and when the silo is empty.

The following table shows the anemometric Beaufort scale, it's an empirical measure that relates wind speed by observing sea and land.

Beaufort	Wind	Speed (m/s)	Speed (km/h)	Land effects
0	Calm	<0,5	0-1	Calm. Smoke rises vertically
1	Light Air	0,6-1	2-5	Smoke drift indicates wind direction. Leaves and wind vanes are stationary
2	Light Breeze	2-3	6-11	Wind felt on exposed skin. Leaves rustle. Wind vanes begin to move
3	Gentle Breeze	4-5	12-19	Leaves and small twigs constantly moving, light flags extended
4	Moderate Breeze	6-8	20-28	Dust and loose paper raised. Small branches begin to move
5	Fresh Breeze	9-11	29-38	Branches of a moderate size move. Small trees in leaf begin to sway
6	Strong Breeze	12-14	39-49	Large branches in motion. Whistling heard in overhead wires. Umbrella use becomes difficult. Empty plastic bins tip over
7	High Wind	15-17	50-61	Whole trees in motion. Effort needed to walk against the wind
8	Gale	18-20	62-74	Some twigs broken from trees. Cars veer on road. Progress on foot is seriously impeded
9	Strong Gale	21-24	75-88	Some branches break off trees, and some small trees blow over. Construction/temporary signs and barricades blow over
10	Storm, Whole Gale	25-28	89-102	Trees are broken off or uprooted, saplings bent and deformed. Poorly attached asphalt shingles and shingles in poor condition peel off roofs
11	Violent Storm	29-34	103-117	Widespread damage to vegetation. Many roofing surfaces are damaged; asphalt tiles that have curled up and/or fractured due to age may break away completely
12	Hurricane	>34	>118	Very widespread damage to vegetation. Some windows may break; mobile homes and poorly constructed sheds and barns are damaged. Debris and unsecured objects are hurled about

The user can find wind maps of Spain in the website below:
http://atlaseolico.idae.es/index.php?pag=descarga_mapas

3-LEGGED SILO

Study of horizontal force on a 3-legged silo

CALCULATION OF HORIZONTAL WIND FORCE

First step is calculating the horizontal wind force on the silo:

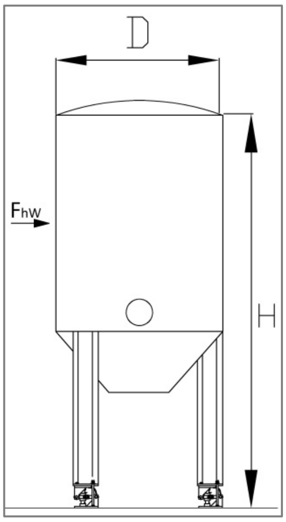

Fig. 2: Horizontal wind force

$\mathbf{F_{hW} = C_w \cdot 0{,}5 \cdot \rho_L \cdot v^2 \cdot A}$

Where,

F_{hW} = Horizontal wind force (N)

C_w = = Drag coefficient, for an upright circle cylinder = 0,8

ρ_L = Air density (kg/m^3) = 1,25 (kg/m^3)

v = Wind speed (m/s)

A = Projected surface area of the silo (m^2)

A = H · D

where,

A = Height of the silo (m)

D = Diameter of the silo (m)

Using these values of C_w and ρ_L:

$\mathbf{F_{hW} = 0{,}5 \cdot v^2 \cdot A}$

EFFECT OF HORIZONTAL FORCE ON ACCESSORIES

Calculation of the horizontal component of the wind force on each accessory:

