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Load Development and Structural Considerations in Silo Design[1]

By
J.W. Carson, Ph.D.
and
R.T. Jenkyn, P.Eng.

SYNOPSIS

Each year an alarming number of silos, bins, and hoppers fail due to bad design, poor construction or improper use. Jenike & Johanson engineers have been called in to investigate more than 50 structural failures in the last five years alone.

Many failures are the result of loading conditions not anticipated by the designer. In this paper we describe design procedures that we have found to be successful. In particular we cover bin load calculations for various filling conditions and flow patterns, force resultants, and design requirements.

INTRODUCTION

Although statistics are not available, hundreds of industrial and farm silos, bins, and hoppers fail in one way or another each year. Sometimes the failure is a complete dramatic structural collapse. Other times cracks are found in a concrete wall, or dents in a steel shell, either of which might appear harmless to the casual observer. Nevertheless, these are danger signals which indicate that corrective measures are probably required.

The economic cost of repairs to this essential – though frequently neglected – component of a bulk material handling system is never small. The owner faces the immediate costs of lost production and repairs, personnel in the vicinity are exposed to danger, and the designer and builder face possible litigation because of their liability exposure.

What can be done to avoid these problems? In this paper we show some of the problems that can occur, why they occur, and the straightforward steps that can be taken to avoid, or at least minimize, such problems.

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[1] Source: Carson, J. W. and R. T. Jenkyn: Load Development and Structural Considerations in Silo Design. Presented at Reliable Flow of Particulate Solids II, Oslo, Norway, August 1993. Used with the permission of the publisher.

SILO DESIGN

The design of bins and silos to store bulk solids involves bulk material, geometric, and structural considerations.

Bulk material considerations are important because the frictional and cohesive properties of bulk solids vary from one solid to another, and these properties affect material behavior considerably. In addition, a given bulk solid's flow properties can vary dramatically with changes in numerous parameters, including particle size, moisture, temperature, and consolidating pressure. This variability of properties makes testing at actual conditions more important for proper bin and silo design than may at first appear.

When considering the *geometric* design of a silo, potential problems include arching across an outlet, ratholing through the material, and the flow pattern during discharge. A bulk material's propensity to arch or rathole is primarily related to it's cohesiveness, while its flow pattern during discharge depends upon internal friction as well as the friction that develops between the material and the silo's hopper walls. The goal of geometric design is to maximize the useable capacity of a silo while minimizing its capital cost, overall height, etc.

Established design procedures [1] include selection of the optimum hopper angles and minimum outlet dimensions. The ideal discharge mode is one where, at steady state, all material flows without obstruction. This is referred to as *mass flow*. The discharge mode where only some of the material flows is called *funnel flow*. In mass flow, the material does not necessarily move at a uniform rate throughout: velocity variations across any horizontal cross-section are possible.

The *structural* design of a silo requires, among other things, knowledge of the distribution of pressures and shear stresses on its walls (caused by the stored material) and how that distribution varies during charging, storage at rest, discharging, and recharging.

Of the three major aspects of silo design (bulk material, geometric, and structural), the bin loads aspect of structural design is the least understood. But unless the structural design is done properly, the integrity of the silo may be compromised. Silo collapse is far too common, yet agreement amongst designers on procedures for determining silo loads has not been forthcoming. This is very apparent when one considers existing codes of practice. There is very little detailed guidance concerning the various loading conditions – some static, some dynamic – which can co-exist.

Even if existing codes were "better," it is unreasonable to expect that **any** code of practice would contain a definitive set of instructions covering **all** cases that might have to be considered. Usually none but the simplest cases can be described. Over-enthusiastic compliance with the *letter,* to the exclusion of the *spirit and intent* of a code of practice, can be misleading, and even dangerous.

In some countries, codes are **recommendations** only, so compliance with them is not mandatory. However, for practical purposes **in the event of a failure**, a code (assuming that one exists) is a minimum mandatory standard. In other words, an engineer may have the right to exercise independent engineering judgment when creating a design, and may even go back to first principles. But if a problem occurs and the engineer must justify his design, he will have difficulty doing so unless it is as good as the minimum provided by the applicable code (or codes), or the inapplicability of the code has been documented [2].

Codes are particularly weak in the area of eccentric flow channel formation. In fact even flow experts often cannot agree on where a flow channel will form in a funnel flow bin or silo, its size, shape, etc. Because of this uncertainty in the ability to predict the occurrence of flow channels, some designers feel that it is prudent to assume the occurrence of worst case flow channels if there is any doubt at all. Part of their rationale is that they consider it to be dangerous to fine tune a design on the basis that some definite predicted flow regime will occur, that operators will operate the silos according to a definite set plan, or that the material's flow properties will not vary [3]. While such an approach should be conservative, it may be too costly to implement.

Several committees in various countries are currently working to revise silo design codes. Many are having great difficulty in enacting new procedures for the design of silos to accommodate flow channels even though they know that they occur and they know that many silo failures have been caused by such flow channels. Every day there are new engineers who are charged with the design of new silos. Most of these new engineers look first to the codes for information on the design of these structures, hoping and expecting that the codes will point them in the right direction. To do this, a code need not be perfect, but it must reflect the latest in technology and be rational. Hopefully, papers like this one will fill some of the gaps while codes are being revised.

