Analysis and Design of Silo Walls

D. Lippold, Peter und Lochner, Beratende Ingenieure für Bauwesen GmbH, Germany, and J. Harder, OneStone Consulting Group GmbH, Germany, describe the silo aeration for the material discharge of large capacity silos in the cement industry and its influence on wall loads.

Introduction

Silos with a substantial capacity in the cement industry may cause large eccentricities during discharge due to their individual bottom aeration sections. A large eccentricity is classed as when a discharge flow channel is more than half the radius of a silo from the silo mid-point. From different investigations[1,2] it is known that horizontal pressures in a flow channel are smaller than in the bulk material outside the flow channel. This results in a reduction in horizontal pressures in the zone in which the flow channel contacts the wall, compared to the horizontal pressure on the remaining wall circumference that corresponds with the fill pressures. In the transition from flow zone to static zone, horizontal pressures even higher than the fill pressure occur due to the load balance. The result is an alternating pressure distribution when discharging large capacity silos, which could lead to critical wall loads in certain cases. Corresponding views are included in the current draft of European Silo Standards prEN 1991-4 and the revised German Silo Standards DIN 1055-6, which fundamentally corresponds to prEN 1991-4 and will presumably be introduced by the end of 2004. Silos with bottom aeration are generally viewed as 'slender' silos.

Process engineering for silo discharging

The largest silos in the cement industry are built with diameters up to 30 m. Typical silos for storage of 20 000 t cement are, for example, 20 m in diameter and 60 m high. Although there are different design variations by the leading suppliers, large capacity silos with diameters above 12 m are mainly executed as central cone versions. The central cone has a material displacement function, which allows the material in the silo to come into motion during discharge.

All silos with a central cone (Figure 1) are designed as quasi flat bottom silos, whereby the silo bottom forms a ring space. This is divided into individual aeration sections that are slightly declined towards the outlet by approximately 10°. The silo bottom is equipped with so-called fluidslides that have an air-permeable fabric on the upper side. The aeration air is blown under the fabric in order to fluidise the bulk material on the fabric. The percentage of coverage of the silo bottom with fluidslides varies between 35 and 50% depending on system and requirements. In order to ensure problem-free discharge of material, air amounts and aeration pressure must be adjusted to each other. The air amounts increase roughly linearly from a minimum air amount with the required discharge throughputs. As a rule, blowers with 500 mbar pressure are sufficient for aeration.

The silo bottom is aerated section by section, so that all sections are aerated in a complete cycle. It is insignificant whether two or more sections are connected for aeration. Correspondingly, only the part of the bulk material above the actively aerated silo section is in motion, and a flow channel forms increasing upwards (Figure 2), which can include almost the entire cross section, depending on discharge amount, silo height and aeration time. Within the flow channel there is a convergent material flow. The gradient of flow is illustrated in the figure by the increasing width of the blue and white material elements. As only the bulk material above the aerated section is in motion, no mass flow will occur in the silo. With mass flow the entire material in the silo would be in motion uniformly. Due to the cyclic aeration of the ring zone, one section after another, the discharge process in the silo must be strongly eccentric.

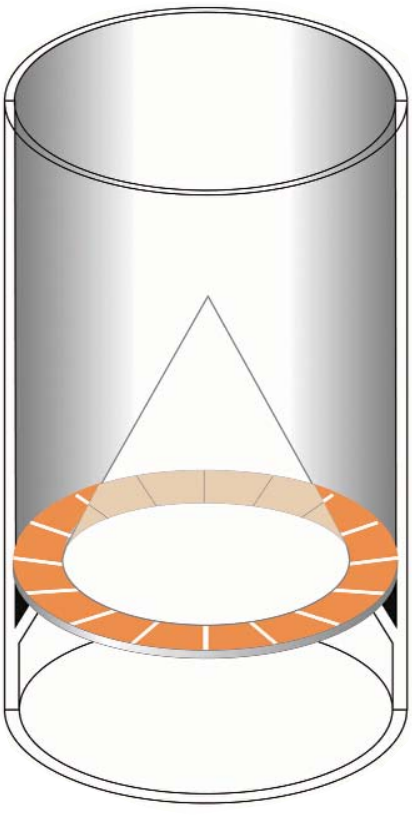


Figure 1. Silo with central cone for the cement industry.