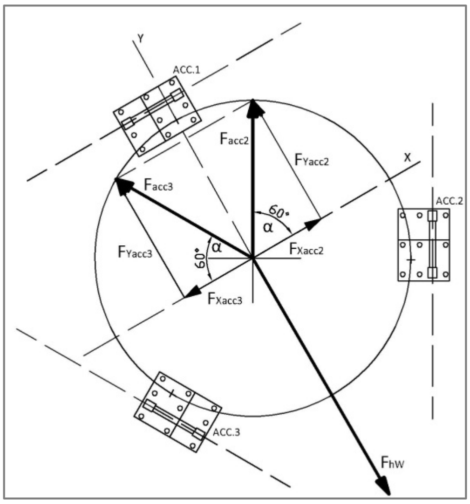

Fig. 3: Silo top view and horizontal wind force

Accessories are allocated with the retention arm tangentially to the contour of the silo and 120° between them.
We will consider that accessories only support forces on the tangent of the silo which means that only two accessories (F_{acc2} and F_{acc3}) will contribute to withstand the horizontal wind force (F_{hW}). We will apply **balance of forces:**

$\Sigma F_X = 0$

$\Sigma F_X = F_{acc2} \cdot \cos\alpha - F_{acc3} \cdot \cos\alpha = 0$

$F_{acc2} = F_{acc3}$

$\Sigma F_Y = 0$

$\Sigma F_Y = F_{acc1} \cdot \sin\alpha + F_{acc2} \cdot \sin\alpha - F_{hW} = 0$

where:

$\alpha = 60°$

$F_{acc2} = F_{acc3} = F_{acc}$

$F_{hW} = 2 \cdot F_{acc} \cdot \sin 60°$

$\mathbf{F_{acc} = 0{,}58 \cdot F_{hW}}$

We should ensure that each mounting accessory for a 3-legged silo, can withstand at least the wind force multiplied by 0,58.

Study of vertical force on a 3-legged silo

CALCULATION OF VERTICAL WIND FORCE

For a 3-legged silo, the involved forces are:

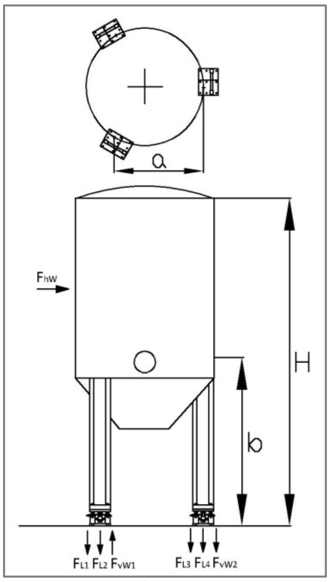

Fig. 4: Vertical forces

$\mathbf{F_{vW} = F_{hW} \cdot \frac{b}{a}}$

where,

D = Diameter of the silo (m)

H = Height of the Silo (m)

F_{L1}= Force exerted by the product weight against the load cell (N)

F_{L2}= Force exerted by the structure weight against the load cell (N)

F_{vW1}=Vertical wind force (lifting wind force): $|F_{vW}|$ (N)

F_{L3}= Force exerted by the product weight against the load (N)

F_{L4}= Force exerted by the structure weight against the load cell (N)

F_{vW2} = Vertical wind force (against the load cell): $|F_{vW}|$ (N)

$F_{hW} = 0{,}5 \cdot v^2 \cdot A$

b = Vertical distance between the force action point and the load cell plane (m). Where: $b = \frac{H}{2}$

a = Horizontal distance between load cells (m). Where: $a_{3\text{-legged silo}} = 0{,}75 \cdot D$

$\mathbf{F_{vW} = 0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot 0{,}75 \cdot D}}$

EFFECT OF VERTICAL FORCE ON WINDWARD

We are going to calculate the resultant vertical force received on legs located on windward when the silo is empty, this is the most critical situation that the mounting accessory must stand:

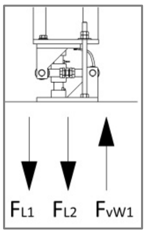

Fig. 5: Windward

$\mathbf{F_{Lifting} = F_{L1} + F_{L2} - F_{vW1}}$

where,

F_{L1} = Force exerted by the product. Empty silo $F_{L1} = 0$ (N)

