THEORY OF STATIONARY SILOS DESIGN APPLIED TO THE CONCEPTION OF ROAD SILO SEMITRAILER LOAD BOX

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Abstract. *Brazil presents a large fleet of load vehicles for road transportation. In the segment of road silos it was evidenced the necessity for obtaining optimized products and allowing the user to transport the maximum load in each travel. This work intends to study only the static design of the road silo, analyzing the existing theory for the stationary silos design and evaluating its applicability to the road silo design, considering the interest in knowing the true influence of the loading/unloading operation of the material confined in the silo. To optimize the road silo design it is necessary to know the different loading conditions to which the product will be submitted for choosing the most critical situation. The design of one road silo case is analyzed with two theories: stationary silos and pressure vessels, demonstrating that the most critical situation must follow the formal theory of pressure vessels and concluding that the critical loading factor is the air pressure used to discharge the product.*

Keywords*: road silo, bulk solids handling, load transportation*

1. INTRODUCTION

Brazil currently possesses a considerable fleet of load vehicles for road transport, being this type of transport the most used for the national movement of goods. The load transport for highways presents an important cost, still more if this cost is paid by the last consumer.

Observing in particular the segment that uses road silos for the load transport, there is necessity for obtaining products that can carry the most possible liquid load. Each manufacturer offers one product in agreement with its availability, however nor always what it is offered is the most adequate to the necessity.

There is no specialized literature on the project of road silos; then, the objective of this work is to analyze the theory used for dimensioning stationary silos, in order to verify its applicability in road silos.

2. ROAD SILO SEMITRAILER

The road silo semitrailer is used for the transport of bulk solid material (grains, powders, ashes, etc). As major characteristics of the product it is important the load box closed similar to a tank, the presence of inspection covers in the upper part, shipment using gravity and system of discharge through internal pressurization .

The benefits because of the transport of solid material through road silos involve better protection of bulk solids in relation to the environment. Fig. 1 shows a road silo manufactured by Randon company.

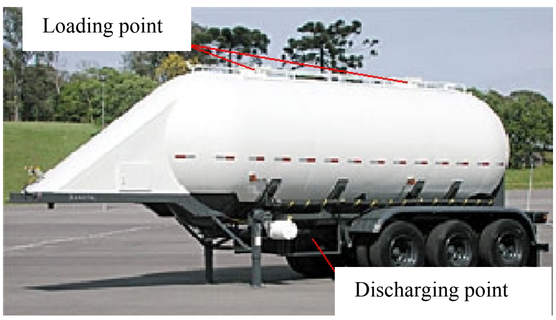

Figure 1. Road silo semitrailer (Randon, 2004).

2.1. Data on solids necessary for the design

The bulk unit weight γ or density ρ and the wall friction coefficient μ are some of the most important material properties, which define the behavior of the particulate solid into the road silo (Woodcock and Mason, 1993).

The stress ratio λ in the vertical walled section of a silo is defined as the ratio of the horizontal stress in the solid near the wall σ_h and the mean vertical stress σ_v, as given by Eq. (1).

Each solid has a specific stress ratio. While an ideal and rigid solid shows λ equal to 0, one fluid has λ near to 1, and any solid generally shows values of λ between 0.3 and 0.6 (Schulze, 2005). Values of λ are gotten experimentally.

$$\lambda = \frac{\sigma_h}{\sigma_v} \qquad (0 < \lambda < 1) \tag{1}$$

The angle of repose of the solid ϕ_r is defined as the maximum angle to the horizontal, assumed by the free surface of a conical pile of bulk solid at rest. Figure 3 shows this situation.

Considering the loading situation, the angle of repose of the solid must be observed to establish the amount of inspection covers to be installed in the top of the load box.

2.2. Sructural analisys of the road silo

The membrane theory of shells is generally adequate for design under symmetrical conditions. Under unsymmetrical conditions, this theory gives a poor measure of real stress states except under special situations, such as smoothly varying pressures. In the road silo, this theory can be considered for dimensioning the barrel section of the silo.