Wall loads during discharge with large eccentricities

Figure 3 shows the wall loads after filling according to prEN 1991-4

(2004 version) in a large capacity silo without displacement cone. The horizontal pressure p_{hf} increases with the height according to the Janssen formula[3] based on an e-function towards the silo bottom, and beside the diameter, it is dependent on the specific weight of the bulk material, the wall friction coefficient of bulk material and wall material, as well as the horizontal pressure ratio. Accordingly, calculation guidelines exist for the wall friction p_{wf} and the vertical load p_{vft} in the depth z. For the discharge of silos with large eccentricities, design loads are given in the prEN 1991-4 for the case that the discharge eccentricity e_o exceeds the critical value of $e_{o,cr} = 0.25\ d_c$, with d_c as the silo diameter. Two cases were differentiated depending on silo size (Figure 4):

- 'Assessment class 3' (general process for silos with a fill capacity greater than 1000 t): if the size of a flow channel cannot be predicted from the discharge system, calculations must be implemented with different approaches for the diameter of the flow channel. This allows the horizontal pressure within and outside of the flow channel and the associated circumferential angle θ_c for the contact zone of the flow channel at the wall for any case to be determined.
- 'Assessment class 2' (general process only for silos with a fill capacity of less than 1000 t): The flow channel contacts the wall with a circumferential angle θ_c of 35° and the horizontal discharge pressure in the flow zone can be set with $p_{hce} = 0$ and outside the flow zone with $p_{hse} = p_{hf}$ as well as $p_{hae} = 2\ p_{hf}$. This view is simplified and the results are on the safe side; the application of general processes for assessment class 3 remains optional.

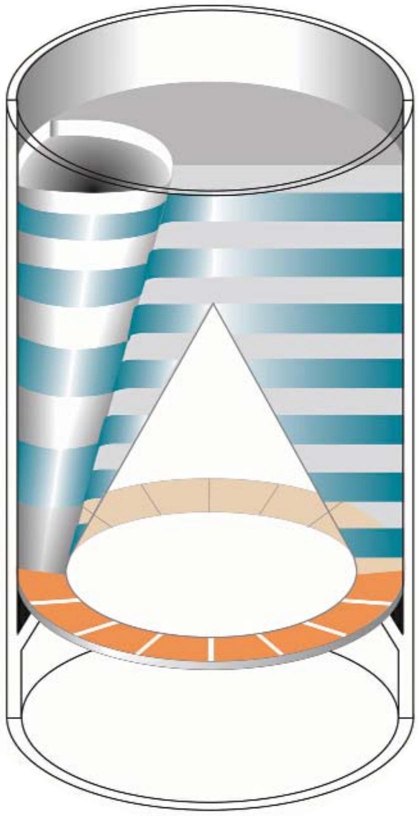


Figure 2. Flow channel during eccentric discharge.