F_{L2} = Force exerted by the structure = $\left(\frac{\text{Structure weight}}{\text{Number of supports}}\right) \cdot 9{,}8$ (N)

F_{vW1} = Lifting wind force = $0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot 0{,}75 \cdot D}$ (N)

$\mathbf{F_{Lifting} = 0 + \left(\frac{\text{Structure weight}}{\text{Number of supports}}\right) \cdot 9{,}8 - 0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot 0{,}75 \cdot D}}$ **(N)**

If $F_{Lifting}$ is negative, it means that when the silo is empty, it will receive a lifting force on windward legs equal to $F_{Lifting}$. We should choose a mounting accessory that withstands at least this lifting force, if it's not the case, we should provide the system with additional restraint methods.

EFFECT OF VERTICAL FORCE ON LEEWARD

We are going to calculate the resultant vertical force received on legs located on leeward, when the silo is full of product, this is the most critical situation that must stand the load cell:

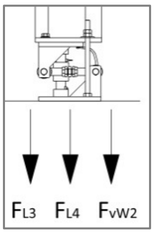

Fig. 6: Leeward

$\mathbf{F_{Against\ load\ cell} = F_{L3} + F_{L4} + F_{vW2}}$

where,

F_{L3}= Force exerted by the product = $\left(\frac{\text{Product weight}}{\text{Number of supports}}\right) \cdot 9{,}8$ (N)

F_{L4}= Force exerted by the structure = $\left(\frac{\text{Structure weight}}{\text{Number of supports}}\right) \cdot 9{,}8$ (N)

F_{vW2} = Wind force against the load cell = $0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot 0{,}75 \cdot D}$ (N)

$\mathbf{F_{Against\ load\ cell} = \left(\frac{\text{Product weight}}{\text{Number of supports}} + \frac{\text{Structure weight}}{\text{Number of supports}}\right) \cdot 9{,}8 + 0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot 0{,}75 \cdot D}}$ (N)

This result indicates the resultant $F_{Against\ load\ cell}$ in the leeward legs when the silo is full. It's necessary to choose a load cell capacity that withstands at least this resultant force.

Example of a 3-legged

There is a 64 m³ capacity silo of 40t. Dead load is 5t. The dimensions are 9m height and 3m of diameter. It's going to be subjected to winds gusting up to 40m/s.

Study of horizontal force on a 3-legged silo

CALCULATION OF HORIZONTAL WIND FORCE

$F_{hW} = 0{,}5 \cdot v^2 \cdot A$

$F_{hW} = 0{,}5 \cdot 40^2 \cdot (9 \cdot 3)$

F_{hW} = 21.600 N, or the equivalent in weight 2,2 t

EFFECT OF HORIZONTAL FORCE ON ACCESSORIES

$F_{acc} = 0{,}58 \cdot F_{hW}$

$F_{acc} = 0{,}58 \cdot 21.600$ N

F_{acc} = 12.600 N, or the equivalent in weight 1,3 t

Accessories for this installation should withstand at least lateral forces of 1,3t

Study of vertical force on a 3-legged silo

LOAD CELL SELECTION

Load Cell Capacity = $\frac{\text{Safety Factor} \cdot \text{Gross Weight}}{\text{Number of legs}}$

Load Cell Capacity = $\frac{1{,}3 \cdot 45.000}{3}$

Load Cell Capacity = 20 t

CALCULATION OF VERTICAL WIND FORCE

$F_{vW} = 0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot 0{,}75 \cdot D}$

$F_{vW} = 0{,}5 \cdot 40^2 \cdot (9 \cdot 3) \cdot \frac{9}{2 \cdot 0{,}75 \cdot 3}$

F_{vW} = 43.200 N, or the equivalent in weight 4,4 t

EFFECT OF VERTICAL FORCE ON WINDWARD (Empty silo)