CAUSES OF SILO FAILURES

There are many different causes of silo failures [4]: shortcomings in the design procedure, construction, usage, maintenance, or some combination thereof. This, in turn, means that more than one individual or group often bears some responsibility when a failure occurs. Potentially responsible parties include the designer, builder, building material supplier, owner, user, and others.

Failures Due to Design Errors

Silo design requires specialized knowledge. The designer must first establish the material's flow properties, then consider such items as flow channel geometry, flow and static pressure development, and dynamic effects. Problems like ratholing and vibration have to be prevented, while assuring reliable discharge at the required rate. Non-uniform loads, thermal loads, and the effects of non-standard fabrication details must be considered. Above all, the designer must know when to be cautious in the face of incomplete or misleading information, or recommendations that come from handbooks, or from people with the "it's always been done this way" syndrome.

Having established the design criteria, a competent design has to follow. Here the designer must have a full appreciation of load combinations, load paths, primary and secondary effects on structural elements, and the relative flexibility of the elements. Special attention must be given to how the most critical details in the structure will be constructed so that the full requirements and intent of the design will be realized.

Flow-related loading conditions which, unfortunately, many designers fail to anticipate include:

- Bending of circular walls caused by eccentric withdrawal. If the withdrawal point from the hopper is not located on the vertical centerline of the silo, and if the resulting flow channel intersects the silo wall, non-uniform pressures will develop around the circumference of the silo leading to horizontal and vertical bending moments.

Many silo designers incorrectly account for these non-uniform pressures by only increasing hoop pressures. The problem of bending moments is particularly common when using silos with multiple hoppers in which only one or two of the hopper outlets are used at a time.

- Non-symmetric pressures caused by inserts. Support beams and other types of internals can impose non-symmetric pressures on the silo wall leading to unacceptable bending stresses.
- Self-induced vibrations. Bins and silos sometimes vibrate. This can be either a high frequency, low amplitude type of cyclic vibration, or a low frequency, high amplitude erratic vibration leading to shocks. The latter have been known to cause structural failures [5].
- Local peak pressure at a point where a funnel flow channel intersects a silo wall.
- Mass flow occurring when funnel flow was expected.
- Migration of moisture from wet to dry particles within the stored solids, which causes the dry particles to expand and impose large radial loads on a silo. (This is an uncommon problem.)

Failures Due to Construction Errors

In the construction phase there are two ways in which problems can be created. The more common of these is poor workmanship. Uneven foundation settlement and faulty construction (such as using the wrong materials or not using adequate reinforcement, such as insufficient quantity of rebars) are but two examples of such a problem. This can usually be avoided by hiring only qualified builders, by close inspection during construction, and by enforcing a tightly written specification [6].

The other cause of construction problems is the introduction of badly chosen, or even unauthorized, changes during construction in order to expedite the work. Any changes in details, material specifications, or erection procedure, must be given careful consideration by both the builder and silo designer.

Failures Resulting from Silo Usage

If a bulk material other than the one for which the silo was designed is placed in it, the flow pattern and loads may be completely different. The load distribution can be radically changed if alterations to the outlet geometry are made, if a side outlet is put in a center discharge silo, or if a flow controlling insert or constriction is added. The designer should be consulted regarding the effects of such changes before they are implemented. Some of the problems which can occur include:

- Collapse of large voids. A collapsing arch or rathole induces tremendous dynamic loads on the structure, which can cause the structure to fail. Vibrating bin dischargers have also been known to fall off bins and silos because of this mechanism.
- Development of mass flow in silos designed structurally for funnel flow. Mass flow can develop if the walls become smoother with time or if the properties of the bulk solid being stored change. This generally results in much higher loads at the top of the hopper section, which can result in structural failure.
- Drastic means of flow promotion. High pressure air cannons and even dynamite are sometimes used to restore flow. The result

may be more dramatic than the user and designer anticipated!

- Buckling of an unsupported wall below an arch of stored bulk material.
- Metal fatigue caused by externally-mounted bin vibrators.
- Dust explosions.

Failures Due to Improper Maintenance

Maintenance of a silo comes in the owner's or user's domain, and must not be neglected. There are two types of maintenance work which are required [7]. The first is the regular preventative work, such as the periodic inspection and repair of the liner used to promote flow, protect the structure, or both. Loss of a liner may be unavoidable with an abrasive or corrosive product, yet maintaining a liner in proper working condition is a must if the silo is to operate as designed.

The second area of maintenance involves looking for signs of distress, (*e.g.,* cracks, wall distortion, tilting of the structure) and reacting to them. If evidence of a problem appears, expert help should be immediately summoned. An inappropriate response to a sign that something is going wrong can precipitate a failure even faster than leaving it alone, including the common instinct to lower the silo fill level.