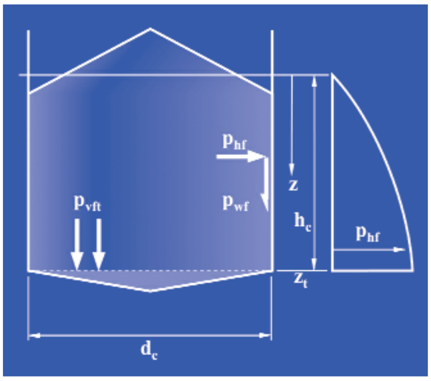


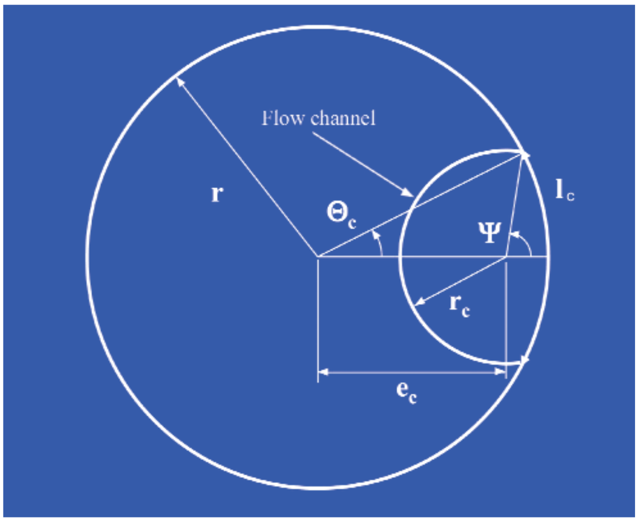
Figure 3. Filling loads in a silo.

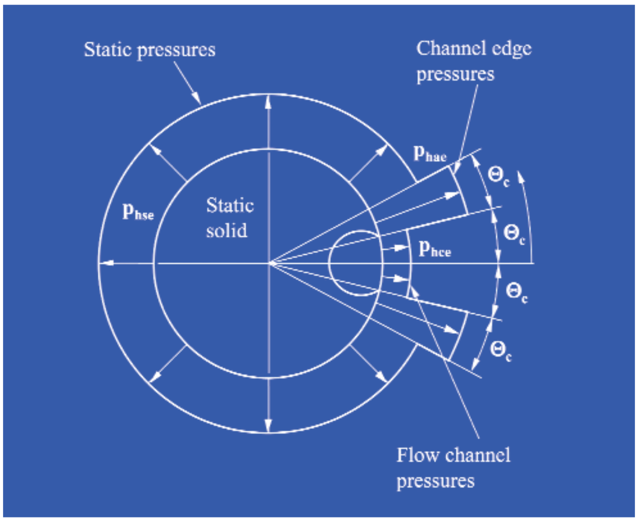
To allow a better prediction of the size of a flow channel for large capacity silos in the cement industry, in the following, an attempt is made to give a qualitative estimation upon the formation of flow channels.

Formation of flow channels

Figure 5 shows the flow channel formation with large eccentricities in a cement silo, where a lower and upper flow channel part have to be separated. While the upper part is only formed by the gradient of the slope at the surface of the material with practically no influence on the horizontal pressures, the lower part is formed by the flow within the material, because of the bottom aeration. The momentary aerated silo section can be located at the right hand side. The flow channel can be differentiated by a slightly darker colour than the rest of the material. As the momentary flow channel has no contact with the silo wall, the circumferential angle $\theta_c = 0$. Since θ_c is dependent on the silo height, for silo dimensions it would be useful to determine θ_c approximately at the height of the cone tip and not at the material surface.

Figure 6 schematically shows the flow channel formation for three different times. At the initial aeration, only the material close to the outlet becomes fluidised and a flow channel





Figures 4a and b. Influencing variables during eccentric discharge. Left: Flow channel geometry and right: pressures.

is formed where $\theta_c = 0$ (t_1). With ongoing aeration the flow length for the bulk material along the fluidslides increases, and also the size of the flow channel increases until the first material at the silo wall becomes fluidised. This means that the material at the silo wall comes into motion. θ_c becomes > 0 (t_2). When all the material above the aeration section is in motion (t_3), with longer aeration time the flow channel size and θ_c will further increase until a maximum $\theta_{c,limit}$ is reached. The circumferential angle θ_c and maximum $\theta_{c,limit}$ are proportional to the size of the aeration section and the area on which the bulk material is in motion. Correspondingly, for a section number of 16, for example, the circumferential angle θ_c is at least > 22.5° (360°/16) when the bulk material above it is completely in motion.