$F_{Lifting} = 0 + \frac{\text{Structure weight}}{\text{Number of legs}} - 0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot 0{,}75 \cdot D}$

$F_{Lifting} = \left(0 + \frac{5.000}{3}\right) \cdot 9{,}8 - 0{,}5 \cdot 40^2 \cdot 9 \cdot 3 \cdot \frac{9}{2 \cdot 0{,}75 \cdot 3} = -27.000 \text{ N}$

Lifting force with an empty silo = -27.000 N, or the equivalent in weight -2,8 t

The negative result indicates that the silo when it is empty will receive a resultant lifting force in the windward legs of 2,8 t. We should choose a mounting accessory that withstands at least this lifting force, if it's not the case, we should provide the system with additional restraint methods.

EFFECT OF VERTICAL FORCE ON LEEWARD (Full silo)

$F_{Against\ load\ cell} = \frac{\text{Product weight}}{\text{Number of legs}} + \frac{\text{Structure weight}}{\text{Number of legs}} + 0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot 0{,}75 \cdot D}$

$F_{Against\ load\ cell} = \left(\frac{40.000}{3} + \frac{5.000}{3}\right) \cdot 9{,}8 + 0{,}5 \cdot 40^2 \cdot 9 \cdot 3 \cdot \frac{9}{2 \cdot 0{,}75 \cdot 3} = 191.000 \text{ N}$

Force against the load cell with a silo full of product = 191.000 N, or the equivalent in weight 20 t

This result indicates that when the silo is full, will receive a resultant force in the leeward legs of 20 t. It's necessary to choose a load cell capacity that withstands at least this resultant force against the load cell.

Conclusions for a 3-legged silo

1) **Verification of load cell selection**
After calculating the resultant force received on each load cell when the silo is full, is necessary to check that the previous calculation made to select load cell capacity for each leg is still correct. In this example, both calculations indicate that the capacity of each load cell should be at least 20 t. If both calculations don't resolve with the same value is necessary to choose the highest capacity obtained because is the most critic case. It's very important to perform this check after finishing calculations.

2) **Verification of the mounting kit**
With the results obtained we will choose a mounting kit with the following parameters:

Nominal load	15...50 t
Max. permissible side offset transverse to retention arm	±4 mm
Permissible horitz. force in direction of the retention arm	47 kN
Maximum permissible lifting force	76 kN
Max. permissible lifting movement, must be adjusted	3 mm
Material: Steel alloy zinc-plated	

a) **Permissible horizontal force on the direction of the retention arm:** refers to the maximum horizontal force that the accessory should withstand. According to the datasheet, the accessory can withstand 47 kN of horizontal force. Our system needs to withstand at least 12,6 kN. This accessory will satisfy the needs of the system without adding additional restraint methods.

b) **Maximum permissible lifting force:** refers to the maximum vertical force that the accessory will withstand. According the datasheet, the accessory can withstand 76 kN of lifting forces. Our system needs to withstand at least 27 kN. This accessory will satisfy the needs of the system without adding additional restraint methods.

4-LEGGED SILO

Study of horizontal force on a 4-legged silo

CALCULATION OF HORIZONTAL WIND FORCE

First step is calculating the horizontal wind force on the silo:

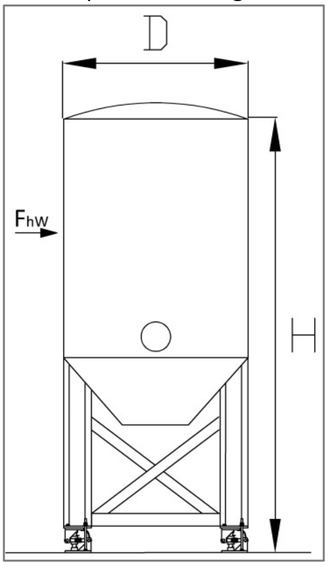

Fig. 7: Horizontal wind force

$$\mathbf{F_{hW} = C_w \cdot 0{,}5 \cdot \rho_L \cdot v^2 \cdot A}$$

where,

F_{hW} = Horizontal wind force (N)

