JENIKE & JOHANSON INCORPORATED

June 18, 2009

Mr. Dennis A. Blauser, CEO
Marietta Silos, LLC
2417 Waterford Rd
Marietta OH 45750

RE: Advantages of reinforced concrete silos

Dear Mr. Blauser:

You have asked Jenike & Johanson, Inc. to comment on the advantages of reinforced concrete over metal (typically steel or aluminum) when used to construct large (30 ft diameter and larger) silos to store bulk solids such as fly ash, cement, lime, etc. In this letter report we focus on design and operational issues, not cost. Both slip form and jump form construction are considered.

First, some caveats:

1. We assume proper design of the silo. This includes [1][1]:
   a. Operating requirements and conditions are thoroughly defined before design is started. This includes such factors as silo capacity, discharge rate and frequency, mixture and material uniformity, material friability, pressure and temperature differences, safety and environmental concerns, etc.
   b. The range of relevant properties of the bulk solid (or solids) to be stored is known. This usually requires flow property tests to be performed by a specialized testing laboratory.
   c. The silo's functional design has been generated by engineers experienced in solids flow.
   d. Detailed design has been performed by competent silo engineers, with consideration given to all reasonably expected loading conditions.
2. We assume proper construction. The silo must be constructed in close agreement with the detailed design, and deviations, if any, must be approved by the silo design engineer.
3. We assume proper silo operation. Routine inspections must be carried out. [2] Any changes in the bulk solid being stored or in operating conditions must be properly considered before

1 Numbers in brackets refer to References at end of text. A copy of each paper is appended.

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implementation, and any signs of distress must be promptly investigated with appropriate action taken.

Before commenting on the benefits of reinforced concrete construction, it is perhaps helpful to provide some background concerning horizontal and vertical loads that must be considered in designing a silo. [3] Horizontal loads are due to hoop tension, out-of-round flexure in a circular wall, and out-of-plane flexure in a flat wall. One of the leading causes of the latter two phenomena is non-uniform pressures that result from eccentric fill or withdrawal from a silo. Vertical loads are due to compression from the accumulated frictional drag of the silo contents, and also compression (and tension) due to overturning caused by external loading such as wind and seismic.

In a reinforced concrete silo, the main criterion governing wall thickness is horizontal loads. Vertical loading is a major consideration only at wall openings, columns, pilasters, etc. In metal silo design, on the other hand, the first consideration is always vertical loading, as explained below.

What then are the advantages of reinforced concrete over metal (bolted or welded) for silo construction?

From our experience, a reinforced concrete silo's ability to withstand the effects of eccentric loads is one of its main advantages over metal, especially when considering large silos.

A silo wall constructed of concrete is reinforced by steel reinforcing bars (rebar), and the amount of rebar is proportioned to carry the hoop tension. It is easy to vary the area of rebar in a unit height of the wall as the hoop tension requirement varies. This is achieved by varying the bar size, spacing, or both. The amount of rebar can be increased to account for the effects of loads other than hoop tension, such as flexure due to non-uniform pressures, connectivity with other structures, thermal loading, seismic or wind loading, etc.

The situation is very different with metal silos. The first consideration when designing such a silo is vertical loading. The critical longitudinal buckling stress for a cylindrical shell (i.e., the strength of a cylindrical silo wall in vertical compression) is inversely proportional to its radius of curvature. Out-of-round bending causes the radius to be both increased and decreased, at different places. It is imperative that a proper analysis is made to predict possible changes in radius, both anticipated and accidental. If a suitable plate thickness to provide the required buckling resistance is uneconomical, vertical stiffeners (internal or external) are required. A flat wall should always be reinforced with vertical stiffeners.

Vertical buckling of inadequately stiffened metal silos causes more silo failures than any other mechanism. [4] Once a silo wall has buckled, it cannot be restored but must be replaced. Buckling often leads to fracture of joints between plates, followed by rapid collapse of the silo.

Once the plate thickness for a cylindrical metal silo wall has been selected according to vertical buckling strength requirements, the next check is the thickness and connections -- welded or bolted -- to withstand applied hoop tension. Where non-uniform pressures are present, it is unlikely (except in small silos) that an increased plate thickness can be found that provides a large enough section modulus to resist out-of-round flexure. Therefore, external ring stiffeners are usually required to provide flexural stiffness, and these are often found to be quite heavy members. A flat wall always requires external stiffeners.

External horizontal stiffeners have additional problems. One must consider that the effects of such reinforcement are localized so if they are too widely spaced, deformation may occur between them. Additional welding or bolting is required, which drives up cost. Finally, the presence of external ledges provides significant area for fugitive material to build up, which can result in corrosion that is hidden from view until a dangerous situation has developed.

Other advantages of reinforced concrete for silo construction include:

1. Theses silos have good resistance to corrosion. This includes both corrosion of internal walls due to the stored bulk solid and also external corrosion caused by moisture. Metal corrosion is a well known problem.
2. There is no concern about electrolytic effects at welds or liner connections.
3. Careless detailing of metal walls may leave inward facing ledges or welds, which can obstruct flow and increase wall pressures. This is avoided with concrete.
4. Concrete is better able to resist abrasive wear than most metals.
5. Concrete is more robust and thus better able to withstand impact loads.
6. Concrete has higher wall friction angles with most bulk solids than most metals. This results in higher frictional drag down the cylinder walls and hence lower pressures acting normal (i.e. perpendicular) to cylinder and hopper walls.
7. It is possible to construct interconnected structures using reinforced concrete. This allows for interstices that can be used for storage and/or process equipment.
8. There is no concern about weld quality or stress risers, such as bolted connections.
9. There is no concern about leakage to the environment, which can be a problem when storing fine powders in bolted silos.

In summary, reinforced concrete has many advantages over metal when designing and building large silos for the storage of bulk solids. As with any structure or piece of equipment, such silos must be properly designed, built and operated in order for these advantages to be realized.

Please contact us if you have any questions or if we can be of further assistance.

Sincerely,

John W. Carson

John W. Carson, Ph.D.
President
Tyngsboro, Massachusetts

JENIKE & JOHANSON

References

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2. Carson, J. W. and Jenkyn, R. T.: How to Prevent Silo Failure with Routine Inspections and Proper Repair. Powder and Bulk Engineering, Vol. 4 No. 1, January 1990.
3. 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.
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Six steps to designing a storage vessel that really works

Herman Purutyan, Brian H. Pittenger, and Dr. John W. Carson Jenike & Johanson

Designing a storage vessel for your plant requires a methodical approach. This article outlines six steps to follow in designing, installing, and starting up a storage vessel that successfully handles your bulk material under your operating conditions.

Have you experienced delays in starting up a new processing system? Or is your existing or new processing system performing poorly? Often the main culprit is a poorly designed storage vessel — such as a bin, silo, or hopper — somewhere in the system. An improperly designed storage vessel is also more likely to fail structurally than other plant equipment and is more prone to dust explosions or fires and to releasing hazardous emissions. These problems produce unsafe conditions for your workers and the community surrounding your plant.

Factors behind a poor design

What leads to improper vessel design? One cause is considering your vessel design after other system equipment has been selected. Another common mistake is designing the vessel without fully investigating your material's flow properties. Knowing your material's name, bulk density, particle size distribution, and angle of repose just isn't enough.

Relying on your past experience in selecting storage vessels can also lead to a poor vessel design. Why? You typically need a new vessel because your material's characteristics or your operating conditions, or both, have changed.

Designing a vessel based on an inadequate budget that's set before the design process really starts can also result in a poorly functioning vessel. In a project's early stages, the engineer in charge is often expected to quote a cost for the vessel based on as little information as "the vessel will be a 14-foot-diameter silo with a cone hopper." Such a simplistic approach can make it hard to go back and increase the budget. So the vessel matching those vague initial specifications can be the vessel you're stuck with in the end.

Steps in properly designing, installing, and starting up a vessel

Avoid vessel performance problems by following a detailed, systematic approach to designing, installing, and starting up your storage vessel. The steps are:

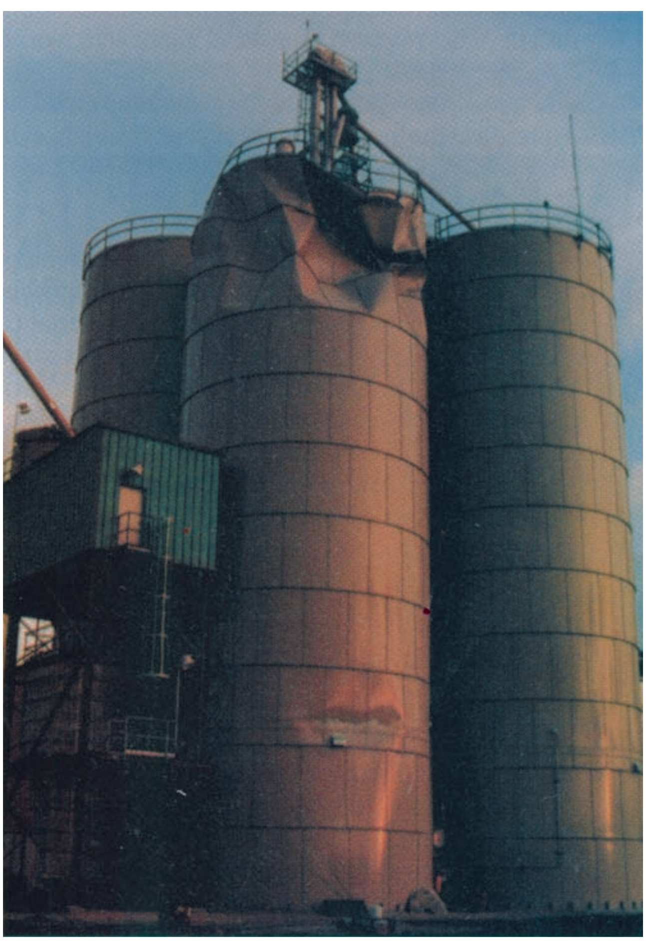
1. Define your operating requirements and conditions.
2. Test your material's flow properties.
3. Develop the vessel's functional design.
4. Develop the vessel's detail design.
5. Fabricate and install the vessel.
6. Start up and maintain the vessel.

Depending on your company's size and whether you're designing a vessel for an existing or new process or for an entirely new plant, the testing, engineering, fabrication, and installation services you need to contract as you follow these steps can vary widely. For instance, if you're adding a vessel to an existing plant, you can hire an independent firm to test your material's flow properties and do the functional and detail designs, and then hire a fabricator to build and perhaps install the vessel at your site. If the vessel will be part of a new plant or major plant addition, the engineering consulting firm managing your project may handle the flow property tests and the functional and detail designs and work with a fabricator or vessel supplier to fabricate and install the vessel.

The following sections explain how you can follow each step and avoid pitfalls along the way.

1 Define your operating requirements and conditions.

Identify your operating requirements and conditions before you design the storage vessel. Among the most important factors to consider are capacity, discharge rate and frequency, mixture and material uniformity, material friability, pressure and temperature differences, safety and environmental concerns, and construction materials. Your application may require you to consider other factors as well.



An improperly designed storage vessel is more likely to fail structurally than other plant equipment. When the hopper section in this corn silo failed, falling corn created a vacuum that sucked the silo's top inward.

Capacity. First consider your storage vessel's required capacity. For help in setting this capacity, look at your plant's business or operating strategies. For instance, a growing trend in many plants is to reduce raw material inventories to free up working capital. If this is the case in your plant, your storage vessel may require a relatively small capacity.