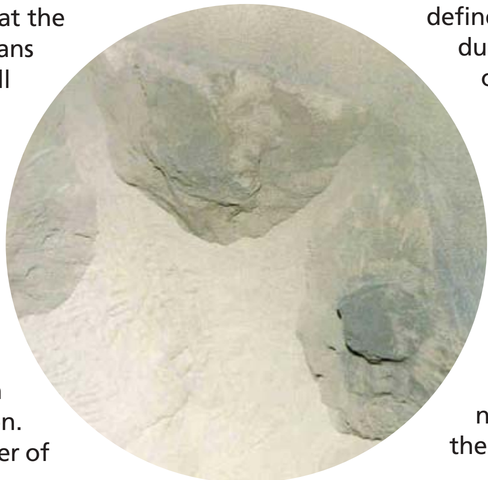


Figure 5. Formation of flow channels in a cement silo.

It can be assumed, that not only the size of an aeration section, but also the arrangement of the fluidslide system and the flow control have an influence on the flow channel formation, as there are radial and tangential fluidslide arrangements. Thus, in practice, the circumferential angle θ_c is influenced by a number of parameters, including the aeration system, the number of aeration sections, the aeration time, the discharge capacity per time, the storing time without movement and the specific bulk materials characteristics such as bulk density, internal angle of friction and wall friction angle.

For an actual comparison of different discharge systems with regard to the wall load, the size of the active aeration section is most significant. Generally, the number of aeration sections increases with increasing silo diameter in order to keep the active aeration surfaces from becoming too large. Correspondingly, the circumferential angle θ_c decreases in silos with a larger diameter and a higher number of aeration sections. The circumferential length l_c of the flow channel at the wall that has an effect on bending moments, however, increases with a constant number of aeration sections and increasing silo diameter.

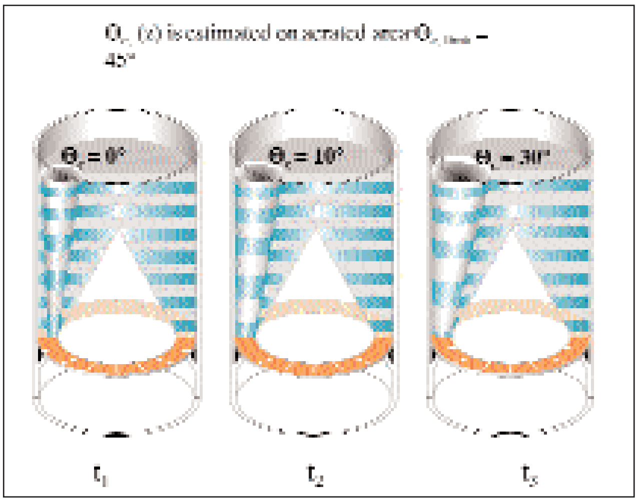


Figure 6. Formation of flow channels for different aeration times $t_3 > t_2 > t_1$.

Generally it should be noted that at a defined silo size the resulting wall stresses due to discharging become smaller as the circumferential angle of flow channels at the silo wall becomes smaller. Accordingly the wall stresses become smaller as the pressure differences in the silo become smaller: these depend on the size and eccentricity of the flow channels. One possible means of reducing the formation of flow channels is, for example, using smaller aeration sections and not connecting neighbouring aeration sections together for silo discharging.

Practical calculation examples

A practical example of a cement silo with 17.2 m inner diameter and a filling height of 40 m shows what effects the horizontal pressure distribution from the described flow channels has on the stress resultants and dimensions of the silo wall. The silo wall is stiffened at the upper and lower edge by adjoining components; the assumed wall thickness is 30 cm. The design loads and relevant stress resultants for two flow channels with the radii $r_c = 0.35\,r$ and $0.5\,r$ are shown. Since loads and stress resultants change with the height, the section is viewed at half filled height ($z = 20$ m) for simplification, which can be seen as representative for the ratio on the entire wall height. In addition, a direct comparison with the design based on the DIN 1055 part 6 standard (May 1987, currently still valid) is possible for this height section.

Figure 7 shows the horizontal pressure distribution along the wall circumference. A larger contact zone at the wall circumference results for the larger flow channels with 0.5 *r* compared to the smaller flow channel with 0.35 *r*, while the pressure differences along the circumference are lower with the larger flow channel diameter. This can be seen in the view of the flow channel as 'silo in the silo'. Thus, with increasing flow channel diameter, the pressures also increase and approach the pressures in the surrounding static bulk material (as can be compared in Figure 8).