Problems in which local bending occurs require the bending theory of shells. Under unsymmetrical loading, the bending theory of shells must be used. Where this analysis is needed, a linear or nonlinear finite element analysis should be undertaken, where the last one is only required for a restricted part.

The unloading operation of the silo by pressure is one of the most critical situations to be considered during the design. It occurs without movement of the road silo, and there are no excitations because of the road roughness.

2.3. Wall pressures on filling and storing

The following calculations evaluate the wall pressures and wall frictional tractions at the end of the filling process. The term pressure denotes a normal stress against a silo wall. The frictional traction is the shear stress acting on the wall associated with the normal stress. The frictional traction is related to the pressure by the friction coefficient μ..

Equation (2) is used for calculating the hydrostatic pressure and could provide the operating pressure in the walls of the silo, but this equation provides an overestimated value, because it does not consider the friction of the solid.

$$p = \rho \cdot g \cdot h \tag{2}$$

2.3.1 Division of silo geometries

Stationary silo geometries are divided into three categories based on the aspect ratio of the stored solid h_b/d_c, given by the ratio of the height h_b and the silo diameter d_c, Fig. 2: a) *slender silo* if h_b/d_c exceeds 1.5, b) *intermediate silo* if h_b/d_c lies between 1.0 and 1.5, and c) *squat silo* if h_b/d_c is less than 1.0.

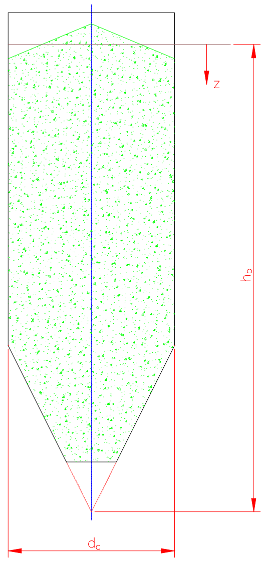

Figure 2. Ratio h_b/d_c

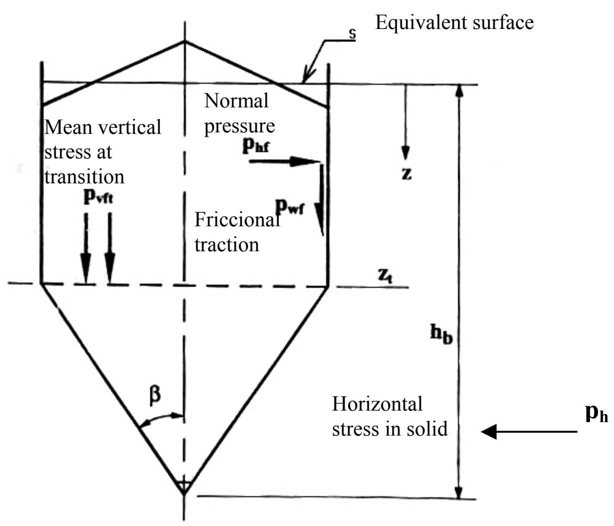

Figure 3. Pressures in barrel after filling (Rotter, 2001)

2.3.2. Symmetrical pressures on barrel section after filling at *slender silo*

The normal pressure p_{hf} on the barrel section of the silo at the depth z below the equivalent surface, the frictional traction p_{wf} on the wall at the depth z, and the mean vertical stress p_{vf} within the stored solid at the depth z are (Fig. 3):

$$p_{hf} = p_{ho} \cdot \left(1 - e^{-z/z_0}\right) \tag{3}$$

$$p_{wf} = \mu \cdot p_{hf} \tag{4}$$

$$p_{vf} = p_{vo} \cdot \left(1 - e^{-z/z_0}\right) \tag{5}$$

with the following reference values:

$$p_{ho} = \frac{\gamma \cdot r}{2 \cdot \mu} \quad \text{(wall pressure at infinite depth)} \tag{6}$$

$$p_{vo} = \frac{\gamma \cdot r}{2 \cdot \lambda \cdot \mu} \quad \text{(vertical stress in solid at infinite depth)} \tag{7}$$

$$z_o = \frac{r}{2 \cdot \lambda \cdot \mu} \quad \text{(\textit{Janssen} reference depth)} \tag{8}$$

where:
- z: distance below the equivalent surface of the solid at maximum filling height,
- μ: wall friction coefficient for the barrel section,
- γ: upper value of the solid unit weight γ_u,
- r: circular silo radius,
- λ: lateral pressure ratio (ratio between horizontal pressure and mean vertical stress in the stored solid), $\lambda = p_h/p_v$.