If the storage vessel will be at your process's front end, the vessel capacity may be dictated by the raw material's delivery schedule, shipping container type and size, and usage rate. For instance, if your plant receives one truckload of material per day, one relatively small silo may be enough. But if a larger quantity is delivered by train or ship once a month, you may need a much larger vessel (or multiple vessels) to store it.

If your vessel will be located at an intermediate process step, base the vessel's capacity on your process requirements. For instance, the vessel may need to hold enough material to prevent shutting down a furnace or reactor when an upstream problem temporarily halts material flow. Or you may need to base the vessel capacity on the quantity of material a batch step requires or the quantity needed to even out differences in the rates of two process steps.

If your vessel is located at the process's back end, base the vessel capacity on your plant's shipping schedule, product orders or sales cycles, shipping container type and size, and your plant's business strategies (such as a just-in-time shipping policy).

Discharge rate. Regardless of where your storage vessel is located, it must deliver material to a downstream process at a required rate. You need to specify the required discharge rate early in the design process and communicate it clearly to the project engineer. For instance, are you stating the discharge rate as an average rate? How did you determine it? Is it based on volume (such as cubic feet per hour) or mass (such as pounds per hour)? Be specific: If your downstream process requires 10 t/h of material but the vessel will discharge material only four times per hour for 5 minutes at a time, the *instantaneous discharge rate* the vessel must provide is 30 t/h. A vessel that can discharge material at only 10 t/h won't be able to deliver enough material to your process in those four 5-minute periods.

Also consider the minimum and maximum discharge rates your vessel must provide in both normal and upset conditions. Some processes are much more sensitive to discharge rate variations than others. For instance, such variations may not be important if your process transfers a certain-size batch after a given time. But if your process combines multiple material streams, each from a different vessel, into one mixture, each vessel must have a uniform discharge rate to maintain the proper proportion of ingredients in the mixture.

Discharge frequency. Specify the vessel's discharge frequency early in the design process. When a material is stored over time, some of its flow properties can change. Ensure that your vessel is designed to handle these changes by considering how long your material will be stored in the vessel between discharges. Will your vessel be used in a one-shift-per-day operation that leaves material at rest in the vessel overnight? Will your process shut down for weekends, leaving some material in the vessel? During planned shutdowns, will you empty the vessel or will you leave material in it? How long will material remain in the vessel during a shutdown — 1 week? Longer?

Mixture and material uniformity. If your vessel will hold a mixture consisting of several ingredients, your process may require that the mixture remain uniformly mixed during storage and discharge. If your vessel stores ingredients for a dry salad dressing mix, for instance, it should discharge all ingredients together in the right proportions rather than herbs first, seasonings next, and croutons last. If your vessel stores dry ingredients for cement, it should discharge the limestone and clay together rather than one after the other to your mill.

If the storage vessel will be at your process's front end, the vessel capacity may be dictated by the raw material's delivery schedule, shipping container type and size, and usage rate.

If your vessel will store only one material, you still may need to be concerned about maintaining the material's particle size uniformity during storage and discharge. Coarse and fine particles with the same chemical content can perform quite differently. If your downstream process is designed to handle a wide particle size range, design the vessel to prevent the discharge of only all fines or all coarse.

Off-spec material or dust that's returned from the process to your vessel can also affect the material's uniformity. Early in the design process, consider whether off-spec material or dust must be returned to your vessel and how it can be returned to prevent affecting the material's uniformity.

Material friability. If your material is friable, a poorly designed vessel will degrade it. For instance, detergent agglomerates can break up during vessel loading and discharge, compromising the final product's quality. Attrition of pasta or cereal flakes during loading and discharge can result in scrapped product.

Pressure and temperature differences. Your material can behave differently depending on the gas pressure and temperature it's exposed to. Identify the gas pressure in equipment upstream and downstream from your vessel. If these differ from the pressure inside the storage vessel, they can affect your material's flow properties. The same is true if your process operating temperature is different than the temperature inside the storage vessel. Determine the temperature conditions, including minimum and maximum ambient temperatures (especially for outdoor storage) and minimum and maximum incoming material temperatures, that can affect your material's behavior so the vessel you design can handle these conditions.

Safety and environmental concerns. Determine whether your material is likely to explode or burn. For instance, materials such as coal and grain generate flammable or ignitable dust. Others such as polyethylene and polypropylene can contain volatiles. Use this information to design the vessel with adequate explosion- and fire-protection features (such as an explosion vent or explosion-suppression system) or to decide whether to use an inert gas (such as nitrogen) in the vessel.

Consider whether material spilled from the vessel or fugitive dust or fumes released from it can injure your workers or pollute the environment. Also determine whether contaminants, atmospheric gases, humidity, and temperature can adversely affect the material stored in your vessel. In either case, design the vessel to safely handle these conditions.

Construction materials. Your material's chemical composition and other properties can limit the choice of construction materials for your vessel. An abrasive material can wear some wall materials. A material containing a corrosive substance such as a salt or acid may require a vessel with epoxy-coated walls. Residue from previous materials in upstream equipment can also affect the walls. For instance, an acid not completely removed during equipment washdown may linger in upstream process equipment, travel with your material into the vessel, and corrode the walls.

2 Test your material's flow properties.

Testing to identify your material's flow properties is critical to successfully designing your storage vessel. Run tests on a representative sample of your material under conditions that match the worst-case conditions you expect the material to be handled in. For instance, if you expect your material to degrade during pneumatic conveying into the vessel, test a sample of material that's been pneumatically conveyed under the same conditions.[1]

You also need to test the material's flow properties under the conditions that will be present in your vessel. When possible, obtain samples from your vessel supplier of the wall materials you're considering so you can test the bulk material's behavior when flowing along these surfaces.

Also get samples of your bulk material from the material supplier you'll use rather than another supplier. Materials with the same chemical composition from different suppliers can have quite different flow properties. If the particle size, shape, moisture content, or other properties of the sample differ from those of your actual material, the test results won't be of much help in designing your vessel.

If you can't obtain a sample of your material because it hasn't been produced yet, you may be able to test a sample from a pilot plant. Although your production-grade material may be different than this sample, testing the pilot-plant sample can help you at least establish a baseline for designing the vessel.

Vessel diameter can be limited by the space available in your plant or the vessel's construction method.

If you can't get a material sample because you haven't yet identified a supplier for it, you can obtain a range of flow property data for the material from others who have conducted flow property tests. For instance, to design a silo that will receive coal from many locations around the world, you can survey flow properties of coal from diverse locations to at least identify some vessel design basics. While clearly less accurate than testing the actual coal samples, using this method is better than making your decision without any coal data.

If your vessel will hold materials from several sources or hold several grades of one material, run a series of tests on samples of each material or grade. The tests can identify which samples have extreme flow properties that will affect your vessel design.

Before running tests, consider which flow properties you need to identify for designing your vessel. Distinguish between tests that provide qualitative, relative data and tests that provide quantitative, absolute data. For instance, tests for angle of repose, flow time through a funnel, and compaction ratios will generate qualitative, relative data that, at best, may help you find differences between samples but won't help you design the vessel.

Instead, use quantitative, absolute tests that identify flow properties important to vessel design. These include tests of the material's cohesive (shear) strength, compressibility and permeability, segregation tendencies, and abrasiveness. Wall friction (friction between the material and vessel wall) is another important test. For most of these tests, you can use the Jenike shear tester, adopted as the only standard flow property test device by the American Society for Testing and Materials (ASTM), International Standards Organization (ISO), and European Federation of Chemical Engineering.

Conduct the tests under the conditions in your process that are most likely to adversely affect your material's flow. For instance, a material generally becomes harder to handle as temperature increases (although freezing can also make a material harder to handle). Increasing the material's moisture content, increasing its storage time at rest, and decreasing its particle size also can cause flow problems. So run your tests with materials at the maximum temperature and moisture and after the maximum storage time at rest that you expect in your process. If your material has a wide particle size range with a significant portion (15 to 20 percent or more) of particles less than ¼ inch, conduct the flow tests on these fine particles only.

3 Develop the vessel's functional design.

Consider your operating requirements and conditions and the material's flow properties to develop your vessel's *functional design*. This functional design specifies the features the vessel needs to function effectively in your application. The vessel features that will be designed during this step include:

- Cylinder height, diameter, and construction material.
- Hopper shape, slope, and construction material.
- Outlet size.
- Feeder type and size (including details for activating the entire outlet, if necessary).

Optional features that you also can determine at this step include:

- Discharge valve type (slide gate, butterfly, and so on) and size.
- Hopper insert or flow aid type, location, size, and construction material.

To determine the vessel's maximum diameter and height, consider your site conditions and construction factors. Vessel diameter can be limited by the space available in your plant or the vessel's construction method. For instance, a vessel that will be fabricated in a supplier's shop probably can't exceed 14 feet in diameter to be transported in one piece to your site. Vessel height can be limited by your surrounding structure's height, your area's seismic or wind-loading conditions, the amount of associated process equipment that must be located above or near the vessel, on-site construction factors (such as crane size), or the vessel foundation design (which can be limited by the area's soil conditions). These limitations can also determine whether you need to install one or more vessels.

The key factor to consider in selecting the vessel's other functional design features is the appropriate flow pattern inside the vessel. Several vessel features — including the outlet size, cylinder and hopper shapes, hopper wall slope, hopper surface material, feeder (located at the outlet), and any required valves, hopper inserts, or flow aids — affect the flow pattern.

The two primary flow patterns in a vessel are *funnel flow* and *mass flow,* as shown in Figure 1. In funnel flow (Figure 1a), an active flow channel forms above the outlet with nonflowing material around the vessel periphery. The result is a first-in last-out flow sequence, with potential caking of stagnant material and sifting segregation in which fines typically exit first. This produces uneven discharge with inconsistent bulk density and uncontrolled flow. As the material level in the vessel drops, layers of the nonflowing material may or may not slide into the flowing channel. This can produce a stable rathole in the vessel, where material outside the channel remains stagnant.

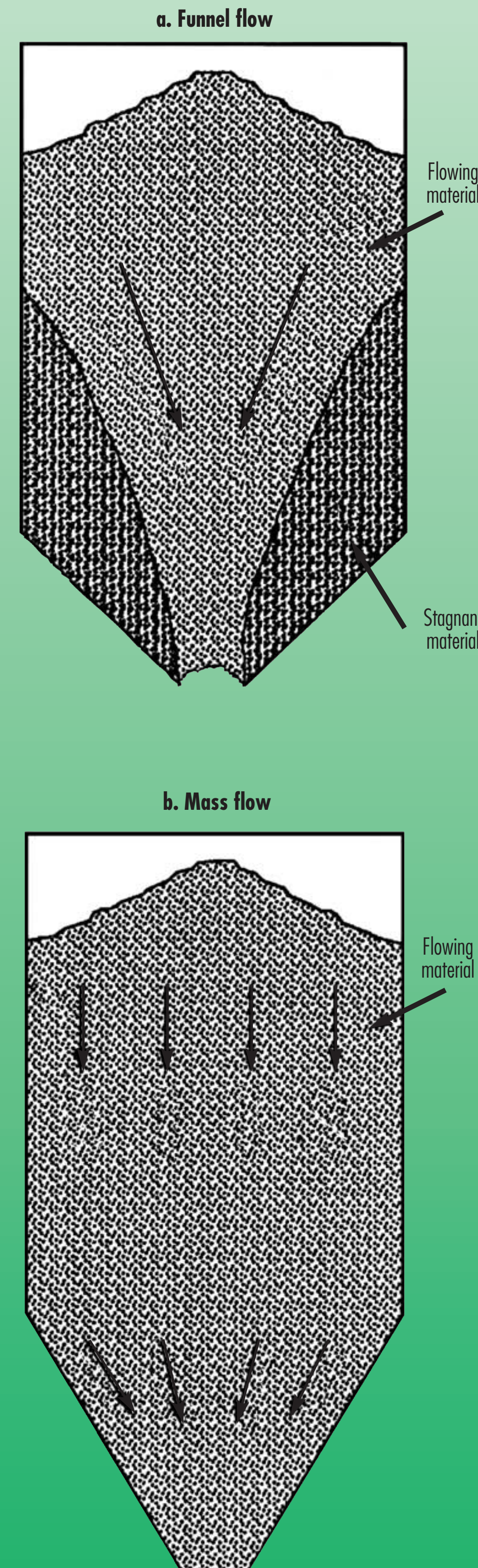
In mass flow (Figure 1b), all the material is in motion whenever any is withdrawn from the vessel. Material from both the vessel center and periphery moves toward the outlet. This provides a first-in first-out flow sequence, eliminates stagnant material, reduces sifting segregation, and provides a steady discharge with consistent bulk density and uniform, well-controlled flow.