Wear due to corrosion and/or erosion can be particularly dangerous. For example, as carbon steel corrodes, the reduced wall thickness can eventually lead to a structural failure. This problem can be compounded through erosive wear of the silo wall. Erosive wear can also be a problem in reinforced concrete silos handling abrasive bulk materials such as coarse ores.

SILO LOADS

The loads which bulk materials exert on silo structures can generally be divided into two categories: those due to *initial fill* and those which are as a result of *flow*. *Initial fill* loads develop, as the name implies, when a silo is filled from an empty condition without any withdrawal taking place. The term *flow-induced* loads, on the other hand, is somewhat of a misnomer since it implies that the material must be in motion for these loads to develop. In fact, the only requirement is that there be some withdrawal of material which allows the flow induced loads to develop. Once this occurs, flow can be stopped and then restarted without having any appreciable effect on the silo loads. In addition, the rate of discharge is usually not a significant variable in affecting the magnitude of the silo loads. The primary reason for this is that most bulk materials are not viscous or visco-elastic, so their rate of movement has little effect on their frictional properties.

Initial Fill

As with all of the loading conditions described herein, it is convenient to consider first the vertical-sided portion of the silo (generally called the *cylinder* section), and then the *hopper* (*i.e.,* sloped section of the silo in which the cross-sectional area is changing with height).

If a silo is filled at a point which coincides closely with the silo's centerline, the loads which develop on the cylinder walls are generally less than those which are flow-induced and are therefore of little interest as far as structural design is concerned. If there is some reason to consider these loads, we recommend the use of the Janssen equation with a k_j value (ratio of horizontal to vertical pressures) of 0.4 and with wall friction angle ϕ' equal to a value determined from tests (see section MATERIAL FLOW PROPERTIES below). For a circular cylinder of diameter D, the Janssen equation is:

$$p = \frac{\gamma D}{4\mu'}\left[1 - e^{-4\mu' K_j z/D}\right] \text{..........................(1)}$$

$$\tau = \mu' p \text{ ....2)}$$

$$\mu' = \tan\phi' \text{..3)}$$

See NOMENCLATURE section at end of paper for a description of each term.

Other types of fill conditions can result in loads on the cylinder walls which are larger than those which are flow-induced. In particular, consider the conditions which occur when a silo is filled off-centered, or if it is filled along a ridge (such as would occur if a continuous belt tripper fill system were used). Pressures around the silo perimeter at any elevation caused by these conditions, can be calculated using the following procedure:

- At any point on the cylinder's perimeter, measure vertically up the wall to the elevation where the material surface contacts the wall, z_1.
- Cut the surface profile with a horizontal slice at the elevation just determined (i.e., where the material surface contacts the wall). Calculate the volume of the surcharge above that slice, then divide that volume by the area of the slice, to give an effective additional head above the slice, z_2.
- Apply Janssen's equation, using $z = z_1 + z_2$.
- Repeat this for sufficient points around the silo perimeter to define the distribution.

While this condition is usually rather localized to a region immediately below the material surface, it can occur at any elevation as the silo is being filled.

As far as the hopper section is concerned, we believe that the following equation adequately predicts the initial fill pressures which act normal (*i.e.*, perpendicular) to the walls of a converging **conical** hopper no matter what type of flow pattern occurs during discharge.

$$p = \gamma\left[\frac{h - z}{n_i} + \left(\frac{q}{\gamma} - \frac{h}{n_i}\right)\left(1 - \frac{z}{h}\right)^{n_i+1}\right] \text{.....(4)}$$

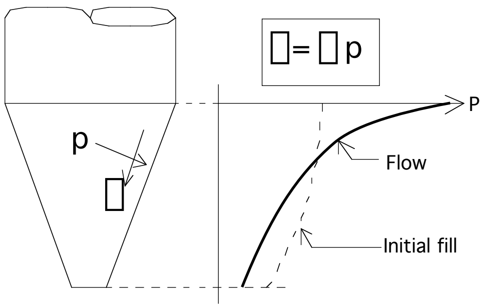
$$n_i = 2\left(1 + \frac{\tan\phi'}{\tan\theta_c}\right) - 3 \text{..............................(5)}$$

Note that "z" in equation (4) starts with a zero value at the top of the hopper, not at the top of the cylinder as in equation (1). The value of q can be calculated by taking the Janssen horizontal pressure p at the bottom of the cylinder and dividing by Kj (recommended value = 0.4)

For hopper geometries other than conical, numerical integration of the equations of equilibrium is required.

As will be shown below, in the case of a mass flow hopper the initial fill loads govern the structural design of the hopper in roughly its bottom two-thirds, whereas flow-induced loads govern in the upper third. See Fig.1. In most funnel flow hoppers, their structural design can be based upon initial fill loads.

Fig. 1: Mass flow hopper



Mass Flow – Single Outlet

Mass flow is a condition in which *all* of the material is in motion whenever any is withdrawn. As indicated in the SILO DESIGN section above, particles can be flowing at different velocities and still satisfy the requirements for mass flow as long as they are moving.