For hopper calculations, the mean vertical stress in the solid at the transition p_{vft}, at transition height z_t is:

$$p_{vft} = p_{vo} \cdot \left(1 - e^{-z_t/z_0}\right) \tag{9}$$

2.3.3. Symmetrical pressures on barrel section after filling for *squat and intermediate silos*

The normal pressure (p_{hf}) on the barrel section of the silo at the depth z below the surface is given by (Fig. 8):

$$p_{hf} = p_{ho} \cdot \left\{1 - \left[\frac{z - h_o}{z_o - h_o} + 1\right]^{-2}\right\} \tag{10}$$

and the frictional traction on the wall at any level is given by Eq. (4) using the Eq. (10) for the p_{hf} value, and h_o is the value of z at the highest solid-wall contact, as can be seen in Fig. 7, which for a symmetrically filled circular silo of radius r with the angle of repose ϕ_r of the solid is given by:

$$h_o = \frac{r}{3} \cdot tg(\phi_r) \tag{11}$$

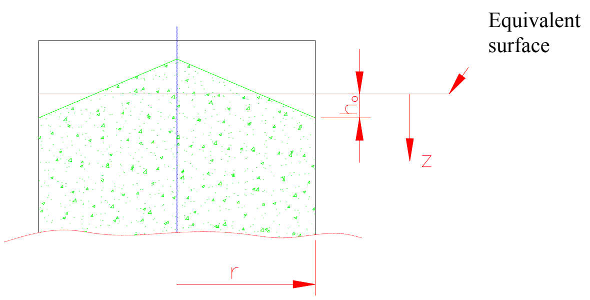

Figure 7. Location of h_o.

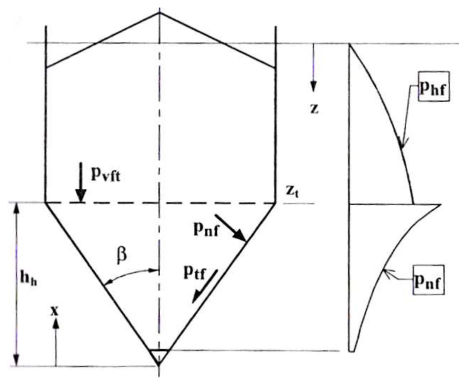

Figure 8. Filling pressures on steep conical hopper walls (Rotter, 2001).

The mean vertical stress p_{vf} within the stored solid at the depth z is assumed by:

$$p_{vf} = p_{vo} \cdot \left\{ 1 - \left[\frac{z - h_o}{z_o - h_o} + 1 \right]^{-2} \right\} \tag{12}$$

Similar to the previous item, Eqs. (6) to (8) can be used for evaluating the values of p_{ho}, p_{vo} and z_o. For hopper calculations, the value of the mean vertical stress in the solid at the transition p_{vft}, at height z_t is:

$$p_{vft} = p_{vo} \cdot \left\{ 1 - \left[\frac{z_t - h_o}{z_o - h_o} + 1 \right]^{-2} \right\} \tag{13}$$