Despite the advantages of mass flow, it isn't always possible, practical, or cost-effective to install a vessel that provides it. In fact, a vessel that provides funnel flow can be acceptable for some applications. For instance, you can use a funnel-flow vessel if your material is free-flowing and coarse enough to prevent aeration and if your process won't be affected by mixture segregation, particle size segregation, or first-in last-out flow.

But when these conditions aren't acceptable, your vessel must provide a mass-flow pattern. Achieving mass flow requires a vessel outlet that's large enough to prevent material from arching (also called *bridging*) over the outlet, hopper walls that are smooth and steep enough to promote material flow at the walls, and an outlet that's entirely active (which requires choosing a feeder that allows this).

Figure 1

Flow patterns



The minimum outlet size that can overcome arching is directly related to your material's cohesive strength. Use the cohesive strength test results you obtained in step 2 to calculate a minimum outlet size. Also consider whether a circular or elongated outlet is better for your application.

Your required discharge rate also affects the outlet size. If the material — particularly a fine powder — deaerates in the vessel, the discharge rate can slow greatly. Use the permeability test results from step 2 to calculate your material's discharge rate for various outlet sizes.

The shape, slope, and construction materials of surfaces in contact with your material also affect the flow pattern. How cohesive and frictional your material is determines what hopper geometry — cone, wedge, transition, or other — your vessel will have. Because a cone hopper must be 10 to 12 degrees steeper than a wedge or transition hopper of the same construction material, the wedge or transition hopper may be more appropriate if you have limited headroom. The outlet width in the wedge or transition hopper can also be equal to one-half the cone hopper's outlet diameter while having the same effect in preventing arching, so if your material's cohesive strength would require a large circular outlet, using a wedge or transition outlet may work fine and also save headroom.

Selecting the proper feeder for the vessel outlet is also important because mass flow can't occur if the feeder can't withdraw material from the entire outlet. A lip, ledge, partially open gate, or mismatched flange at the outlet can also be fatal to mass flow.

To choose a feeder, consider whether your material is fine or fluidizable. Most dry solids feeders can't hold back fluids. For instance, a screw feeder can't contain a fluidized material, so if the material in the vessel never settles during filling or becomes fluidized, it will flood out of the feeder.

If your vessel will have a unique design and you don't know all your operating conditions or material flow properties, you can test the vessel and feeder design in a scale model. However, you need to understand which of your material's flow properties can be scaled down, because not all of them can. For instance, wall friction results can be scaled down, but the results for the minimum outlet size to overcome arching can't.

4 Develop the vessel's detail design.

Developing your vessel's *detail design* requires selecting its construction materials, fabrication and installation methods, and structural design. Once the detail design is completed, your design engineer can generate engineering drawings of the vessel. The drawings will be used to fabricate the vessel and in many cases are given to firms submitting bids for the vessel fabrication. To ensure that all relevant functional design details from step 3 are properly incorporated into the detail design, you must communicate all functional design points from step 3 to the engineer.

For instance, your functional design may specify a Type 304 stainless steel hopper surface with a number 2B finish, but if you don't communicate *all* the details clearly, the engineer may interpret this specification as simply a Type 304 stainless steel hopper surface. This means you may end up with a surface fabricated from mill finish or number 1 finish Type 304 stainless steel, which is much more frictional than a number 2B finish surface and will cause flow problems.

Determining how to fabricate your vessel is one of the first things to consider in the detail design. The three most common fabrication options are reinforced concrete, welded steel or aluminum, and bolted steel or aluminum.

A reinforced concrete vessel is typically used for large-capacity applications. It typically has a 35-foot or larger diameter and a total volume greater than 30,000 cubic feet. The vessel is often fabricated in a bank or group of multiple vessels. A welded steel or aluminum vessel can be of various sizes and fabricated in the shop or at your site. Shop fabrication, which provides close control of the welding process, is an option only for a vessel with a diameter of 14 feet or less. This fabrication method also allows a special vessel coating such as epoxy to be applied (and cured, if necessary) before the vessel is shipped. A bolted steel vessel can have a 100-foot or greater diameter and consists of shop-fabricated (and, sometimes, shop-coated) pieces assembled in the field.

To select a fabrication method, consider the construction material and surface coating or lining you need, the cost and installation (or shipment) method for each type of fabrication, and the service life of vessels fabricated by each method.

Also consider your vessel's installation requirements in the detail design. If your vessel will be in a hard-to-access area and you have a limited amount of downtime to install the vessel, it may have to be designed and built in sections. For instance, designing a vessel with a hopper in multiple sections may eliminate having to move walls, other equipment, pipes, and electrical components in your plant and reduce the vessel's installation time. While the hopper's cost will be more than that of a one-piece unit, the overall project's cost can be reduced because installing the vessel in sections will require less downtime.

You need to determine the vessel's structural design, too. This requires calculating the pressures that your material will apply to the vessel walls. The pressures depend on the material's flow properties, the vessel flow pattern, and the vessel geometry. Various codes, including those of the American Concrete Institute (ACI) and American Society of Agricultural Engineers (ASAE), address aspects of structural design and vessel construction, but none covers all the conditions you must consider.

Carefully consider how to add such items as access doors, poke holes, flow aids, and level sensors to the vessel. If you place them poorly, they can cause flow problems. For instance, an aeration pad installed on the hopper surface to prevent potential flow problems may actually create them. To avoid this situation, have the engineering drawings reviewed by the individuals who specified the vessel's operating requirements, determined your material's flow properties, and prepared the functional design.

5 Fabricate and install the vessel.

Before and during fabrication, you need to ensure that the vessel fabricator correctly interprets the detail design as well as understands the basis for the design. Otherwise, the fabricator can make a mistake, such as trying to improve your vessel's number 2B finish by polishing it, unaware that polishing this surface often increases wall friction and can stop the material flow in your vessel. Other details, such as a slightly oversized flange, can also appear to be trivial to the fabricator, who may make the flange smaller so it fits the vessel outlet better. The result can be a flow stoppage.

Before installation, inspect the vessel against the detail design to ensure that the vessel meets your design specs and intent. It's easier to fix problems now than after the vessel is installed.

In mass flow, all the material is in motion whenever any is withdrawn from the vessel.

At installation, which can be handled by a vessel supplier, an engineering contractor, or your plant staff, ensure that the hopper's sloping walls — where wall friction is critical — are protected. If the vessel requires field welding, these surfaces should be draped with fireproof cloth to prevent weld spatter from marring them. Minimize any welding on the sloping surface, and vertically orient welds so they follow the direction of material flow.

Sometimes a shop-fabricated vessel is shipped with a protective coating. Before you load material into such a vessel, remove the coating and restore the surface to its original condition. It's a common misconception that material flow will remove the coating and expose the underlying surface. In fact, if the coating is more frictional than the wall surface, no flow will occur at the walls and the coating will remain. Once you've loaded material into your vessel, the only way to remedy this problem is to unload the vessel (now a real problem) and clean the walls.

You can have similar problems if you load your vessel with a material other than the one the vessel was designed for. Sometimes this is done in early flow trials to "work out the vessel's bugs" — but the bugs that result can be entirely different from those produced by your design material. If you use a different material for flow trials, use one with flow properties similar to those of your design material.

Loading your vessel with a material produced during a process startup can also produce problems. The startup material often has substantially different moisture content, particle size, chemical composition, and even surface structure, and it won't give accurate results in your flow trials.

6 Start up and maintain the vessel.

After installation, those who installed the vessel should be present at startup. You may also want the engineer who handled the vessel's detail design to be present. Startup involves loading the vessel with your material and checking that the material discharges as required from the outlet.

After startup, routinely inspect your vessel to prevent small problems from growing into large ones. Inspect the hopper's sloping surfaces for any changes in condition, such as liner or coating wear, that can produce flow problems. Inspect the vessel walls for thin spots caused by wear and corrosion, especially around the cylinder-hopper interface and near the outlet. This can help you circumvent serious structural problems. Inspect the welds and support structure to identify any deterioration that needs repair. Routinely inspect the vessel's relief valves to prevent overpressurizing the vessel, and also inspect related dust collection filters, feeder gaskets, and seals.[2]

If you decide to store a different material in your vessel, be sure to consider more than just the material's bulk density. If the material's flow properties are different from those of your original material, the flow pattern through the vessel can be different and impose different stresses on the vessel. This can cause a vessel wall section not designed to handle high stress to experience loads exceeding the section's design limits, resulting in vessel failure. Before placing a different material in your vessel, measure the material's flow properties and review your vessel design in light of these properties.

Some final advice

While it's impossible to cover all the details of designing a storage vessel for reliable operation in one article, the six steps described here provide a good road map for starting this journey. Work with experts — whether they're from your firm or are independent engineers or consultants — to carefully consider the details of your application. Making the design project a top priority and directing the appropriate resources toward it can help you design a vessel that performs reliably and safely. **PBE**

References

1. Find more information on how to conduct flow property tests in articles listed under "Solids flow" in *Powder and Bulk Engineering*'s comprehensive "Index to articles" (in the December 1998 issue and on *PBE*'s Web site, www.powderbulk.com).
2. See "How to prevent silo failure with routine inspections and proper repairs," by Dr. John W. Carson and Richard T. Jenkyn in *Powder and Bulk Engineering,* January 1990, pages 18-25.

For further reading

Find more information on selecting storage equipment in articles listed under "Storage" and "Solids flow" in *Powder and Bulk Engineering*'s comprehensive "Index to articles" (in the December 1998 issue and on *PBE*'s Web site, www.powderbulk.com).

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How to prevent silo failure with routine inspections and proper repairs

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Silos that store bulk solids fail due to structural problems caused by bad design, poor construction, or improper use. A damaged or collapsed silo can disrupt the smooth and efficient operation of a plant by reducing storage capacity, spilling the stored solids, damaging nearby equipment, endangering workers, and generating dust. This article describes the causes of silo failure, provides three examples of silo failure, and then describes how to prevent silo failure by initiating routine inspections and making proper repairs.

The silo, bin, or hopper you use for storing bulk solids can develop structural problems if it's badly designed, poorly constructed, or improperly used. Such structural problems can cause your silo to fail. Because a silo is essential to a bulk solids handling system, the cost of silo failure is never small.

Sometimes the structural problems are cracks or distortions, such as bulges, in the silo walls. This kind of damage may force you to reduce the amount of solids stored in the silo to a level below the point of the damage, reducing the silo's usable capacity and slowing plant production. Cracks and distortions can also cause solids to spill out of your silo and generate fugitive dust, which may alarm workers near the silo.