C_w = = Drag coefficient, for an upright circle cylinder = 0,8

ρ_L = Air density (kg/m^3) = 1,25 (kg/m^3)

v = Wind speed (m/s)

A = Projected surface area of the silo (m^2)

$A = H \cdot D$

where,

A = Height of the silo (m)

D = Diameter of the silo (m)

Using these values of C_w and ρ_L:

$$\mathbf{F_{hW} = 0{,}5 \cdot v^2 \cdot A}$$

EFFECT OF HORIZONTAL FORCE ON ACCESSORIES

Calculation of the horizontal component of the wind force on each accessory:

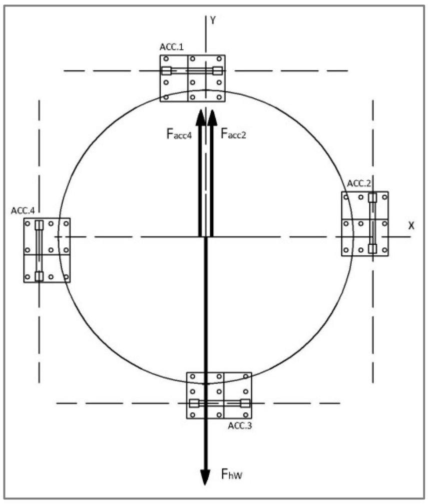

Fig. 8: Silo top view and horizontal wind force

Accessories are allocated with the retention arm tangentially to the contour of the silo and 90° between them.

We will consider that the accessories only support forces on the tangent of the silo which means that only two accessories (F_{acc2} and F_{acc3}) will contribute to withstand the horizontal wind force (F_{hW}). We will apply **balance of forces:**

$\Sigma F_X = 0$

$\Sigma F_Y = 0$

$\Sigma F_Y = F_{acc2} + F_{acc4} - F_{hW} = 0$

where:

$F_{acc2} = F_{acc4} = F_{acc}$

$F_{hW} = 2 \cdot F_{acc}$

$\mathbf{F_{acc} = 0{,}5 \cdot F_{hW}}$

We should ensure that each mounting accessory for a 4-legged silo, can withstand at least the wind force multiplied by 0,5.

Study of vertical force on a 4-legged silo

CALCULATION OF VERTICAL WIND FORCE

For a 4-legged silo, the involved forces are:

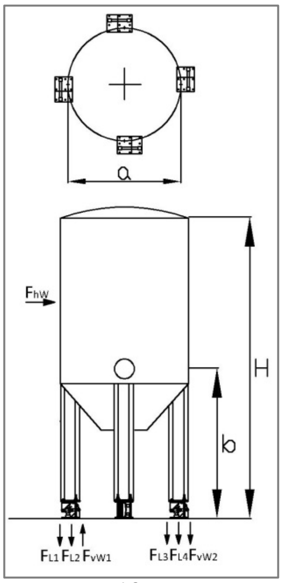

Fig. 9: Vertical forces

$$\mathbf{F_{vw} = F_{hw} \cdot \frac{b}{a}}$$

where,

D = Diameter of the silo (m)

H = Height of the Silo (m)

F_{L1}= Force exerted by the product weight against the load cell (N)

F_{L2}= Force exerted by the structure weight against the load cell (N)

F_{vW1}=Vertical wind force (lifting wind force): $|F_{vw}|$ (N)

F_{L3}= Force exerted by the product weight against the load (N)

F_{L4}= Force exerted by the structure weight against the load cell (N)

F_{vW2} = Vertical wind force (against the load cell): $|F_{vw}|$ (N)