2.3.4 Pressures on *steep* hoppers for *slender silos*

In a *steep* hopper (Fig. 8) the pressures are governed by frictional sliding of the solid against the wall. Hoppers which are too flat to develop the complete wall friction are termed *shallow* (intermediate and squat silos), and have a large apex half angle β. The normal pressures p_{nf} acting on the walls of a conical hopper after storing under symmetrical filling conditions can be found through the following equation:

$$p_{nf} = F_f \cdot p_{vf} \tag{14}$$

The frictional traction acting down the hopper is given by:

$$p_{tf} = \mu_h \cdot p_{nf} \tag{15}$$

The mean vertical stress at height x above the apex of the hopper cone is evaluated by:

$$p_{vf} = \frac{\gamma \cdot h_h}{n-1} \cdot \left[\left(\frac{x}{h_h} \right) - \left(\frac{x}{h_h} \right)^n \right] + p_{vft} \cdot \left(\frac{x}{h_h} \right)^n \tag{16}$$

in which the coefficient n is calculated by:

$$n = 2 \cdot \left(F_f \cdot \mu_h \cdot \cot\beta + F_f - 1 \right) \tag{17}$$

where according to Fig. 8:
h_h: vertical height between the hopper apex and the transition,
x: vertical coordinate upwards from hopper apex,
μ_h: wall friction coefficient for the hopper,
β: hopper apex half angle,
p_{vft}: mean vertical stress in the solid at the transition, given by Eq. (9).

For filling conditions, the value of F_f may be taken from experimental data of Motzkus (1974) as:

$$F_f = \frac{1 + a \cdot \mu \cdot \cot\beta}{1 + \mu \cdot \cot\beta} \tag{18}$$

where the empirical constant a assumes values between 0 and 1, taken here as 0.8 for filling purposes.

2.3.5. Pressures on *shallow* hoppers for *squat and intermediate silos*

Pressures acting on the walls of shallow hoppers may be calculated using Eqs. (14) to (18), but p_{vft} with Eq. (13).

2.4. Stresses generated by the internal pressure in the wall of the silo

Although the air pressure is low for discharging the bulk solid, the silo can be considered as a pressure vessel of thin walls (ASME, 1995), Fig. 9. According to Beer and Johnston (1996), the principal normal stresses σ_1 and σ_2 (termed as *tangential stress* and *longitudinal stress* respectively) and the maximum shear stress τ_{max} in a cylindrical pressure vessel are defined by:

$$\sigma_1 = \frac{p \cdot r}{t}, \qquad \sigma_2 = \frac{p \cdot r}{2 \cdot t}, \qquad \tau_{máx} = \sigma_2 = \frac{p \cdot r}{2 \cdot t} \tag{19}$$

where:

p : pressure increment between the pressure of the silo and the and the atmospheric pressure;
r : internal radius of the silo load box;
t : wall tickness of the silo.

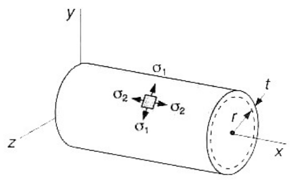

Figure 9. Principal stresses for a cilindrical vessel

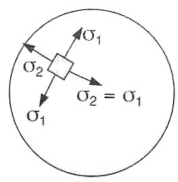

Figure 10. Principal stresses for a spherical vessel

Now considering the extremities of the load box, we can consider the equations for spherical pressure vessels. In accordance with Beer and Johnston (1996), the principal stresses are equal, Fig. 10. The equilibrium equation is similar to the longitudinal stress equation σ_2 of a cylindrical vessel. Thus, the stress σ_1 and σ_2 in the extremities of the silo are:

$$\sigma_1 = \sigma_2 = \frac{p \cdot r}{2 \cdot t} \tag{20}$$

The maximum shear stress in the extremity of the silo is:

$$\tau_{máx} = \frac{1}{2} \cdot \sigma_1 = \frac{p \cdot r}{4 \cdot t} \tag{21}$$

2.5. Plate thickness evaluation

The plate thickness evaluation of the load box takes in consideration the yielding stress σ_e of the selected material and a safety coefficient CS:

$$\sigma = \frac{\sigma_e}{CS} \tag{22}$$

2.5.1. Cylindrical region of the load box

The minimum thickness necessary to satisfy the requirements of the tangential stress t_t, the longitudinal stress t_l and the maximum shear stress t_{cc} results in:

$$t_t = \frac{p \cdot r}{\frac{\sigma_e}{CS}}, \qquad t_l = \frac{p \cdot r}{2 \cdot \left(\frac{\sigma_e}{CS}\right)}, \qquad t_{cc} = \frac{p \cdot r}{2 \cdot \left(\frac{\sigma_e}{CS}\right)} \tag{23}$$