Structural problems may also cause your silo to completely collapse, which not only damages or destroys the silo, but can damage nearby equipment, destroy the stored solids, disrupt plant production, and even injure or kill workers who happen to be near the silo when it collapses.

This article describes the causes of silo failure and then presents three examples of silo failure in various applications, along with an analysis of each failure. Methods of preventing silo failure are described next, including information on how to initiate routine inspections and make proper repairs.

Causes of silo failure

A silo can fail as a result of several factors: uneven foundation settling, faulty construction (such as using the wrong materials or not using adequate reinforcements, such as rebars), explosions, and loading conditions the designer didn't anticipate. Such loading conditions generally fall into one of the following categories:

- A large void (such as a horizontal arch or a vertical rathole) that forms within the body of the stored material and later collapses, resulting in a significant dynamic load on the silo walls.
- Nonuniform pressures acting on a circular silo wall that are caused by an off-center channel in the material adjacent to the wall.
- Local peak pressure at a point where a funnel flow channel intersects a silo wall.
- Development of mass flow in a silo structurally designed for funnel flow.
- Asymmetric pressures caused by inserts (such as beams) across the cylinder section of a silo.
- Use of drastic flow-promotion means, such as explosives, excessive vibration, or air injection.
- Migration of moisture from wet to dry particles within the stored solids, which causes the dry particles to expand and imposes strong radial loads on a silo.
- Buckling of an unsupported wall below an arch of stored solids.

Examples of silo failure

The following three case studies illustrate examples of silo failure and the extent of the damage that can result. An analysis of how the silo failed, how it was repaired, and how the failure could have been avoided is included.

Canola meal silo. A silo for storing canola meal, constructed of glass-lined, lapped-and-bolted steel plate, was 30 feet in diameter and 60 feet high and had a flat concrete floor. The silo was one of three designed and built by a contractor who normally built farm silos. A sweep arm unloader inside the silo discharged the meal to a central outlet chute at the bottom of the silo. However, the device propelling the sweep arm failed occasionally; as a result, the sweep arm didn't always travel all the way around the silo bottom.

Failure and investigation. The upper part of the silo wall buckled, forming a classic longitudinal, diamond-shaped pattern that displaced the silo wall radially by several inches (Fig. 1).

An examination of the silo's interior revealed that an almost empty flow channel in the stored canola meal covered about one-fourth of the circumference of the buckled area against the silo wall. The rest of the silo was filled almost to the roof with stagnant meal. Clearly, the sweep arm had been discharging meal from only one part of the silo, which allowed a flow channel to form against the wall in that quadrant.

As the flow channel emptied, the radial outward pressure on that part of the wall reduced to zero, causing the wall adjacent to the flow channel to straighten out. As the wall straightened and lost support from the stored meal, the wall's critical buckling strength decreased to the point that the vertical load from the rest of the nonflowing, stagnant meal caused the wall to buckle.

Repair. The silo was repaired by replacing the damaged plates. Then several 4- and 6-inch channel stiffeners were added to the silo to maintain the silo's vertical buckling strength within required design limits under the silo's conditions of nonuniform internal pressure and horizontal flexure. The channel stiffeners, installed at 4-foot intervals up the silo's side (Fig. 2), were also added to the two other identical but undamaged silos at the site used for storing canola meal. The sweep arm mechanism, the sweep arm discharge flights, and the outlet geometry in each silo were also modified to improve their operation.

How the failure could have been avoided. The silo failed because the contractor who built the silos had never built anything this large or for this use, and, as a result, performed no tests to determine flow properties of the canola meal. The contractor also didn't consider the effects of nonuniform wall loading.

The formation of eccentric flow channels is common in silos with sweep arm unloaders and also in silos with vibrating dischargers that aren't operated while the material is being discharged. As a result, this silo should have been designed with adequate stiffening, such as reinforcing bars or channels, to prevent wall distortion and buckling under asymmetric loading conditions.

Reinforced concrete grain-storage facility. A 12-compartment grain-storage facility was built with four round, reinforced concrete silos, each 26 feet in diameter and 100 feet high, with eight irregularly shaped bins arranged between them (Fig. 3). Half of each silo's circumference faced the exterior; the other half, facing the interior, was braced by four interconnecting walls. The outlet on each silo was adjacent to the interior walls.

To feed material from the silos to a new grain dryer, the user then added a new outlet on the exterior wall of each of the four silos (Fig. 3), but did so without determining how solids flowing through the new outlets would redistribute the material pressure and affect the structure.

Fig. 1 Buckled steel-wall silo

Failure and investigation. Vertical cracks appeared in the silo walls soon after the new outlets were added, and then a distinct outward bulge appeared on the exterior wall of the first silo used to feed the grain dryer (Fig. 4). The bulge was located about 90 degrees away and 40 feet up from the new outlet.

Examining the structure after the silo failed revealed that adding the new outlets had changed the pressure distribution of the solids inside the silos, which was the prime cause of the failure. But the analysis also showed that the original silo design had serious defects. First, the walls were designed for tension only, acceptable for a single silo with central fill and outlet points but not for a multi-

Fig. 2 Repaired steel-wall silo

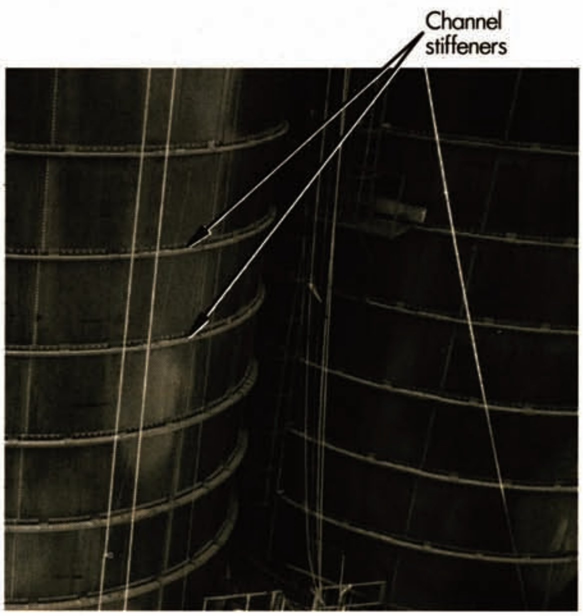
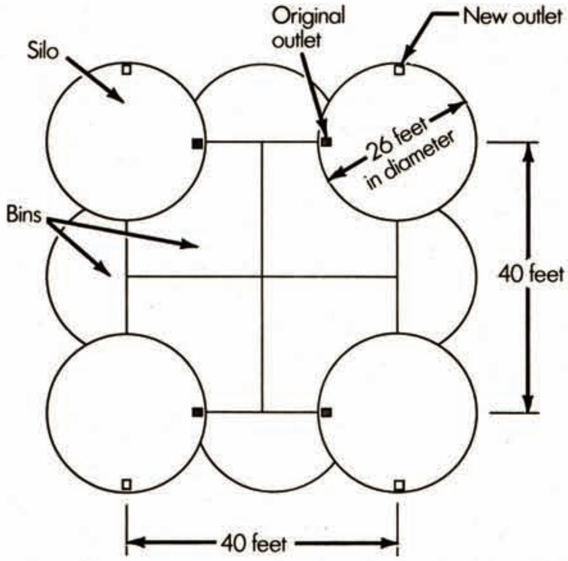
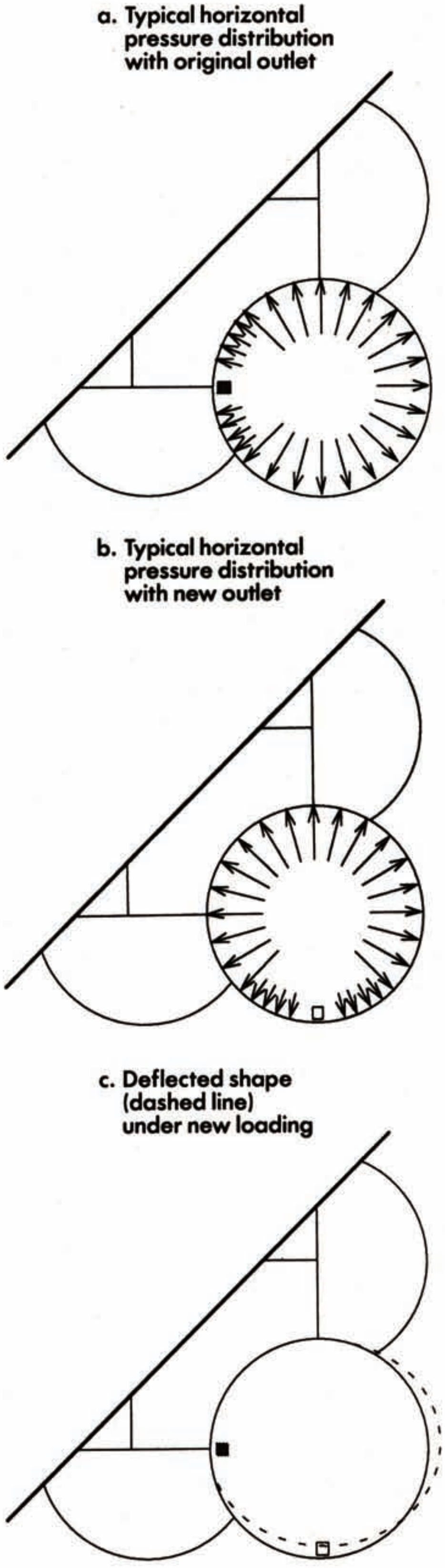


Fig. 3 Reinforced concrete grain-storage facility with four round silos and eight irregularly shaped bins



compartment set of silos: Each silo's fixed connections with other walls, and solids pressures from adjacent bins, created very different solids pressure distributions than in a standard single silo.

Fig. 4 Horizontal pressure distribution for each outlet and resulting silo deflection



Second, the silos were poorly constructed: Reinforcing bars were irregularly spaced and had inadequate laps, which meant the end of one bar didn't overlap the beginning of the adjacent bar enough to provide good support.

In this condition, the original silos were capable of standing, but with a safety factor of nearly zero. Adding the new outlets increased the pressures and caused a nonuniform distribution of these pressures, making failure inevitable.

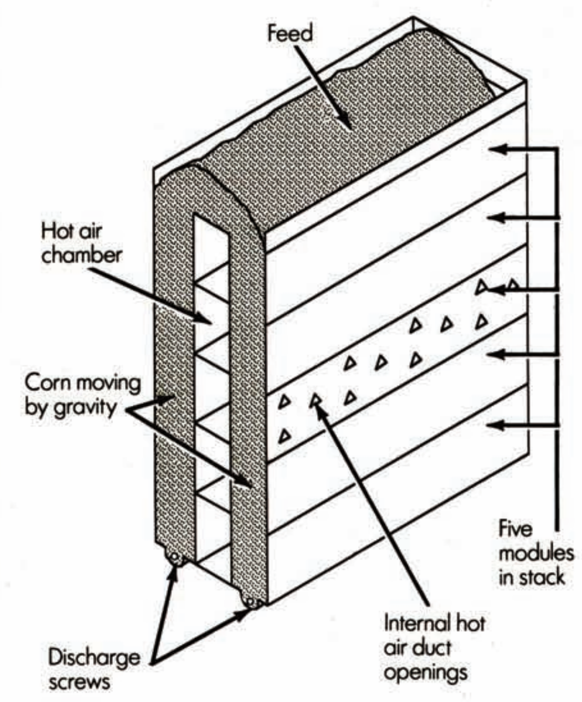
Repair. To prevent further damage, all four silos were strongly reinforced. Because the silos were nested as part of a larger set of containers, exterior reinforcing bars couldn't be added. Instead, a new wall formed of bars and sprayed with a concrete-like material was installed on the interior of each silo.