A mass flow bin or silo can still exhibit a no-flow condition of arching if the outlet is too small relative to the particle size (arching due to *interlocking*) or if the outlet is too small relative to the material's *cohesive strength*. Mass flow silos can also develop self-induced vibrations as material discharges [5].

If we assume that the outlet size is large enough to prevent the formation of a stable arch, and furthermore that self-induced vibrations do not occur upon discharge, the loads that develop on the silo walls are fairly well defined. In the cylinder section, a good starting point is to use the Janssen equation but with a range of K_j and wall friction values as follows:

$$0.25 \le K_j \le 0.6 \quad \text{.......(6)}$$

$$\phi' \, calc. = \phi' \, meas. \pm 5^\circ \quad \text{.......(7)}$$

The "plus" sign should only be used in this equation when calculating maximum shear stresses for cylinder buckling calculations. Otherwise the "minus" sign should be used.

If an applicable silo code predicts higher pressures, it should be used for the reasons stated in the SILO DESIGN section above.

In the hopper section, we recommend the use of the following equation [8] to predict flow-induced loads in conical hoppers:

$$p = \gamma K_f \left[\frac{h - z}{n_f} + \left(\frac{q}{\gamma} - \frac{h}{n_f} \right) \left(1 - \frac{z}{h} \right)^{n_f + 1} \right] \quad \text{....(8)}$$

$$K_f = \frac{1}{\frac{2}{3}\left(1 + \frac{\tan\phi'}{\tan\theta_c}\right) - \frac{1}{6(\sigma'/\gamma B)\tan\theta_c}} \quad \text{....(9)}$$

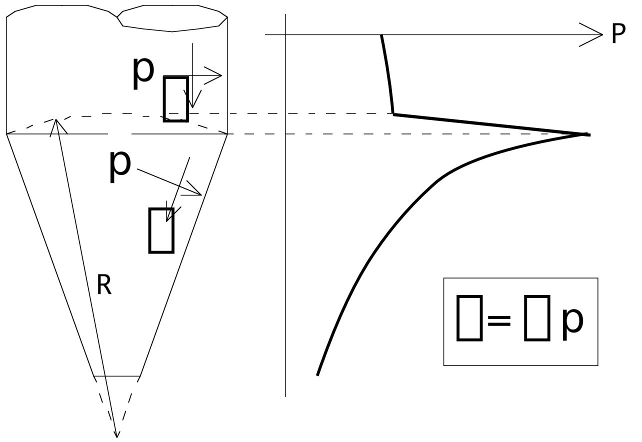
$$n_f = 2K_f \left(1 + \frac{\tan\phi'}{\tan\theta_c}\right) - 3 \quad \text{.......(10)}$$

The value of "z" in equation (8) starts at zero at the top of the hopper, as in equation (4). The value of q can be calculated by taking the Janssen horizontal pressure p at the bottom of the cylinder and dividing by K_j. To be conservative, a minimum value of K_j should be used for the calculation of p.

These equations result in higher pressures in roughly the upper third of the mass flow hopper than occur during initial fill, but lower pressures in the bottom two-thirds of the hopper section. See Fig. 1.

Because of the rapid switch in the state of stress that occurs at the top of a mass flow hopper section, some increase in wall pressure is often experienced in the section of the cylinder just above the top of the hopper. To account for this condition, we recommend that the peak pressure be spread along the vertical wall as shown in Fig. 2. First, draw a circular arc centered on the theoretical apex of the conical hopper, and

Fig. 2: Spreading of mass flow pressure peak into cylinder section



passing through the top of the cone. The elevation of the highest point on the arc is approximately the maximum elevation at which the increased peak pressure is experienced. The wall pressure distribution below this elevation (down to the top of the cone) can be assumed linear.

A silo in which the fill and withdrawal points are located along the vertical centerline, and which behaves in mass flow, will probably experience some non-uniformity of pressures around its circumference. This could be caused by the wall being out-of-round or out-of-plumb, the intrusion of construction joints, or segregation of the contained bulk material. It is common practice, although by no means always correct, to compensate for these effects by multiplying the calculated wall pressure p by some "over pressure factor" for the purpose of design. We recommend that this should be a *minimum* requirement, and that a designer should make a rational attempt to estimate pressure non-uniformities and their effects.

Funnel Flow – Single Outlet

As noted above, since there is no flow along the hopper walls in a funnel flow pattern (except perhaps when the hopper is being emptied at the end of the discharge sequence), it is reasonable in most cases to consider that the design pressures acting normal to the hopper walls are the same as those which occur during initial fill. Therefore no additional calculations are needed for the hopper section. This presumes, of course, that the outlet size and feeder arrangements are such that no arching or ratholing can occur as material is discharged. It is also important that there be no self-induced silo vibrations acting to magnify pressures [5].