2.5.2. Spherical region of the load box

The minimum thickness necessary to satisfy the requirements of the normal stress t_{esf} and the maximum shear stress t_{ce} results in:

$$t_{esf} = \frac{p \cdot r}{2 \cdot \left(\frac{\sigma_e}{CS}\right)}, \qquad t_{ce} = \frac{p \cdot r}{4 \cdot \left(\frac{\sigma_e}{CS}\right)} \tag{24}$$

3. CASE STUDY

The dimensioning of a load box of a road silo semitrailer is presented. First, the liquid load is calculated considering the properties of the bulk solid to be transported. Then, the minimum plate thickness is determined for different regions of the silo.

3.1. General data

In this work one road silo for cement transportation is selected, with a gross load capacity *PBTC* of 41500 kg and tractioned by a 4x2 unit with tare *TCM* of 7500 kg. The silo semitrailer has a tare *TSR* equal to 7000 kg. The value of liquid load *CL* results equal to:

$$CL = PBTC - TCM - TSR \tag{25}$$
$$CL = (41500 - 7500 - 7000)\ \mathrm{kg} = 27000\ \mathrm{kg}$$

Taking into account the density of the cement ρ equal the 1500 kg/m³, the volume of the material is approximately equal to 18 m³. Thus, the silo cannot transport more than 27000 kg of cement and the load box must have a geometric volume higher than 18.0 m³.

The load box of the silo is manufactured with carbon steel of yielding strength σ_e equal to 500 MPa and safety coefficient *CS* equal to 4. The operating pressure to discharge the silo $p_{operação}$ will be equal to 0.2 MPa, but the design pressure p_{design} will be equal to 0.3 MPa. The silo will have an internal diameter $\varnothing_{int}$ of 2300 mm.

3.2. Geometric volume of the load box

In the extremities of the silo will be located two semi-spheres of diameter equal to the variable $\varnothing_{int}$ of the silo. In addition, three internal cones with superior diameter equal to 2300 mm direct the bulk solid for the discharge, Fig. 11.

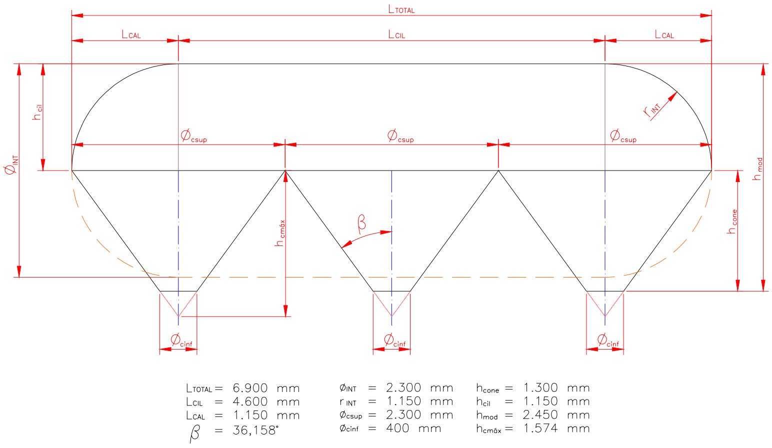

Figure 11. Load box.

The total length of the load box is equal to 6900 mm, the length of the cylinder is equal to 4600 mm and the length of each extremity is equal to 1150 mm. The height of the cone is 1300 mm and its inferior diameter is equal to 400 mm.