How the failure could have been avoided. The original silo design and the addition of new outlets were inadequately researched. The silo designer followed simplified silo design approaches outlined in handbooks and codes, but didn't consider complex and subtle loading conditions.

Before new outlets were cut in the walls of the silo, a structural engineer should have analyzed the effect the new load distribution would have on the structure. Any new loading conditions should have been based on solids flow principles and on tests that determined the flow properties of the stored solids. Special consideration also should have been given to the effects of bending moments that develop in silo walls as the result of nonuniform or peak pressures.

Multicell grain dryer. A rectangular multicell grain dryer was constructed of light-gauge steel (Fig. 5). Each of the five stacked modules in the dryer was 32 feet long, 8 feet wide, and 9 feet high and was designed to be truck-mounted and portable. Each module

Fig. 5 Rectangular multi-celled grain dryer



consisted of two walls, which formed the exterior of the grain dryer, connected to a central, tube-like hot-air chamber by inlet and exhaust air ducts.

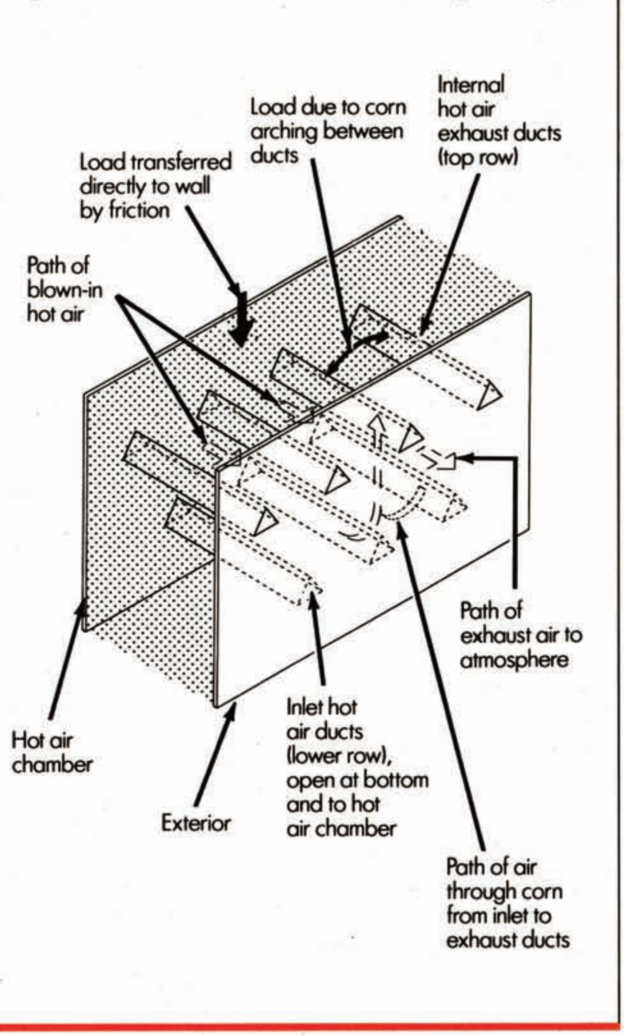
During development, the manufacturer filled a single module with wet corn and discovered that about half the corn's weight was carried by the module's floor plate. Next, the manufacturer built the large multicell unit, stacking five of the modules on top of each other and reinforcing the bottom module with vertical stiffeners, based on the assumption that half of the gross contents would be carried by the floor and half would be carried by the walls.

During operation, the wet corn would be fed into the top of the dryer and would flow down the sides of the dryer, between the air inlet and exhaust ducts, around the hot-air chambers (Fig. 5). The dry corn would flow out of the dryer through the discharge screws at the bottom of the dryer.

Failure and investigation. The first time the dryer was completely filled with wet corn, one vertical wall buckled up to the height of the third module. This meant that the vertical load on the walls was much greater than anticipated, and stacking three modules — much less five — created too great a load on the modules.

An examination revealed that as the dryer height increased, the weight of the corn was distributed in different proportions between the walls and the floor than it would be in a one-module structure. In fact, virtually 100 percent of the weight of the corn in the top four chambers was transferred to the walls by friction between the corn and the dryer walls and by bridging between the air ducts (Fig. 6).

Fig. 6 Load distribution in multicelled grain dryer



Repair. No repair was made, and the design of the multicell grain dryer was scrapped.

How the failure could have been avoided. Modeling an unusual structure is a good idea, but only if extrapolating the results to the design of larger structures is done carefully. Flowing bulk solids often impart loadings to a structure that are counter to an engineer's formal training and experience. In this case, the manufacturer made an intuitive assumption without adequate experience with bulk solids flow principles.

Using the usual handbooks and codes on bin and silo design didn't provide enough information to determine the solids pressures on this structure's air ducts and on the walls of the dryer or to determine the critical buckling loads of a flat plate. Because it isn't easy to predict how bulk solid loads will be distributed, where and how pressure peaks will develop, and how much force will result in a structure, the manufacturer probably should have consulted a bulk solids handling expert.

Preventing silo failure

Performing routine inspections to identify potential problems and making proper repairs based on a sound understanding of loading principles are important steps in preventing silo failure. The following information outlines how to inspect and repair a silo.

Providing routine inspections. While it's impossible to specify how often a silo should be inspected, scheduling regular cursory inspections of a properly operating silo minimizes the chances that any solids flow or load distribution problems will affect the silo. Base your inspection schedule on how much the silo is used; for example, if you use the silo continuously, inspect it at least every few months. It's generally a good idea to inspect a silo while it's operating so you can observe any unusual movements, noises, or flow problems.

If your silo is affected by a significant event — such as a change in silo operation, a storm, or a natural disaster — inspect it immediately. Specific examples of significant events include: an unexplained solids spill at the silo's base, a major discharge problem, a change in the type of stored material, an explosion in or near the silo, a tornado or high winds outside the silo, or an earthquake.

Problems to look for when inspecting a silo vary with the silo's construction. The three major types of construction include bolted silos, welded silos, and reinforced concrete silos.

Bolted silos. Regularly inspect the exterior of your bolted silo, looking for spills of stored solids, distorted walls, thinning walls caused by corrosion or abrasive wear, and loose or missing bolts. Also look at the silo foundation and its grouted joints to make sure they're intact, check the edges of all lap joints to see if any are wavy rather than straight, and look for hammer marks, which may indicate past flow problems. At less frequent intervals (perhaps every 12 months), inspect the silo's interior surface — particularly in the hopper section — to see if it has become polished with use.

Welded silos. Regularly inspect the exterior of your welded silo, looking for spills of stored solids, distorted walls, and thinning walls caused by corrosion or abrasive wear. Also inspect the silo foundation and grouted joints and look for hammer marks. Roughly every 12 months, inspect the silo's interior to see if the silo's walls have become polished with use. Also inspect for cracks that may result, for example, from vibration caused by a feeder or flow-promoting device. In particular, inspect all welded connections.

Reinforced concrete silos. Regularly inspect the exterior of your reinforced concrete silo, looking for distorted walls; regular crack patterns (horizontal and vertical); chipped, or *spalled,* concrete; rust stains; and leaks. Inspect the silo's interior less frequently, looking for cracks, particularly vertical cracks, which often appear first on the inside wall face of a reinforced concrete silo and then propagate to the exterior wall face.

Making proper repairs. Once your inspection has identified a structural problem, you must repair it. However, before implementing a repair, do three things: define the loading conditions, calculate the loading forces produced by the loading conditions, and determine what repair will restrain the loading forces.

Define the loading conditions. Your silo's loading conditions are based on the flow properties of the solids stored in it as well as on the silo's design. Because several rather poorly defined loading conditions — some static, some transient — can co-exist in your silo, defining loading conditions can be harder than it seems.

That's because a silo holds both flowing and nonflowing solids and has both static and transient loading conditions. As a result, a silo's loading conditions are more similar to that of an aircraft (which has different loading conditions on the ground than in flight) than to that of a building (which is always stationary).

Very little literature and few codes of practice offer detailed guidance on defining loading conditions; none of the codes of practice include a definitive set of instructions covering all possible cases. In addition, compliance with the letter, not the spirit and intent of the code, may result in improperly defined loading conditions. You can't guess the properties of a particular solid based on a code's tabulation of "typical" bulk solids properties; for example, the flow properties of a bulk solid can't be determined or looked up in a table based on the bulk solid's generic name alone.

To ensure that all possible loading conditions are considered, it's best to consult a bulk solids handling expert. The expert can run tests on a representative sample of the solid to determine some or all of its flow properties. The expert can determine the following properties (which are functions of loading pressure and may be affected by temperature, time at rest, or changes in moisture content):

- Internal friction and cohesive strength.
- Coefficient of friction between the stored solids and the wall surface.
- Bulk density.
- Particle size distribution and its effect on internal friction, cohesive strength, bulk density, and coefficient of wall friction.
- Air permeability.

Once the flow properties of the stored solids have been determined, you should consider other factors in the silo's design before making a repair. These include whether the silo exhibits mass flow or funnel flow, and whether the silo's outlet is concentric or eccentric — or, if the silo has multiple outlets, whether the outlets' resulting flow channels will intersect as the channels run through the stored solids.

Calculate the loading forces produced by the loading conditions. Literature and codes of practice also give little guidance on calculating loading forces produced by the loading conditions. However, you must consider several factors. One is whether a circular bin or hopper wall is experiencing only ring tension or also horizontal bending as the result of an eccentric flow channel along the silo wall; flat walls, such as those used in rectangular bins and hoppers, always experience horizontal bending.

Another factor to consider is vertical forces, particularly in vertical cylinder walls. Vertical forces are caused by the accumulation of wall friction effects at any point from the top surface of the stored solids down to the bottom, as well as effects from dead loads, such as the silo roof and the weight of the silo's cylinder section. Vertical bending can also occur in cylinder walls; for example, local peak pressure may occur at the point where a funnel flow channel intersects the cylinder wall.

Other factors to consider include how loading forces may affect certain structural components, such as a ring beam installed at the junction of a silo's vertical cylinder section and hopper bottom, and how earthquakes may affect the silo's support structure.

Determine what repair will restrain the loading forces. Once the loading conditions — and the loading forces they produce in the silo's existing structural elements — have been determined, you must determine how to repair your silo and restrain the loading forces. Repairs to your silo's structural elements must add appropriate strength and stiffness to the silo walls. Some ways to do this include increasing the silo's wall thickness, reinforcing walls with vertical or horizontal stiffeners, and beefing up the foundation. Use cost-effective materials and installation procedures for the repair. Calculating the most cost-effective repair scheme is typically an iterative process, in which you first consider the size of existing structural elements and the effects of proposed repairs by hand and then, if necessary, by computer, using the finite-element method. Because you'll want the repair to last, you'll also want to calculate the longevity required; this includes considering the effect abrasive wear or corrosion will have on the repaired area.

Conclusion

While only a very small fraction of silos fail, the failures are so costly that the need to properly design, inspect, and repair silos is clear. Properly designing your silo for the solids it will store and thoroughly analyzing the silo's structure when its usage changes will help you avoid silo failure. Routinely inspecting your silo will also help identify problems before they cause the silo to fail. However, you should only repair your silo after determining its loading conditions, calculating the loading forces that act upon it, and determining how repairs to its structural elements can restrain those loading forces. **PBE**

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Load Development and Structural Considerations in Silo Design[1]

By
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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 straight-forward steps that can be taken to avoid, or at least minimize, such problems.

[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.