As far as the cylinder section is concerned, there are two main conditions to consider. First, if the flow channel does not intersect the cylinder wall, it is safe and reasonable to assume that the pressures acting against the walls will be the same as during initial fill. If, on the other hand, the flow channel does intersect the cylinder wall, one must consider whether or not the flow channel is centered (*i.e.,* intersects the cylinder wall at the same elevation around its circumference). If the flow channel is *centered*, one can assume a Janssen stress field above the *effective transition* (*i.e.,* the elevation at which the flow channel intersects the cylinder walls). As with mass flow cylinder pressures, we recommend using a range of K_j and wall friction values as described above.

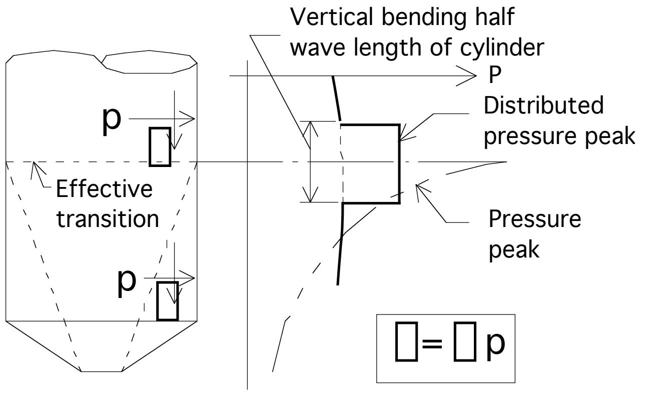
At the effective transition where the flow channel strikes the wall, there is a rapid increase in wall pressure due to the convergence which the material is undergoing. Within the flow channel itself, it is reasonable to assume that the pressures will vary as if this were a mass flow hopper but with the hopper angle replaced by the flow channel angle, and the wall friction value replaced by the internal friction of particles sliding on each other. How this pressure distribution is transmitted to the vertical walls of the cylinder is not well-defined. It is safe, but probably somewhat conservative, to assume that the pressure which acts normal to the cylinder walls is the same pressure which acts normal to the flow channel.

As with the conditions which occur at the bottom of a cylinder just above a mass flow hopper, there is some progression of this pressure peak, which occurs just above the effective transition in a funnel flow silo. For this we recommend that the total radial outward force given by the peak pressure, multiplied by the effective area over which it acts, be converted to a smaller uniform pressure spread over a wall height equal to one vertical bending half wave length. This should be centered at the elevation of the effective transition. See Fig. 3.

Since the side slope of the flow channel – and thus the elevation at which it intersects the cylinder wall – is variable, the above procedure should be used to develop an envelope of peak pressures to be used in design of the cylinder wall.

If the flow channel is not symmetric but still intersects some or all of the cylinder wall, the loading conditions become much more complex. The resulting eccentric flow channel can cause non-uniform pressures to act on the silo walls. In cylindrical reinforced concrete silos this causes horizontal and vertical bending moments which act in addition to the membrane forces and can lead to serious cracking if the walls are not designed to withstand such loading, as is often the case with concrete silos constructed with a single layer of reinforcing steel. In addition, there are many documented cases of dented or collapsed steel bins and silos as a result of eccentric flow channels. The shape of the flow channel, the locations at which the flow channel intersects the silo walls, and the pressure within the flowing and non-flowing regions must all be estimated to permit these bending moment calculations.

Fig. 3: Funnel flow hopper – flow channel intersecting cylinder wall



Several studies have been conducted in an attempt to predict the shape of flow channels in funnel flow bins. One of the older and better known of these studies is that which was performed by Giunta [9]. He postulated that for a silo having a circular outlet with a diameter large enough to prevent arching and ratholing, the flow channel shape would consist of a cone emanating from the outlet and flaring out to some diameter. In the upper portion of the bin or silo, he postulated that the flow channel shape would be cylindrical with a diameter set by the maximum size of the conical flow channel. Giunta tested his hypothesis on an 18 in. diameter flat-bottom bin having a single, central outlet. Test materials included industrial starch, pulverized coal, and iron ore concentrate. He found reasonably good agreement between the actual flow channel shape and his theory.

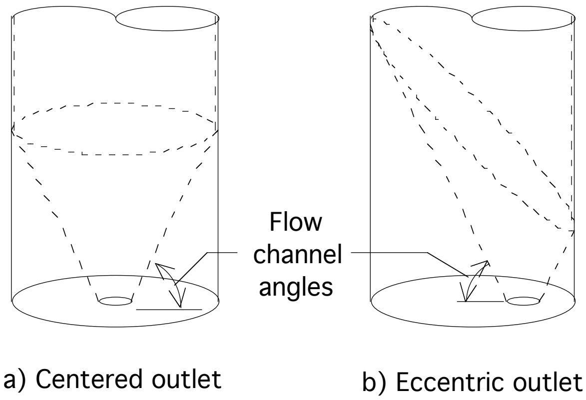
There are a number of limitations in applying Giunta's work as pointed out by Carson *et al* [11]. Unfortunately, as the work of these authors illustrates, there is no straightforward and universal method by which the shape of a funnel flow channel can be predicted.