Figure 9 shows the bending moment at half height of the silo wall in circumferential direction. Characteristics for the established pressure distribution are the bending moments that create considerably higher tensile stresses on the inner side than the outer side of the wall. The larger flow channel diameter produces the appropriately larger bending moment. Simultaneously, these bending moments are considerably larger with tension on the wall inner side than those in the design with patch loads towards the outside. This use of patch loads was the relevant load case based on DIN 1055 part 6 (May 1987) to date for the load from the bulk material pressures, and should now as before be viewed as an additional load case. The ring tensile forces are almost constant over the silo circumference and practically the same for both flow channel diameters, which is why no presentation is

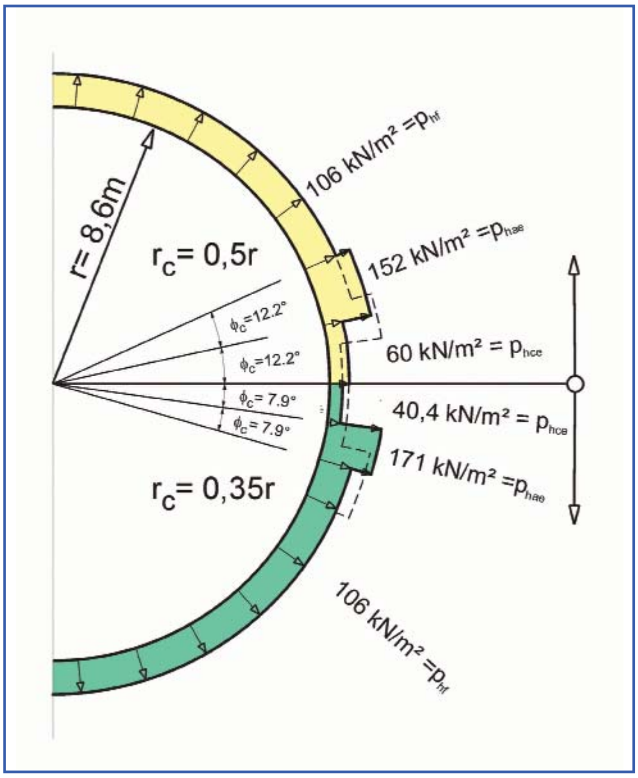


Figure 7. Horizontal pressure distribution in a silo due to a flow channel.

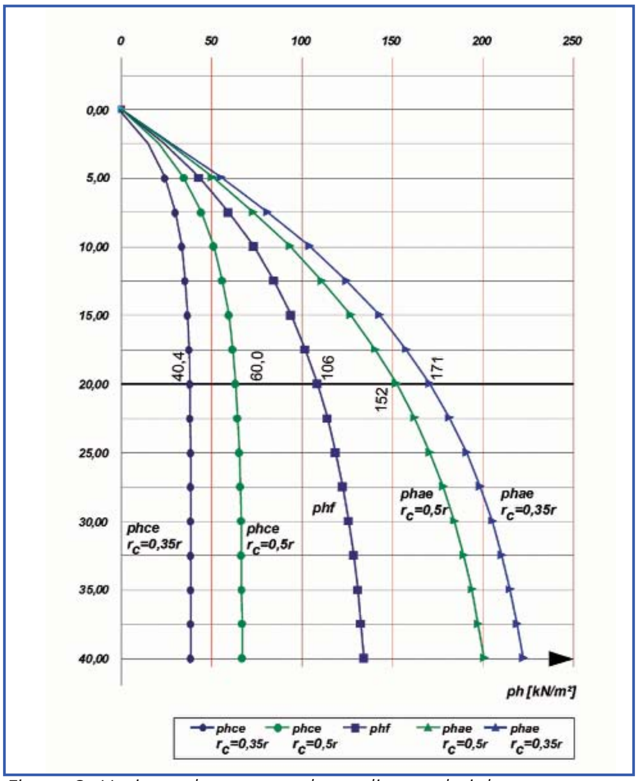


Figure 8. Horizontal pressures depending on height.

made here. They can be sufficiently accurately determined from the fill pressure of the resting material via the so-called container formula at $n_x = p_{hf} \times r$ = 106 x 8.6 = 912 kN/m. Compared to load approaches with patch load, they are considerably less, since larger discharge loads are anticipated.