The equations for calculating the volume of the cylinder V_{cil}, the volume of the extremities V_{cal} and the volume of the cones V_{cone} can be found elsewhere. The geometric volume of the load box V_{GCC} can be found through:

$$V_{GCC} = \frac{1}{2} \cdot (V_{cil} + 2 \cdot V_{cal}) + 3 \cdot V_{cone} \tag{26}$$

$$V_{GCC} = \frac{1}{2} \cdot \left\{ \left(\frac{\pi}{4} \cdot 2{,}3^2 \cdot 4{,}6 \right) + 2 \cdot \left[\pi \cdot 1{,}15^2 \cdot \left(1{,}15 - \frac{1{,}15}{3} \right) \right] \right\} + 3 \cdot \left[\frac{\pi}{12} \cdot 1{,}3 \cdot \left(2{,}3^2 + 2{,}3 \cdot 0{,}4 + 0{,}4^2 \right) \right] = 19{,}25\ \mathrm{m}^3$$

Thus, it is verified that the volume of the load box V_{GCC} is approximately 7% greater than the volume of bulk solid V_{MAT}, satisfying the requirement for having one load box capable to contain the calculated V_{MAT}.

3.3. Determination of the amount of inspection covers

As the repose angle ϕ_r of the cement is equal to 28º, it will be necessary at least 4 inspection covers, Fig. 12.

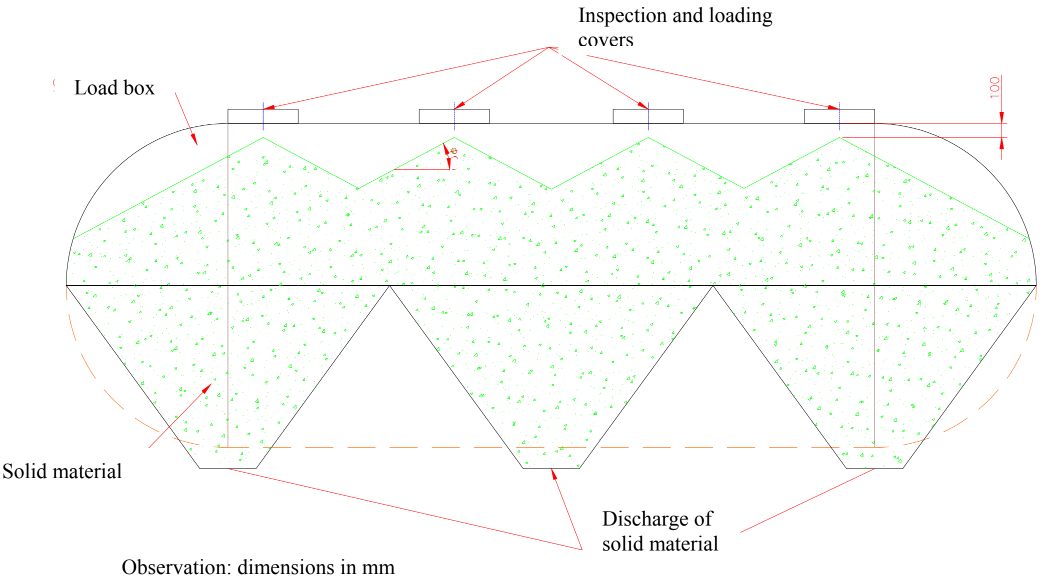

Figure 12. Graphical determination of the amount of inspection covers.

3.4. Evaluation of pressures in the wall of the silo

A simplification of the silo through its division in modules was realized according to Figs. 13. and 14, where the load over each module acts separately. The liquid load and the volume of each module are 9000 kg and 6 m³.

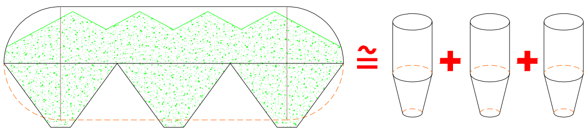

Figure 13. Hypothesis of the solid distribution.

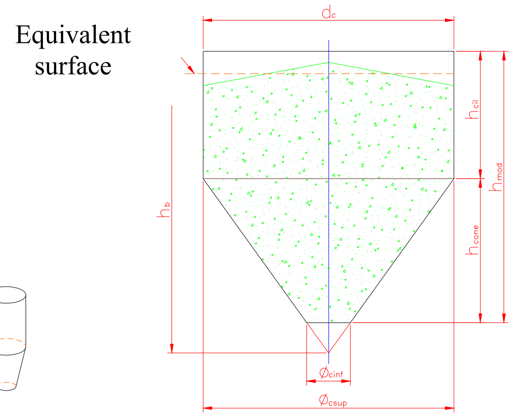

Figure 14. Main dimensions of a module.