With non-free flowing bulk solids, relatively steep flow channels form which tend to become more or less circular in cross-section some distance above the outlet. If the outlet is circular and its diameter is less than the bulk solid's critical rathole diameter, a stable rathole will form whose diameter is approximately the same as that of the outlet. With elongated outlets, the diameter of the flow channel will be approximately equal to the length of the diagonal of the outlet. Again, if this diameter is less than the bulk solid's critical rathole diameter, the flow channel will empty out when the silo level is lowered. The diameter of the resulting rathole will be approximately equal to the diameter of the flow channel.

In both of the above cases, the wall pressure will be essentially constant at any elevation **unless** the outlet is near the wall. Only then will the steep flow channel intersect the wall. However, if this occurs, the resulting horizontal bending moments can be very large because of the highly non-uniform wall pressures.

The other extreme is with free flowing materials. As shown by Carson *et al,* the steady state flow channel angle with such materials is considerably less steep than the angles postulated by Giunta. Furthermore, the authors found that with eccentric outlets, the resulting flow channel expanded at roughly the same angle as in a bin with a centered outlet, and the eccentric flow channel's axis of symmetry was approximately vertical. See Fig. 4. Unfortunately, this study failed to identify any correlation between steady state flow channel angle and material flow properties such as effective angle of internal friction or angle of repose. Clearly, much more work needs to be done with larger models, more bulk solids, and full scale silos before any definitive conclusions can be reached. In the meantime, the authors of silo design codes should write silo design requirements to reflect a high degree of uncertainty, not only about actual pressures, but also about the angle of convergence of flow channels and their boundaries.

Fig. 4: Flow channels with centered and eccentric outlets in a funnel flow bin or silo

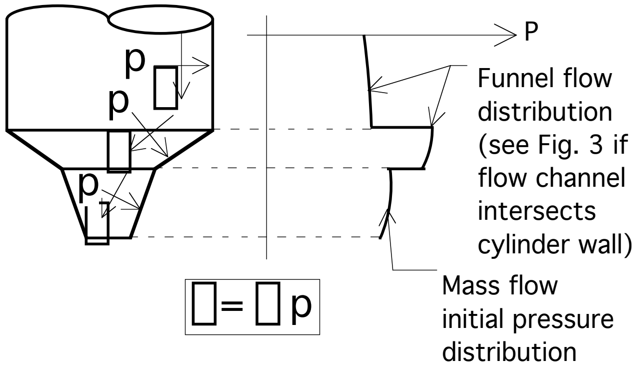


Bulk solids that fall in between the extremes of those that are free flowing and those which rathole, produce flow channels which fall between the extremes described above. Each case needs to be studied closely so as to avoid problems with the design.

Expanded Flow – Single Outlet

An expanded flow silo is defined as one in which the lower hopper section has walls which are steep enough and smooth enough for flow to occur along them, whereas in the upper section of the hopper the walls are either too shallow or too rough for this to occur. Provided that the flow channel in the lower hopper section expands sufficiently to prevent ratholing at the top of this section (*i.e.,* the diameter of the flow channel exceeds the critical rathole diameter of the material), ratholing will not occur within the silo. Furthermore if one assumes that the outlet is sufficiently large such that arching does not occur, and that no self-induced vibration occurs during discharge, then the following combination of loads can be considered. (See Fig. 5) In the cylinder section and in the upper portion of the hopper where flow does not occur along the hopper walls, the bin loads will be the same as those which would occur in a funnel flow silo of the corresponding dimensions. The

Fig. 5: Expanded flow silo



lower hopper section where flow does occur along the hopper walls, can be designed as if this were a mass flow hopper. However, since some convergence of the flow channel will occur above this section, there will be no peak pressure at the top of this hopper section as occurs at the top of a mass flow hopper where it intersects the cylinder. Therefore, the governing loading condition is usually that of initial fill pressures.

Multiple Outlets

If more than one outlet is present in a silo, it is essential to design the silo structurally to withstand the worst possible loading condition [12]. This usually occurs when one or more of the outlets is active while the rest are inactive. Even if all of the outlets are active but are discharging at different rates, preferential flow channels can develop even though functionally the silo is designed for mass flow.

To account for these various design conditions, the silo should be designed for funnel flow loading conditions with an off-centered flow channel occurring above one or more of the active outlets. The most severe combination of flow channels must be considered when calculating the eccentric loads.

MATERIAL FLOW PROPERTIES

Most silo design codes include, either in the code itself or in the commentary section, a tabulation of "typical" properties of a number of bulk materials. One should approach the data in such tables very cautiously. Interpolating properties or guessing properties on the basis of superficial similarities in the description of materials should be vigorously avoided. It is important to remember that it is not possible to know, or to look up, the required flow properties of a granular material from its generic name alone. This is true not only of the bulk material by itself, but also of the surface on which it is sliding. For example, providing values, or a range of values, for wall friction of "coal on steel" sounds simple but can be very misleading. Before using such data, one should consider the following questions:

- What type of coal (*e.g.,* bituminous, lignite, anthracite) was used in developing the data in this table?

- What was the particle size, moisture content, ash content, etc. of the coal which is being described?