The shear forces in circumferential direction are shown in Figure 10 as additional internal forces. With the silo design typical up until now, corresponding shear forces also resulted from the patch loads in principle; however, these were previously not seen as relevant for wall design, and therefore they were not considered (this is compared below). Please note that the design loads shown according to the drafts of standards are only simplifications of what in reality are very complicated conditions in the silos shown, and in practice, their conversion for each application must be appropriately critically scrutinised.

Results of the wall design

For the ring reinforcement at the outer side of the wall there are practically no changes compared to previous designs, since here, as before, the approach with patch loads is significant. However, deviations can result as mathematical effects through negligibly changed parameters and modified formulas; nevertheless they should not exceed 10 - 15% in normal cases. The ring reinforcement at the wall inner side is clearly increased due to the high bending moment compared to previous designs, a significant result of the design load with flow channel. This indicates that the decisive load on a cylindrical silo wall in addition to the absolute size of the maximum pressure is very strongly influenced by the pressure distribution, and that not only localised pressure increases, but also a pressure decrease, brings problems. Table 1 shows a comparison of the required ring reinforcement based on 'old' and 'new' standards.

The shear forces are another very significant aspect in the circumferential direction which result from the design loads described above. When using the previously valid standard, DIN 1045 (July 1988), relatively small shear stresses occur, which cannot lead to conclusions about any problems. In the future, the proof of the established shear resistance without shear rein-

<table>
<tr><th colspan="4">Table 1. Comparison of the required ring reinforcement at mid-height (z=20 m)</th></tr>
<tr><th></th><th>Outside silo wall
cm²/m</th><th>Inside silo wall
cm²/m</th><th>Silo wall total
cm²/m</th></tr>
<tr><td>Internal forces and bending moments
due to DIN 1055 part 6 (May 1987)</td><td>35.8</td><td>23.6</td><td>59.4</td></tr>
<tr><td>Internal forces and bending moments
κ-method, due to DIN 1055 part 6
(May 1987) distribution outside/inside 60/40%</td><td>37.1</td><td>24.7</td><td>61.8</td></tr>
<tr><td>Internal forces and bending moments
according to flow channel method due to
draft prEN 1991-4 respectively DIN 1055-6
r=0.5r_c</td><td>23.8</td><td>33.7*</td><td rowspan="2">70.8</td></tr>
<tr><td>Due to standard design</td><td>37.1*</td><td>24.7</td></tr>
<tr><td colspan="4">*Relevant for the design</td></tr>
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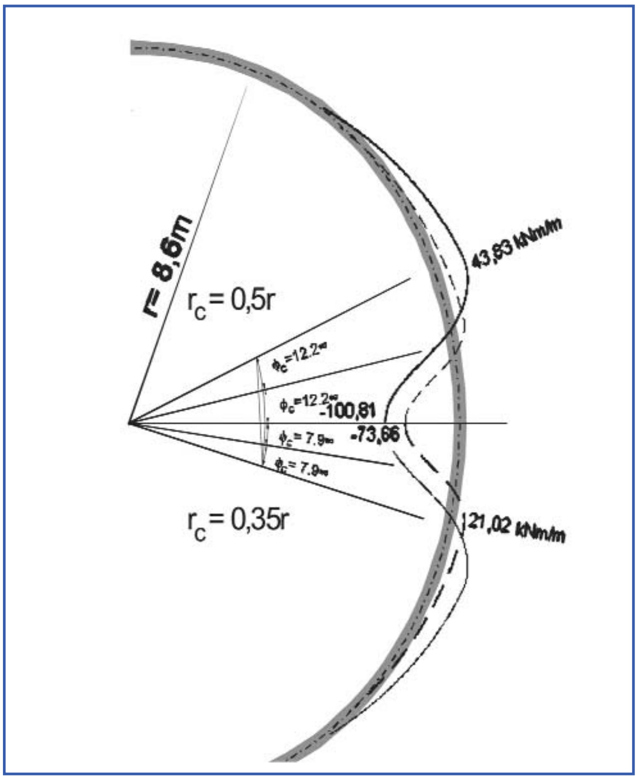

Figure 9. Bending moments depending on circumference.