$F_{hW} = 0,5 \cdot v^2 \cdot A$

b = Vertical distance between the action point of force applied and the load cell plane (m). Where: $b = \frac{H}{2}$

a = Horizontal distance between load cells (m). Where: $a_{4\text{-legged silo}} = D$

$$\mathbf{F_{vw} = 0,5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot D}}$$

EFFECT OF VERTICAL FORCE ON WINDWARD

We are going to calculate the resultant vertical force received on legs located on windward, when the silo is empty, this is the most critical situation that must stand the mounting accessory:

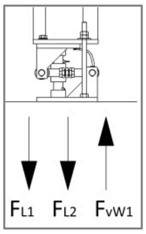

Fig. 10: Windward

$$\mathbf{F_{Lifting} = F_{L1} + F_{L2} - F_{vW1}}$$

Where,

F_{L1} = Force exerted by the product. Empty silo $F_{L1} = 0$ (N)

F_{L2} = Force exerted by the structure = $\left(\frac{\text{Structure weight}}{\text{Number of supports}}\right) \cdot 9,8$ (N)

F_{vW1} = Lifting wind force = $0,5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot D}$ (N)

$$\mathbf{F_{Lifting} = 0 + \left(\frac{\text{Structure weight}}{\text{Number of supports}}\right) \cdot 9,8 - 0,5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot D}\ (N)}$$

If $F_{Lifting}$ is negative, it means that when the silo is empty, it will receive a lifting force on windward legs equal to $F_{Lifting}$. We should choose a mounting accessory that withstands at least this lifting force, if it's not the case, we should provide the system with additional restraint methods.

EFFECT OF VERTICAL FORCE ON LEEWARD

We are going to calculate the resultant vertical force received on legs located on leeward, when the silo is full of product, this is the most critical situation that must stand the load cell:

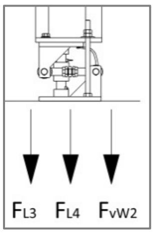

Fig. 11: Leeward

$$\mathbf{F_{Against\ load\ cell} = F_{L3} + F_{L4} + F_{vW2}}$$

where,

F_{L3}= Force exerted by the product = $\left(\frac{\text{Product weight}}{\text{Number of supports}}\right) \cdot 9,8$ (N)

F_{L4}= Force exerted by the structure = $\left(\frac{\text{Structure weight}}{\text{Number of supports}}\right) \cdot 9,8$ (N)

F_{vW2} = Wind force against the load cell = $0,5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot D}$ (N)

$$\mathbf{F_{Against\ load\ cell}} = \left(\frac{\text{Product weight}}{\text{Number of supports}} + \frac{\text{Structure weight}}{\text{Number of supports}}\right) \cdot \mathbf{9,8 + 0,5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot D}}\ (N)$$

This result indicates the resultant $F_{Against\ load\ cell}$ in leeward legs when the silo is full. It's necessary to choose a load cell capacity that withstands at least this resultant $F_{Against\ load\ cell}$.

Example of a 4-legged

There is a 64 m³ capacity silo of 40t. Dead load is 5t. The dimensions are 9m height and 3m of diameter. It's going to be subjected to winds gusting up to 40m/s.

Study of horizontal force on a 4-legged silo

CALCULATION OF HORIZONTAL WIND FORCE

$F_{hW} = 0{,}5 \cdot v^2 \cdot A$

$F_{hW} = 0{,}5 \cdot 40^2 \cdot (9 \cdot 3)$

F_{hW} = 21.600 N, or the equivalent in weight 2,2 t

EFFECT OF HORIZONTAL FORCE ON ACCESSORIES

$F_{acc} = 0{,}5 \cdot F_{hW}$

$F_{acc} = 0{,}5 \cdot 21.600$ N,

F_{acc} = 11.000 N or the equivalent in weight 1,2 t

Los accesorios necesarios para esta instalación deben aguantar fuerzas horizontales de al menos 1,2 t.