- What type of steel and what surface finish were used for the tests? If carbon steel was used, was the variation from a smooth, polished surface to a rough surface (*e.g.,* due to corrosion) considered? If stainless steel was used, was the surface rough (mill finish plate) or smooth (2B finish sheet or polished plate)? If the steel was mechanically polished, was the direction of polish lines taken into account?

In our opinion, most such tabulations provide a disservice to design engineers in that they tempt the engineer to use them in spite of the warnings which are given either within the table or in accompanying text. An engineer can be lulled into a sense that he or she has some quantitative data that is useful for design, whereas in fact, no such assumption is valid.

Material flow tests should be run whenever possible to accurately quantify the flow properties (and range of flow properties) of the bulk material to be handled. This is particularly important when the bulk material being handled is not free flowing, or when its flow properties are unknown, uncertain, or variable. Defining whether or not a material is "free flowing" is somewhat subjective and a matter of debate. In our opinion, the best way to define this is to base it on the flow properties of the bulk material and how those flow properties dictate the type of flow which will occur in a given bin or silo. For example, if it is known (either through experience or through flow properties tests) that a given bulk material will not form a stable arch or rathole in a given bin or silo, one might reasonably conclude that this material in this silo is "free flowing." This same material in another silo having a different flow pattern or silo dimensions might no longer be considered "free flowing."

If tests are to be done, we recommend the following [13]:

- *Flow function and effective angle of internal friction*. Measurements of a material's cohesive strength and internal friction angles should generally be run on the fine fraction of the bulk material, since it is the fines which exhibit most strength. Furthermore, concentrations of fines are usually unavoidable because of particle segregation [14]. Once these parameters have been measured, it is possible to follow design procedures to calculate minimum outlet dimensions to prevent arching as well as critical rathole diameters.

- *Bulk density*. Generally this is measured by consolidating the bulk material to various pressures and then measuring the resulting bulk density at those pressures. Such tests should be run both on the fine fraction (in order to use the resulting values to calculate arching and ratholing dimensions) as well as on the full particle size range. The larger value should be used when calculating bin loads.

- *Wall friction*. Generally it is easier to run this test on the fine fraction of the material, and the resulting values typically don't vary significantly with particle size. It is important to run this test on both the material of construction of the cylinder section as well as that of the hopper. Consideration should be given to variations in the initial condition of the silo walls as well as conditions that can occur after usage due to abrasive wear, corrosion, etc. In general, the smoother the wall surface, the higher the wall pressure acting against it.

- *Abrasive wear*. A tester is available [15] which can quantitatively predict the actual life of a bin or silo wall material due to a bulk material sliding across it. This tester can also be used to determine the change in wall friction due to wear.

Each of the above parameters can vary with the same bulk solid if any one or more of the following conditions change:

- Moisture content
- Time of storage at rest
- Particle size distribution
- Temperature
- Chemical changes

Note that we have not included in the above listing the measurement of the value of K_j. In our opinion, this parameter is more silodependent than material-dependent. Therefore, attempts to measure its value for a given bulk solid are inappropriate.

FORCE RESULTANTS

Tension

In a circular bin or hopper wall with uniform pressure on the circumference, the only horizontal force resultant is ring tension. This is easy to calculate and accommodate in design.

If the hopper bottom is supported at its top edge (*i.e.,* the junction with the vertical wall), it will be loaded in tension along the line of slope, as well as ring tension. This too is easy to calculate and design for, but it is important to check for meridional bending.

Vertical Force, Upper Section

There is a vertical compression force in the walls of the upper silo section due to the accumulation of wall friction effects from the top surface down to the level of the support. This is the sum of the horizontal outward pressures at each increment of depth, multiplied by the depth increment and the wall friction coefficient. Add to this any loads from the roof closure and self weight.

The critical buckling stress in the wall is the criterion governing the thickness required to carry this vertical compression. This condition seldom dictates the thickness of reinforced concrete walls, but is a major consideration in designing thin-walled steel or aluminum silos.

Bending in Flat Walls

Flat walls appear in rectangular bins or hoppers, or in a chisel-shaped hopper between a circular upper section and a slotted outlet. This bending is always combined with tension in the plane of the wall. In the upper section of a bin, vertical compression may also be present. A flat reinforced concrete wall in bending must have two layers of reinforcing steel, adequately anchored at the ends by lap splices running into the adjoining walls. In a steel design it is usually assumed that the tension or compression is carried by the wall plate, and the bending is carried by the external stiffeners.

The flat walls of a rectangular or chisel-shaped hopper, operating in mass flow, must remain as nearly flat as possible, or the mass flow pattern may be lost.

Horizontal Bending of a Circular Wall

This is the major resultant of a funnel flow, single eccentric flow channel reaching the upper bin wall. The horizontal radial outward pressure of the material on the wall is not uniform on the circumference, so out-of-round bending is induced. Non-uniform pressures in symmetrically filled and emptied silos can also result in bending which needs to be evaluated.

Combined bending and tension effects can best be calculated using a finite element model of the bin wall loaded by the internal pressures calculated over the whole circumference and height. Alternatively, a hand calculation of bending and tension in a ring can be performed.