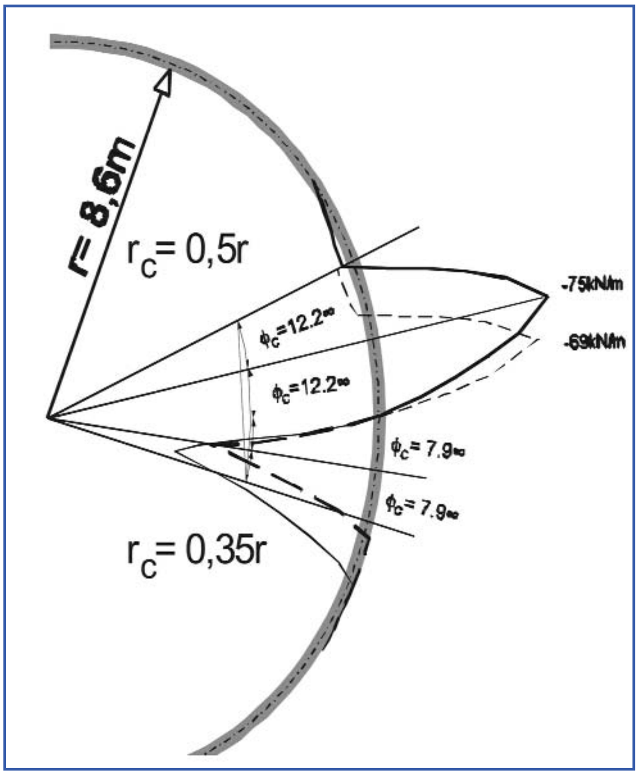

Figure 10. Shear forces depending on circumference.

forcement must be shown based on DIN 1045-1, whereby the axial forces in the section must be considered. The ring tensile force in the silo wall drastically reduces the incorporated shear resistance. In the example described, this leads to an inadequate shear resistance of the silo wall for the calculated shear forces of a reinforced wall without post-tensioning with typical dimensions based on DIN 1045-1. Simply stated: no adequate shear forces can be transmitted via open cracks in silo walls.

The fact that the design formula listed in 1045-1 is not applicable to the typically large tensile forces in silo walls, and the lack of information about the limit of the scope of validity also presents a problem at present. Based on current knowledge, it cannot be expected that proof can be given in a different manner. The application of shear reinforcement fails due to the same obstacle. The insufficiently researched influence of cyclically alternating loads from the circulating aeration of the discharge sections is also of significance. Previously implemented model design calculations clearly indicate that the inadequate shear resistance of the silo wall under tension could be the main cause for severe damages.

Reducing a too high ring tensile stress in the silo wall is a useful solution for critical cases. This leads to the use of post-tensioning in the circumferential direction as already successfully used for many years for silos and stores with a diameter of 20 m and more. Although this is a more technologically demanding solution, it does not need to be more expensive than a wall without post-tensioning. In addition, the post-tensioning brings well-known advantages for limiting the width of cracks, which is an important aspect for the durability of the wall. Post-tensioning could already be used with considerably smaller diameters than previously typical, in order to avoid long-term damage.

Conclusions and recommendations

It has been shown that the silo discharge system has a considerable influence on the size and eccentricity of the flow channel formation and the resulting wall loads in silos with a central cone. Depending on the discharge system, the number of aeration sections and discharge quantities, critical cases can occur with regard to wall loads. Generally, such critical cases should undergo an extensive analysis that includes the ideas presented. If it is decided that the case must be considered critical, post-tensioning in circumferential direction may be a solution. ◆

Literature

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