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

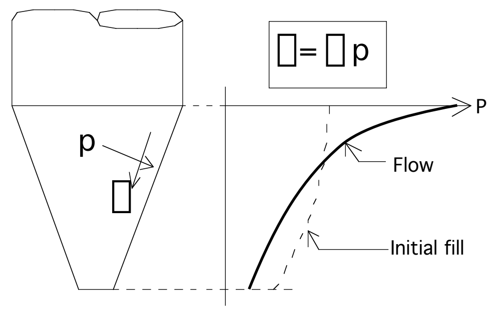
$$n_i = 2\left(1 + \frac{\tan\phi'}{\tan\theta_c}\right) - 3 \text{ ....(5)}$$

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:

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

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

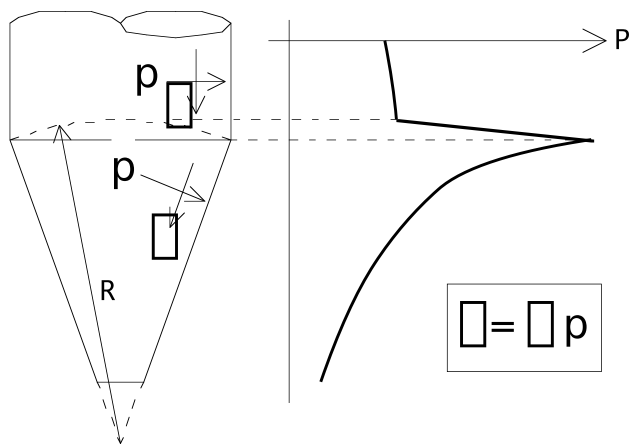
$$n_f = 2K_f\left(1 + \frac{\tan\phi'}{\tan\theta_c}\right) - 3 \text{......................(10)}$$

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

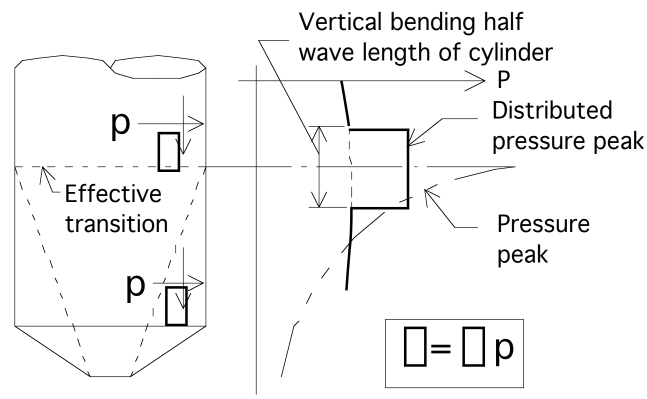
As noted above, since there is no flow along the hopper walls in a funnel flow pattern (except perhaps when the hopper is being emptied at the end of the discharge sequence), it is reasonable in most cases to consider that the design pressures acting normal to the hopper walls are the same as those which 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.

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



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.

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.

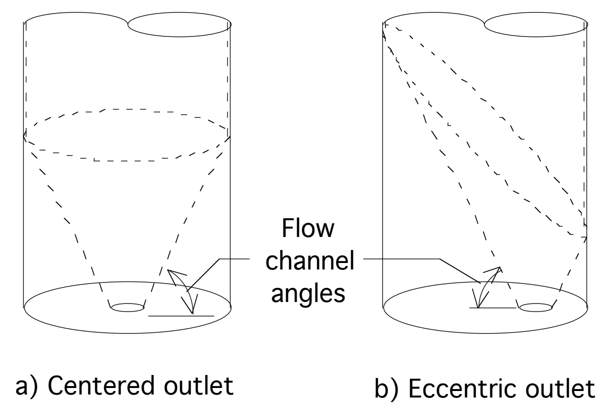
There are a number of limitations in applying Giunta's work as pointed out by Carson *et al* [11]. Unfortunately, as the work of these authors illustrates, there is no straightforward and universal method by which the shape of a funnel flow channel can be predicted.

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

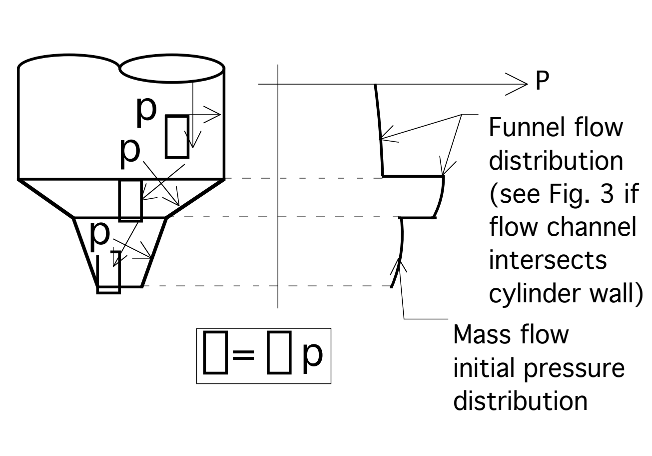


Bulk solids that fall in between the extremes of those that are free flowing and those which rathole, produce flow channels which fall between the extremes described above. Each case needs to be studied closely so as to avoid problems with the design.

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
- γ = bulk density
- θ_c = conical hopper angle (measured from vertical)
- μ = coefficient of sliding friction between bulk solid and wall surface
- $\sigma/\gamma B$ = see Fig. 58 to 62 of ref. [1]
- τ = shear stress acting along wall surface in direction of flow
- ϕ' = wall friction angle between bulk solid and wall surface

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Silo Failures: Case Histories and Lessons Learned [1]

by
Dr. John W. Carson

Silos and bins fail with a frequency which is much higher than almost any other industrial equipment. Sometimes the failure only involves distortion or deformation which, while unsightly, does not pose a safety or operational hazard. In other cases, failure involves complete collapse of the structure with accompanying loss of use and even loss of life.

Presented are numerous case histories involving structural failure which illustrate common mistakes as well as limits of design.

1. INTRODUCTION

Although statistics are not available, hundreds of industrial and farm silos, bins, and hoppers experience some degree of failure each year. [1-3] Sometimes the failure is a complete and dramatic structural collapse. Other times the failure is not as dramatic or as obvious. For example, cracks may form 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 a silo failure is never small. The owner faces the immediate costs of lost production and repairs, personnel in the vicinity are exposed to significant danger, and the designer and builder face possible litigation because of their liability exposure.

The major causes of silo failures are due to shortcomings in one or more of four categories: design, construction, usage, and maintenance. Each of these is explored below, with examples and lessons learned.

2. FAILURES DUE TO DESIGN ERRORS

Silo design requires specialized knowledge. The designer must first establish the material's flow properties [4], then consider such items as flow channel geometry, flow and static pressure development, and dynamic effects. Problems such as ratholing and self-induced silo 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

[1] Source: Carson, J. W.: Silo Failures: Case Histories and Lessons Learned, presented at the Third Israeli Conference for Conveying and Handling of Particulate Solids, Dead Sea Israel, May 2000

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.

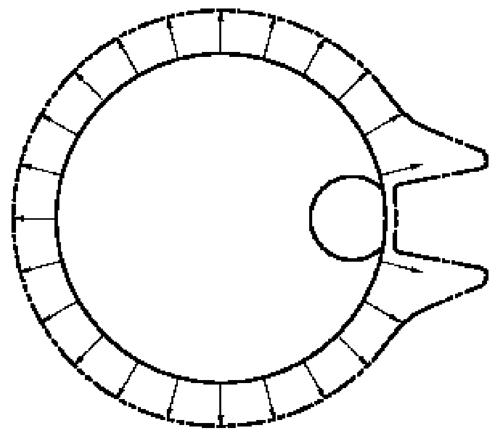
Having established the design criteria, a competent design has to follow. Here the designer must have a full appreciation of load combinations, load paths, primary and secondary effects on structural elements, and the relative flexibility of the elements. [5,6] Special attention must be given to how the most critical details in the structure will be constructed so that the full requirements and intent of the design will be realized.

Five of the most common problems which designers often ignore are described below, along with a few examples of each.

2.1 Bending of circular walls caused by eccentric withdrawal

This is one of the most common causes of silo structural problems, since it is so often overlooked. It results when the withdrawal point from the hopper is not located on the vertical centerline of a circular silo [7,8], and is particularly common when using silos with multiple hoppers in which only one or two of the hopper outlets are used at a time. 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. See Figure 1. Many silo designers incorrectly account for these non-uniform pressures by only increasing hoop tension. [9,10]

Fig. 1, Non-uniform pressures caused by eccentric withdrawal

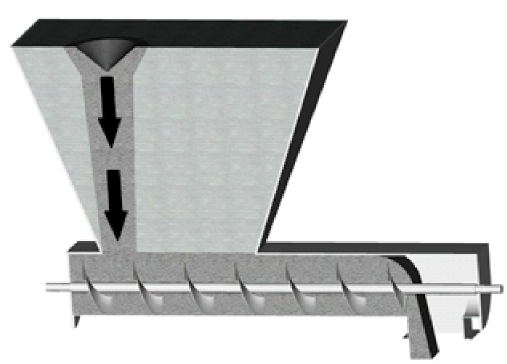


Some examples:

- A silo storing sodium sulfate consisted of a 4.3 m diameter by 15 m tall cylinder section, below which was a short conical hopper, a transition hopper, and 460 mm diameter screw feeder. A significant inward dent developed about mid-height in the cylinder section. It extended about one-quarter of the way around the circumference and was centered slightly offset from the long axis of the screw at its back end. The problem was caused by eccentric withdrawal due to an improperly designed screw feeder. See Figure 2.

- A silo consisting of a 3.5 m diameter cylinder, 20° (from vertical) cone section, 3 m diameter vibrating discharger, and pantleg discharge chute was used to store reground PVC flake. Flow was metered through each chute leg using a rotary valve. The vibrating discharger was used

Fig. 2, Constant pitch screw feeder caused eccentric withdrawal



infrequently (30 sec. on, 5 minutes off), and only one leg of the pantleg was used most of the time. A dent formed in the cylinder section centered over the active pantleg.

- A blending silo utilized 24 external tubes to withdraw plastic pellets at various elevations from the cylinder and cone sections. Significant wrinkles developed in the cylinder section above several of the tubes.

The lessons to be learned here are:

- Whenever possible, design your silo for center fill and center withdrawal.
- If eccentric fill or withdrawal is contemplated, perform a structural check first to make sure that the silo can withstand the non-uniform loading conditions and resulting bending moments.
- Be particularly careful with silos that have an elongated hopper outlet. An improperly designed screw feeder or belt feeder interface, or a partially opened slide gate, will often result in an eccentric flow pattern with accompanying non-uniform loads.
- If a sweep arm unloader is used, be aware that operating it like a windshield wiper (back-and-forth in one area) will create a preferential flow channel on one side of a silo.
- If multiple outlets are required, consider splitting the discharge stream outside of the silo below the main central withdrawal point.
- If a vibrating discharger is used but not cycled on and off on a regular basis, an eccentric flow channel may form, particularly if a pantleg chute is below the outlet.
- Consider non-uniform pressures when designing silos with blend tubes.

2.2 Large and/or non-symmetric pressures caused by inserts

Support beams, inverted cones, blend tubes, and other types of internals can impose large concentrated loads and/or non-symmetric pressures on a silo wall leading to unacceptable bending stresses.