The most important effect on a steel plate shell is the reduction in vertical buckling strength resulting from an increase in the radius of curvature when the shell deflects out-of-round. If the construction is of reinforced concrete, the reinforcing steel must be provided in two layers, with adequate capacity for the bending and ring tension at any point.

Vertical Bending of Upper Wall

In mass flow, as well as in a case of funnel flow at the point that the flow channel strikes the wall, a peak pressure develops at the effective transition. This may be on the full perimeter or an isolated patch, and is also transient. In funnel flow this peak pressure may be several times greater than the pressures above and below, and occurs on a very shallow band. The force resultant is bending in the vertical direction. In a concrete wall the result may be the development of horizontal cracks.

Vertical Force on a Flat Bottom

This is calculated using a value of K_j which will maximize the vertical pressure. One must remember that a large portion of the gross weight of contained material is carried by the bottom when the height-to-diameter ratio is small. This portion decreases rapidly as the height-to-diameter ratio increases.

Forces at Ring Beam

Perhaps the most common, even typical, design of a steel storage silo is circular, with a vertical upper section and a conical bottom hopper, supported at discrete points around the circumference of a ring beam at the junction between the two parts. A concrete silo will commonly have a steel bottom hopper supported from a ring beam which is either separate from the vertical wall, or built into the wall. This ring beam accumulates the meridional tension from the hopper shell, and possibly the gross weight of the bin by vertical friction load from the upper wall. The tension from the hopper contributes a horizontal and vertical component. The horizontal component from the hopper creates compression in the ring beam.

The sum of the vertical forces creates bending, shear, and torsion in the ring beam. The bending moments are negative (tension top) over the support points, and positive at mid-span. Shear occurs at the supports. Torsion develops due to the curvature of the beam, and is at a maximum at the points of contraflexure of the spans.

An additional force resultant is the rolling moment. The line of action of the vector sum of the forces applied to the ring beam is unlikely to pass through the shear center of the beam cross section. The beam therefore tends to be rolled inside out. The net effect of rolling is an additional vertical moment, applied at all points on the circumference.

The ring beam must be designed to accommodate all these forces in combination.

OTHER CONSIDERATIONS

Feeder Design

In addition to the geometry and materials of construction of the silo, equally important is the type of feeder which is used, as well as details of the interface between the hopper and the feeder. This is particularly important if a mass flow design is to be used in which case the feeder must ensure that the outlet area is fully “live” [16, 17]. Feeder design is also important with funnel flow or expanded flow silos since, depending upon the details of the interface, the flow channel may either be centered or eccentric. Also important is the operation of a gate at the outlet. If such a gate is used in anything but a full open or full closed position, it may upset the development of mass flow or the type of flow channel which develops in funnel flow or expanded flow. A partially closed gate – even if only just projecting into flowing material – can prevent flow along significant portions of the hopper wall.

Thermal Loading

Many bulk solids are fed into silos at a temperature significantly different from that of the surroundings. In such cases, calculations have to be made to estimate values for rate of heat flow out of, or into, the silo, temperature gradients through the wall, and change of temperatures in the silo contents. From this, design can proceed to such things as heating input, selection of insulation, (*e.g.,* to maintain the contents at a carefully controlled temperature, to prevent freezing) or strengthening the walls to safely resist thermal stresses.

There are two distinct and different conditions to be analyzed [18]. The worst thermal effects are usually found in the walls of a silo above a hot material surface. Here the temperature is maintained at a high level while fresh material continues to be fed into the silo. As hot material continues to be fed into the silo, the surface rises. Material already in place, and successive levels of wall, are buried. Material at a high temperature comes in contact with the wall at a lower temperature. This causes a brief temperature excursion affecting a narrow band of the wall, following which all the temperatures will start to fall as heat flows through the wall to the outside, and a zone of cooled material develops against the wall.

The other condition to be considered in design exists below the material surface, where temperatures fall as heat flows to the outside. A temperature gradient develops through some thickness of the granular material, from the hot interior to the cooler wall. Gravity loads will therefore co-exist only with reduced thermal loads. It is of interest to know the time taken for this temperature gradient to develop to some critical point, such as temperature falling below freezing at the inside face of the wall.

NOMENCLATURE

D = cylinder diameter
h = hopper height
K_f = defined by equation (9)
K_j = Janssen ratio of horizontal to vertical pressure
n_i = defined by equation (5)
n_f = defined by equation (10)
p = pressure acting normal (*i.e., perpendicular*) to a silo or hopper wall
q = vertical pressure acting at top of hopper
z = vertical coordinate
z_1 = vertical distance along cylinder wall starting at point of intersection of top pile
z_2 = additional vertical height added to z_1 to account for pile height
□ = bulk density
$□_c$ = conical hopper angle (measured from vertical)
□ = coefficient of sliding friction between bulk solid and wall surface
□/□□ = see Fig. 58 to 62 of ref. [1]
□ = shear stress acting along wall surface in direction of flow
□□ = wall friction angle between bulk solid and wall surface

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