3.4.1. Type of silo according with its geometry

Considering that h_b=2624 mm and d_c=2300 mm, the ratio h_b/d_c is equal to 1.14. This value is in the interval 1.0 to 1.5, what it means that this silo is of the intermediate type. Therefore, the pressures values in the walls of the silo are obtained with the equations of the sections 2.3.3 and 2.3.5.

3.4.2. Evaluation of p_{ho}, p_{vo} e z_o

In order to calculate the pressures in the walls of the silo it is necessary to know some reference values: the *wall pressure at infinite depth* p_{ho}, *the vertical stress in solid at infinite depth* p_{vo} and the *Janssen reference depth* z_o, remembering that this values are the same for *slender* and *intermediate* silos (sections 2.3.2 and 2.3.3).

According to Eqs. (6) to (8), we have:

$$p_{ho} = \frac{14715 \cdot 1.15}{2 \cdot 0.496} = 17.06\,\text{kPa}\,, \qquad , p_{vo} = \frac{14715 \cdot 1{,}15}{2 \cdot 0.54 \cdot 0.496} = 31.60\,\text{kPa}\,, \qquad z_o = \frac{1{,}15}{2 \cdot 0.54 \cdot 0.496} = 2.1468\,\text{m}$$

In addition, the h_o value is needed for *intermediate* silos, as defined by Eq. (11):

$$h_o = \frac{1.15}{3} \cdot tg(28^o) = 0.2038\,\mathrm{m}$$

3.4.3. Evaluation of pressures in the cylinder of the silo

The *normal pressure* acting on the wall of the cylindrical section of the silo p_{hf} is found with the Eq. (10), which is used to calculate the *frictional traction* p_{wf} with the Eq. (5). The *mean vertical stress* p_{vf} within the stored solid at the depth z is solved with the Eq. (12).

$$p_{hf} = 17.06 \cdot \left\{ 1 - \left[\left(\frac{2.624 - 0.2038}{2.1468 - 0.2038} \right) + 1 \right]^{-2} \right\} = 13.68\,\mathrm{kPa}$$

$$p_{wf} = 0.496 \cdot 13.68 = 6.78\ \mathrm{kPa}$$

$$p_{vf} = 31.60 \cdot \left\{ 1 - \left[\left(\frac{2.624 - 0.2038}{2.1468 - 0.2038} \right) + 1 \right]^{-2} \right\} = 25{,}33\,\mathrm{kPa}$$

3.4.4. Evaluation of pressures in the cone of the silo

The mean vertical stress in the solid at the transition of the barrel with the cone p_{vft} is obtained with the Eq. (13):

$$p_{vft} = 31.60 \cdot \left\{ 1 - \left[\left(\frac{1.574 - 0.2038}{2.1468 - 0.2038} \right) + 1 \right]^{-2} \right\} = 20.73\,\mathrm{kPa}$$

The value of F_f is obtained according to Eq. (18) with the empirical constant a equal to 0.8; then n uses Eq. (17):

$$F_f = \frac{1 + 0.8 \cdot 0.496 \cdot \cot(36.158^o)}{1 + 0.496 \cdot \cot(36.158^o)} = 0.92$$

$$n = 2 \cdot \left(0.92 \cdot 0.496 \cdot \cot(36.158^o) + 0.92 - 1\right) = 1.089$$

The mean vertical stress p_{vf} at height x above the apex of the hopper cone is obtained with Eq. 16, (x=h_h=1.574 m):

$$p_{vf} = \frac{14715 \cdot 1.574}{1.089 - 1} \cdot \left[\left(\frac{1.574}{1.574} \right) - \left(\frac{1.574}{1.574} \right)^{1.089} \right] + 20.73 \cdot \left(\frac{1.574}{1.574} \right)^{1.089} = 20.73\,\mathrm{kPa}$$

The normal pressure acting on the wall of the hopper cone p_{nf} is obtained with the Eq. (14):

$$p_{nf} = 0.92 \cdot 20.73 = 19.07\,\mathrm{kPa}$$

The frictional traction acting in the hopper, p_{tf}, is obtained with the Eq. (15):

$$p_{tf} = 0.496 \cdot 19.07 = 9.46\,\mathrm{kPa}$$

Still for complementation, the pressures on the silo as being of slender type were calculated with the equations of sections 2.3.2 and 2.3.4, as shown in Tab. 1.