Two examples:

- A tear developed in the cone section of a 4□m diameter silo storing reground polyester pellets. This tear was located where a support strut for an inverted conical insert was welded to the cone wall. Upon emptying the silo, it was found that the insert support plates were severely deformed and detached from the cone wall.
- Tests showed that a certain agglomerate could experience particle attrition under the loads generated in a large silo. To reduce the potential of this happening, an insert was designed to be located in the cylinder section of an 8 m diameter silo. This 15 m tall inverted cone extended from just below the transition to within 2 m of the top of the silo. The designers were provided with the loads, which would act on this insert; however, they believed the values to be too conservative, so they designed the support structure for smaller loads. Shortly after being put into operation, the insert supports failed, causing the insert to fall and impact a BINSERT□ inner cone below, the supports of which also failed as a result of the impact.

Lessons learned:

- Don't ignore loads on inserts, since they can be extremely large. [11] In addition, non-uniform pressures may develop if the flow pattern around the insert is even slightly asymmetric.

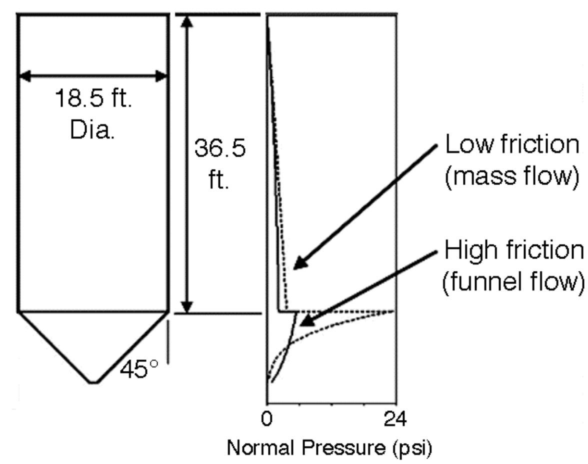
- Open inserts (such as a BINSERT or blend tube) can also have large loads acting on them. Consideration must be given to the consequences of the insert becoming plugged, thereby preventing material from flowing through it. In this case, the vertical load greatly exceeds the dead weight of the material inside the insert and the cone of material above it.

2.3 Ignoring flow patterns and material properties

Sometimes *mass flow* develops in silos, which were structurally designed for *funnel flow*. [4] Even if this doesn't occur, the local pressure peak, which develops where a funnel flow channel intersects a silo wall, can be devastating. [6]

In some circumstances, ignoring the properties of the bulk solid to be stored can be worse than assuming an incorrect flow pattern. Consider, for example, designing a steel silo to store coal. Lacking a sample of coal which could be tested to form the design basis, the designer may resort to an often quoted design code [12] which lists the wall friction angle for “coal on steel,” with no consideration as to the type of coal, its moisture, particle size, ash content, or the type of steel, its surface finish, etc. Flow and structural problems are common when this approach to design is taken.

Fig. 3, Comparison of wall normal pressures due to assumed funnel flow and actual mass flow



Two examples:

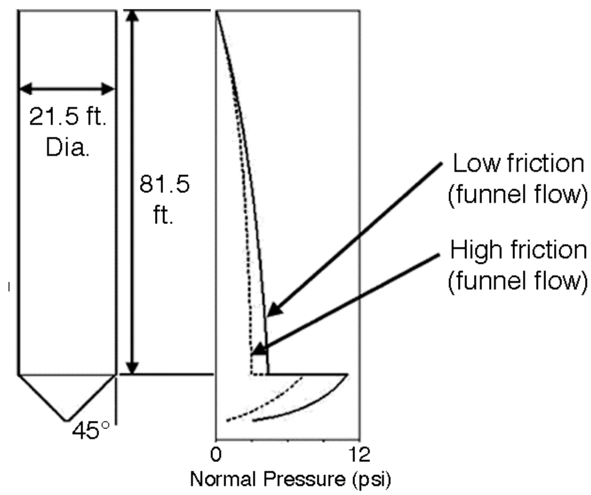
- Several bolted silos storing lubricated plastic pellets split apart along a radial seam near the top of the hopper section. Although the silos were designed structurally for funnel flow, no flow tests were performed to see if this flow pattern would occur. Lab tests performed after the failure showed that mass flow developed along the 45° cone walls. See Figure 3.

- Two similar bolted silos also storing plastic pellets failed in a similar manner. Lab tests showed that the wall friction was not low enough for mass flow. However, the wall friction angle was much lower than the silo designer assumed. Thus, less of the pellet mass was supported by shear along the vertical cylinder walls, resulting in much higher wall pressures in the hopper than was assumed by the designer. See Figure 4.

Lessons learned:

- Know your material's flow properties, and the type of flow pattern that is likely to develop in your silo. [13]

Fig. 4, Comparison of wall normal pressures due to assumed high wall friction and actual low friction



- If the flow properties are likely to vary (due, for example, to changes in moisture, particle size, temperature, different suppliers), make sure that the silo is designed to handle this variation.

- If your design is close to the mass flow/funnel flow limit, consider the possible effects of slight changes in material properties or the interior surface of the silo (particularly its hopper section). The latter is particularly important if the hopper walls are likely to be polished with use.

- Buyers beware! If you don't know which flow pattern is going to develop in your silo, or the possible consequences of designing for the wrong one, retain the services of a silo expert who can advise you.

- Using tables of values of material properties is risky at best and should only be used as a last resort if no samples of the actual material to be stored are available. A better approach would be to check with a silo expert who may have past experience handling the material. Inclusion of additional safety factors in the design, to account for unknown variations, is also often warranted.

2.4 Special considerations with bolted tanks and reinforced concrete construction

Many silos are constructed of bolted metal panels (usually steel or aluminum), while others are constructed of reinforced concrete. Both types of construction have specific design requirements.

Bolted connections transfer loads through various load paths, and can fail in at least four different modes: bolt shear, net section tension, hole tear-out, and piling around bolt holes. Which mode results in the lowest failure load depends on specifics of the metal (*e.g.,* its yield and ultimate strengths, thickness), the bolts (*e.g.,* size, strength, whether or not fully threaded, how highly torqued), spacing between bolt holes, number of rows of bolts, etc. [14-16]

Compressive buckling must also be considered, particularly if the bolted silo has corrugated walls or is constructed from aluminum.

Reinforced concrete construction presents different problems [17,18]. Concrete is strong in compression but very weak in tension. Thus, reinforcing steel is used to provide resistance to tensile stresses. A silo that has only a single layer of horizontal reinforcing steel is capable of resisting hoop tension, but has very little bending resistance; therefore if non-uniform pressures occur (*e.g.,* due to an eccentric flow channel), the silo is likely to crack. Unfortunately, the inside face of the silo wall, where cracks are difficult to detect, is where the maximum tensile stresses due to bending are most likely to occur. Undetected cracks can continue to grow until the silo is in danger of imminent collapse.

An example:

- Vertical cracking of concrete was observed in a 21 m diameter raw coal silo shortly after it was put into operation. The cracks were located in the portion of the silo that contained a single layer of reinforcing steel. In an attempt to stop the cracks from growing further, they were injected with an epoxy, but this proved ineffective. Later, post-tensioning strands were added to the outside of the silo. Five years later, enough delamination had occurred on the inside of the wall to expose significant lengths of rebar and allow them to be pulled out and drop down the wall. Extensive repairs and reinforcing were required in order for the silo to be used safely.

Lessons learned:

- Consider all the various modes by which a bolted joint can fail, and follow recognized design procedures.

- Check to ensure that the design can withstand compressive buckling.

- Determine the likelihood of eccentric fill or discharge and design accordingly. In particular, do not use a single layer of reinforcement if eccentric loading is possible.

2.5 Special considerations concerning temperature and moisture

The walls of outdoor metal silos can expand during the day and contract at night as the temperature drops. If there is no discharge taking place and the material inside the silo is free flowing, it will settle as the silo expands. However, it cannot be pushed back up when the silo walls contract, so it resists the contraction, which in turn causes increased tensile stresses in the wall. This phenomenon, which is repeated each day the material sits at rest, is called *thermal ratcheting*. [19-23]

Another unusual loading condition can occur when moisture migrates between stagnant particles, or masses of stagnant particles, which expand when moisture is added to them. If this occurs while material is not being withdrawn, upward expansion is greatly restrained. Therefore, most of the expansion must occur in the horizontal plane, which will result in significantly increased lateral pressures on, and hoop stresses in, the silo walls.

Two examples:

- A 24 m diameter bolted steel silo storing fly ash split apart about two weeks after it was first filled to capacity. Nearly 10,000 tons of fly ash discharged in the accident, which occurred at night when no fly ash was being filled into or discharged from this silo. Calculations revealed that the silo was underdesigned, and the probable cause of failure was thermal ratcheting.

- A 7.3 m diameter silo stored a mixture of wet, spent brewer's grains, corn, and other ingredients. No problems occurred as long as the material was not stored for any significant time. However, after sitting several days without discharge during a holiday period, the silo walls split apart dropping 700 tons of material onto the ground. Strain gauge tests in a lab test rig showed that when moisture migration caused the corn particles to swell, pressures on the silo wall increased by more than a factor of five.

Lessons learned:

- Include factors of safety in the design of outdoor metal silos to account for the effects of thermal ratcheting. [24]

- Assess the likelihood of significant moisture migration occurring while the bulk solid is stationary, and design accordingly.

3. 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. Faulty construction, such as using the wrong materials or not using adequate reinforcement, and uneven foundation settlement are but two examples of such a problem.

The other cause of construction problems is the introduction of badly chosen, or even unauthorized, changes during construction in order to expedite the work or reduce costs.

3.1 Incorrect material

Close inspection of contractors' work is important in order to ensure that design specifications are being followed. This includes checking for use of correct bolts (size, strength, etc.), correct size and spacing of rebar, specified type and thickness of silo walls, etc.

An example:

- During investigation of the fly ash silo failure described above (2.5), it was discovered that less than 1% of the bolts recovered had the specified marking on their head, and none of these were used in the critical vertical seams. Strength tests on these incorrect bolts revealed that some had tensile strengths less than the minimum required for the specified bolts.

Lessons learned:

- Use only qualified suppliers and contractors.

- Closely inspect the installation.

- Make sure that specifications are clear and tightly written [25].

3.2 Uneven foundation settlement

Foundation design for silos is not appreciably different than for other structures. As a result, uneven settlement is rare. However, when it does occur, the consequences can be catastrophic since usually the center of gravity of the mass is well above the ground.

Example:

- A 49 m diameter by 14.5 m tall grain silo experienced a catastrophic failure one cold winter night. Investigation revealed that because of inadequate design of the concrete footing and changes to it during construction, the foundation was significantly weakened. Failure occurred when the contents of the silo exerted outward forces on the steel shell, which overloaded the foundation causing it to crack. The failing foundation in turn pulled out on the steel shell. Low temperatures created additional thermal stresses at the bottom of the shell.

Lessons learned:

- Use experienced soils engineers and foundation designers.

- Use reputable contractors.

- Closely inspect the work. (See comments above in Section 3.1.)

3.3 Design changes during construction

Unauthorized changes during construction can put a silo structure at risk. Seemingly minor details are often important in ensuring a particular type of flow pattern (especially mass flow), or in allowing the structure to resist the applied loads.

Example:

- A buckle was observed in the side wall of a spiral aluminum silo storing plastic pellets. Once the silo was emptied it was discovered that many of the internal stiffeners had also buckled in the region of the shell buckling. Analysis revealed that the most probable cause of buckling was lack of sufficient welds between the stiffeners and the shell.

Lessons learned:

- Make sure that both the silo builder and designer carefully consider and approve any changes in details, material specifications, or erection procedure.

- Closely inspect all construction.

4. FAILURES DUE TO USAGE

A properly designed and properly constructed silo should have a long life. Unfortunately, this is not always the case. Problems can arise when the flow properties of the material change, the structure changes because of wear, or an explosive condition arises.