Study of vertical force on a 4-legged silo

LOAD CELL SELECTION

Load Cell Capacity = $\frac{\text{Safety Factor} \cdot \text{Gross Weight}}{\text{Number of legs}}$

Load Cell Capacity = $\frac{1{,}5 \cdot 45.000}{4}$

Load Cell Capacity = 17 t

CALCULATION OF VERTICAL WIND FORCE

$F_{vW} = 0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot D}$

$F_{vW} = 0{,}5 \cdot 40^2 \cdot (9 \cdot 3) \cdot \frac{9}{2 \cdot 3}$

F_{vW} = 32.400 N, or the equivalent in weight 3,4 t

EFFECT OF VERTICAL FORCE ON WINDWARD (Empty silo)

$F_{Lifting} = 0 + \frac{\text{Structure weight}}{\text{Number of legs}} - 0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot D}$

$F_{Lifting} = \left(0 + \frac{5.000}{4}\right) \cdot 9{,}8 - 0{,}5 \cdot 40^2 \cdot 9 \cdot 3 \cdot \frac{9}{2 \cdot 3}$ = -20.150 N

Lifting force in an empty silo = -20.150, or the equivalent in weight -2,1 t

The negative result indicates that the silo when it is empty will receive a resultant lifting force in the windward legs of 2,1 t. We should choose a mounting accessory that withstands at least this lifting force, if it's not the case, we should provide the system with additional restraint methods.

EFFECT OF VERTICAL FORCE ON LEEWARD (Full silo)

$F_{Against\ load\ cell} = \frac{\text{Product weight}}{\text{Number of legs}} + \frac{\text{Structure weight}}{\text{Number of legs}} + 0{,}5 \cdot v^2 \cdot A \cdot \frac{H}{2 \cdot D}$

$F_{Against\ load\ cell} = \left(\frac{40.000}{4} + \frac{5.000}{4}\right) \cdot 9{,}8 + 0{,}5 \cdot 40^2 \cdot 9 \cdot 3 \cdot \frac{9}{2 \cdot 3}$ = 143.000 N

Force against the load cell in a silo full of product = 143.000 N, or the equivalent in weight 15 t

This result indicates that when the silo is full, will receive a resultant force in the leeward legs of 15 t. It's necessary to choose a load cell capacity that withstands at least this resultant force against the load cell.

Conclusions for a 4-legged silo

1) **Verification of load cell selection**
After calculating the resultant force received on each load cell when the silo is full, is necessary to check that the previous calculation made to select load cell capacity for each leg is still correct. In this example, both calculations resolves that the capacity of each load cell should be at least 17 t, and the resultant force that each load cell need to withstand when the silo is full, is 15 t, as both results are not equal, is necessary to choose the highest value. Is very important to perform this check after finishing calculations.

2) **Verification of the mounting kit**
With the results obtained we will choose a mounting kit with the following parameters:

Nominal load	15...50 t
Max. permissible side offset transverse to retention arm	±4 mm
Permissible horitz. force in direction of the retention arm	47 kN
Maximum permissible lifting force	76 kN
Max. permissible lifting movement, must be adjusted	3 mm
Material: Steel alloy zinc-plated	

a) **Permissible horizontal force in direction of the retention arm:** refers to the maximum horizontal force that the accessory should withstand. According to the datasheet, the accessory can withstand 47 kN of lateral forces. Our system needs to withstand at least 11 kN. This accessory will satisfy the needs of the system without adding additional restraint methods.

b) **Maximum permissible lifting force:** refers to the maximum vertical force that the accessory will withstand. According the datasheet, the accessory can withstand 76 kN of lifting forces. Our system needs to withstand at least 20,15 kN. This accessory will satisfy the needs of the system without adding additional restraint methods.

From Utilcell we hope this technical note can be of help when making wind calculations on silos, only as a guideline and not serve as a contractual specification. We reserve the right to change the content of this technical note at any time without notice.
Remaining at your disposal for any further information.