3.5. Comparative analysis of pressures acting in the road silo semitrailer

Table 1 shows the comparison of pressures because of the bulk solid in the silo with the unloading air pressure.

The cylinder region shows pressure lower than the design air pressure. The p_{hf} value is approximately 4.56% of the p_{design}. Thus, when dimensioning the load box, the p_{hf} on the walls of the silo can be neglected, because of the silo must operate with a pressure of 200 kPa ($p_{operação}$), and the sum of p_{hf} and $p_{operação}$ will not go to exceed the value of p_{design}. Analyzing the values of p_{wf} and p_{vf}, we can see that these represent, respectively, 2.26% and 8.44% of the p_{design} value. Therefore, the observation for neglecting the use of p_{hf} in this work can also be applied to p_{wf} and p_{vf}.

It is also verified that the pressures acting on the cone are lower than the design pressure p_{design}. It is observed that p_{nf} has approximately 6.36% of the p_{design} value. This difference of values between p_{nf} and p_{design} allows that the action of p_{nf}

on the cone can be neglected. The values of p_{tf} and p_{vf} have, respectively, 3.15% and 6.91% of the p_{design} value, being equally neglected in the project

Table 1. Pressures acting on the cylinder and cone of the silo

Region	Pressure	*Intermediate* silo (kPa)	*Slender* silo (kPa)	Operation air pressure (kPa)	Design air pressure (kPa)
Cylinder	p_{hf}	13.68	12.03	200	300
	p_{wf}	6.78	5.97		
	p_{vf}	25.33	22.29		
Cone	p_{nf}	19.07	15.10		
	p_{tf}	9.46	7.49		
	p_{vf}	20.73	16.42		

3.6 Evaluation of the thickness of the load box considering the operation pressure

Considering the values of p, r_{int}, σ_e and CS already computed; the minimum thicknesses of the cylindrical body of the load box to support the tangential stress (t_t), the longitudinal stress (t_l) and the maximum shear stress (t_{cc}) are:

$$t_t = \frac{0.3 \cdot 1150}{\frac{500}{4}} = 2.76\,mm \qquad t_l = \frac{0.3 \cdot 1150}{2 \cdot \left(\frac{500}{4}\right)} = 1.38\text{ mm} \qquad t_{cc} = \frac{0{,}3 \cdot 1150}{2 \cdot \left(\frac{500}{4}\right)} = 1.38\text{ mm}$$

The minimum thickness of the semi spherical extremity of the load box considering the normal stress t_{esf} and the maximum shear t_{ce} are calculated as:

$$t_{esf} = \frac{0.3 \cdot 1150}{2 \cdot \left(\frac{500}{4}\right)} = 1.38\text{ mm} \qquad t_{ce} = \frac{0.3 \cdot 1150}{4 \cdot \left(\frac{500}{4}\right)} = 0.69\text{ mm}$$

4. CONCLUSIONS

The dimensioning of the silo can use only the design air pressure p_{design}, ignoring the pressures corresponding to the stored bulk solid in the load box. There is no significant modifications in the silo dimensions, because the increment of pressure is *absorbed* by the use of a safety coefficient.

Analyzing the values obtained for the thickness of the cylindrical region of the load box we can verify that the tangential stress is more critical compared to the longitudinal stress and the maximum shear stress. For the tangential stress, the minimum thickness of the load box in the cylindrical region is approximately 2.76 mm.

Analyzing the values obtained for the thickness of the spherical region of the load box, it is observed that the normal stress is more critical than the maximum shear stress. For the spherical region, the minimum thickness of the load box must be approximately 1.38 mm.

On basis of the obtained values, the load box can easily be optimized using different thicknesses of plates in its construction.

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