If a different bulk material is placed in a silo than the one for which the silo was designed, obstructions such as arches and ratholes may form, and the flow pattern and loads may be completely different than expected. The load distribution can also 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 or a silo expert should be consulted regarding the effects of such changes before they are implemented.

4.1 Dynamic loads due to collapsing arches or ratholes, self-induced vibrations, or explosions

When a poorly flowing material is placed in a silo which was not designed to store and handle it, flow stoppages due to arching or ratholing are likely. Sometimes these obstructions will clear by themselves, but, more often, operators will have to resort to various (sometimes drastic) means to clear them. No matter which method is used, the resulting dynamic loads when an arch or rathole fails can collapse the silo. [26]

Self-induced silo vibrations can also result in significant dynamic loads for which most silos are not designed to withstand. [27,28] In addition, few if any silos can withstand the loads imposed by an explosion -- either internal or external.

Two examples:

- A 13 m diameter by 23 m tall reinforced concrete silo stored waste coal. Below the cylinder was a 30° conical hopper terminating at a 4.6 m diameter vibrating discharger. Flow from the silo was controlled by a vibrating pan feeder. A rathole formed above the discharger, then partially collapsed. The resulting impact separated the vibrating discharger from the cone section and drove the vibrating pan feeder into the floor.

- Three large bolted steel silos were used to store distiller's dry grain with solubles. Each silo's cylinder section was 7.9 m in diameter by 15 m tall, below which was a 30° conical hopper and 3 m diameter vibrating discharger. Flow was controlled with a 300 mm diameter screw feeder. Severe structural damage occurred in all three silos, including 300 to 900 mm indentations in portions of the cylinder walls, two completely split radial seams in one of the static hopper sections, and one of the vibrating dischargers dropping off from its supports. The structural problems were directly related to the poor flow characteristics of the material. In fact, its flow properties were so poor that plant personnel occasionally resorted to using dynamite to break it up!

Lessons learned:

- Know the flow properties of your material and the flow properties assumed in the design of your silo. If the source of your material changes, or if you plan to store a different material in your silo, have the new material tested for flow properties. Get advice from experts before putting the new or changed material into your silo.

- Use extreme caution in attempting to restore flow if an arch or rathole forms. Under these circumstances, personnel should not be allowed to be in close proximity to the silo. Consideration should be given to top reclaim using experts trained in this technique.

- Avoid accumulations of dust or ignitable gases, which could cause an explosion.

4.2 Changes in flow patterns

Changing material properties or polishing of the inside surface of the silo may cause mass flow to develop in a silo which was structurally designed for funnel flow. (The opposite can also occur – funnel flow in a silo designed structurally for mass flow – but this generally is not as serious a problem.) Mass flow will result in a dramatically different wall pressure loading than with funnel flow, particularly at the top of the hopper section.

Two examples:

- Six 7.9 m diameter by 22 m. tall silos were used to store high-density polyethylene fluff and pellets. Below each cylinder section was a 30° cone terminating at a rotary valve feeder. A radial hopper seam split open on one silo, spilling one million pounds of material onto the ground. The cause of this failure was determined to be mass flow loads. The silo was structurally designed only for funnel flow. See Figure 5.

Fig. 5, End-result of mass flow developing in a silo designed structurally for funnel flow

- Four outdoor bolted silos were used to store barley and corn. As with the previous example, failure occurred by splitting of a radial seam near the top of the hopper, which was the result of unexpected mass flow loads. In this case, the cone walls were apparently polished by the barley, and the wall friction decreased further when the outside air temperature dropped below freezing.

Lessons learned:

- Know your material's flow properties and the flow properties used in the design. Avoid materials and/or conditions that could result in a flow pattern for which the silo was not designed.

- Routinely inspect the interior of your silo, checking for abrasion marks, which may indicate mass flow. [29]

- Inspect the exterior of a bolted silo on a regular basis. Pay particular attention to the bolted joints near the top of the hopper, noting any waviness along the edges of the sheets, elongation of bolt holes, or cracks between bolt holes, all of which are signs of over-stress.

4.3 Buckling of unsupported wall

A pressurized cylinder is more resistant to compressive buckling than an unpressurized one. [9] In addition, if this pressure is caused by a bulk solid (as opposed to a liquid or gas), it is even more resistant. The reason is as follows: Gas or liquid pressure is constant around a silo's circumference and remains unchanged as the silo starts to deform. On the other hand, the pressure exerted by a bulk solid against a silo's wall increases in areas where the walls are deforming inward, and decreases where the walls are expanding. This provides a significant restraining effect once buckling begins.

Now consider what happens if an arch forms across a silo's cylinder section, and material below it is withdrawn. Not only is the restraining effect of the bulk solid lost, but the full weight of the silo contents above the arch are transferred to the now unsupported region of the silo walls. Buckling failure is likely when this occurs.

Example:

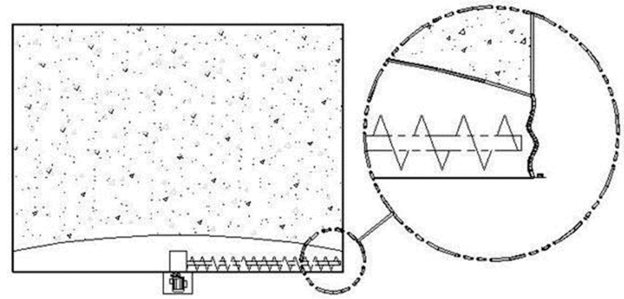
- A 7.6 m diameter by 27 m tall bolted flat-bottom silo was used to store soybean meal. Discharge occurred by a sweep arm screw unloader. The material's flow properties varied considerably, from free flowing to extremely cohesive. An arch formed above the unloader, and spanned the full diameter of the silo. Material below this was removed by the unloader, so the full one million pounds was transferred to the unsupported thin silo wall causing it to fail by vertical buckling. See Figure 6.

Lessons learned:

- Know your material's flow properties.

- If flow stops, investigate the cause before attempting to restart discharge.

Fig. 6, Buckling of unsupported wall above a sweep arm unloader



5. FAILURES DUE TO IMPROPER MAINTENANCE

Maintenance of a silo comes in the owner's or user's domain, and must not be neglected. Two types of maintenance work are required. The first is the regular preventative work, such as the periodic inspection and repair of the walls and/or 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 necessary if the silo is to operate as designed. Other examples of preventative maintenance items include roof vents, level probes, feeders, dischargers, and gates.

The second area of maintenance involves looking for signs of distress (*e.g.,* cracks, wall distortion, tilting of the structure) and reacting to them. [29] If evidence of a problem appears, expert help should be immediately summoned. An inappropriate response to a sign that something is going wrong, including the common instinct to lower the silo fill level, can cause a failure to occur with greater speed and perhaps greater severity.

5.1 Corrosion and erosion

Silo walls thinned by corrosion or erosion are less able to resist applied loads than when they were new. This is a particular problem when handling abrasive materials or when using carbon steel construction in moist or otherwise corrosive environments. Combining the effects of abrasion with corrosion significantly accelerates the problem. This can occur, for example, with special aging steels. Abrasive wear causes the surface layer to be removed, thereby exposing new material and speeding up the aging process which significantly weakens the structure.

Three examples:

- A coal silo was fabricated from aging steel. After about five years of use, the hopper detached from the cylinder section while the silo was full. The cause was determined to be thinning of the silo wall due to abrasion from coal and corrosion.

- A tile silo storing coal failed after many years in use. This progressive failure occurred because of weathering effects on the exterior and corrosive conditions due to wet coal on the interior. These combined to corrode the steel reinforcing bars, which then failed.

- Six coal silos at a chemical plant lasted for about 30 years, after which time two of the six experienced a structural failure, which prompted a close inspection of all six silos. The carbon steel walls were found to have thinned significantly, to the point that actual holes were visible in places. Corrosion, both exterior and interior, was to blame.

Lessons learned:

- Carefully inspect your silos on a regular basis. Determine the minimum wall thickness required for structural integrity and compare to the actual wall thickness.

- Do not use aging steels for silo construction if the surface will be exposed to abrasive wear.

- Prevent buildup of material, which could trap moisture on the exterior of outdoor silos.

5.2 Lack of routine inspection

Silo failures often cause significant damage and sometimes result in death. Often these failures could have been prevented or the damage could have been minimized with information that could have been gained through routine inspection.

Example:

- The hopper section of a stone bin at a mining operation fell off when the bin was full, killing a person working below. The problem was particularly attributed to material buildup on horizontal external structural members which, combined with moisture from the air, created a corrosive environment, resulting in excessive thinning of the silo wall.

Lessons learned:

- Inspect silos routinely, both internally and externally. [29] This is particularly important with bolted and reinforced concrete silos, and silos which are exposed to a corrosive environment. For example, look for any signs of corrosion, exposed rebar, unusual cracking, or spalling of concrete.

- If conditions change (e.g., a different material is to be stored) or unusual events occur (e.g., very high winds, an earthquake), inspect the silo before putting it back in operation.

- Perform a detailed structural inspection before designing modifications to a silo.

5.3 Improper reaction to signs of distress

A common reaction to signs of silo distress is to ignore them, often because personnel are unaware of both the meaning and consequences of doing so. Another common reaction is curiosity. People have lost lives because, due to their curiosity, they were in the wrong place at the wrong time. Even if danger signs are understood, it is common for inappropriate action to be taken in an attempt to "reduce" the chance of failure. In some extreme cases, catastrophic failure has been induced where, with appropriate action, the damage could have been relatively minor.

Two examples:

- A bolted steel silo with a sweep arm unloader was used to store soybean meal. The meal hardened, so the sweep arm was operated back and forth to try to discharge the meal. This process continued for some time, even though wrinkles were observed in the silo wall above the area where the sweep arm was operating. Eventually the indentations became so great that the silo collapsed.

- Another bolted silo storing grain stood up some 14 years before failure. Shortly after startup in the spring after the grain had been sitting essentially stationary all winter, the silo started tilting at approximately mid-height. Not realizing the consequences of continued withdrawal, the owner operated the discharge system. Two days later, the silo collapsed completely.

Lessons learned:

- Since a weakened silo is a very dangerous structure, limit access to the area surrounding it to only those personnel who need to be there, and make sure that they have the education and experience to deal with the situation. Extreme caution should always be exercised.

- At the first sign of silo distress, cease discharging immediately and assess the integrity of the structure.

- Investigate the cause of the distress. Retain experts with knowledge of silo structures to assist in the investigation.

6. CONCLUSIONS

Silos that are designed, built, operated, and maintained properly, will provide long life. Each of the case histories given above illustrates the effects of one or more of the shortcomings possible in design, construction, usage, and maintenance. In each example, the cost of repairs or rebuilding, the cost of litigation, and the cost of insurance added up to several times the cost of doing the job properly in the first place.

The best approach to the design of a silo, bin, or hopper for bulk materials is one that is reasoned, thorough, conservative, and based on measured parameters. Design engineers are not legally protected by sticking to a code of practice. Compliance with the locally applicable code is, of course, necessary, but it should never be regarded, by itself, as a sufficient condition to the performance of a satisfactory design.

It is the responsibility of the designer to ensure that the design is based on sound, complete knowledge of the materials being handled, that the design is competent, and that it covers all foreseeable loading combinations. It is the joint responsibility of the designer, builder, and owner that construction is of an acceptable standard, and fulfills the intent of the design. It is then the responsibility of the owner to properly maintain the structural and mechanical components. It is also the responsibility of the owner to ensure that any intended alteration in usage, discharge geometry or hardware, liner material, or any other specified parameter, is preceded by a design review with strengthening applied as required.

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