SILO FAILURES: WHY DO THEY HAPPEN?

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Abstract: Silos and bins fail with a frequency that is much higher than that of almost any other industrial equipment. Sometimes the failure involves only distortion or deformation that, while unsightly, does not pose a safety or occupational hazard. In other cases, failure involves complete collapse of the structure with accompanying loss of use and even loss of life. Three major causes of silo failure are identified: design errors, construction errors, and utilization errors. Numerous case histories are used to illustrate common mistakes, limits of design, and lessons learned.

Keywords: silo, structural failure, buckling, silo design, silo construction, silo operation, silo maintenance

1. Introduction

At approximately 10:00p.m. on a cool September evening in 1996 in southwestern USA, a thunderous cracking sound rang out to shatter the calm. The only employee in the vicinity of a new 80ft diameter fly ash silo realized that he had just heard the warning sound of imminent danger. In the dark of night, he had only his instincts to lead him at full speed away from the failing structure. The first rays of the next morning's sun revealed the devastated silo and the very spot he'd stood, not 30 feet away, buried under 20 feet of fly ash.

The purpose of this brand new bolted steel silo (Figure 1) was to store 9000tons of fly ash from the adjacent coal fired power generation station. The silo split apart about two weeks after it was first filled to capacity. Up to this point, no ash had ever been discharged. Curiously, the collapse occurred at night when the silo was being neither filled nor emptied.

During the course of the investigation into this failure, several deficiencies were revealed. Calculations showed that the silo was underdesigned and did not identify or account for a phenomenon called thermal ratcheting [1–5]. The walls of outdoor metal silos expand during the day and contract at night as the temperature drops. If there is no discharge is taking place and the material inside the silo is free flowing, it will

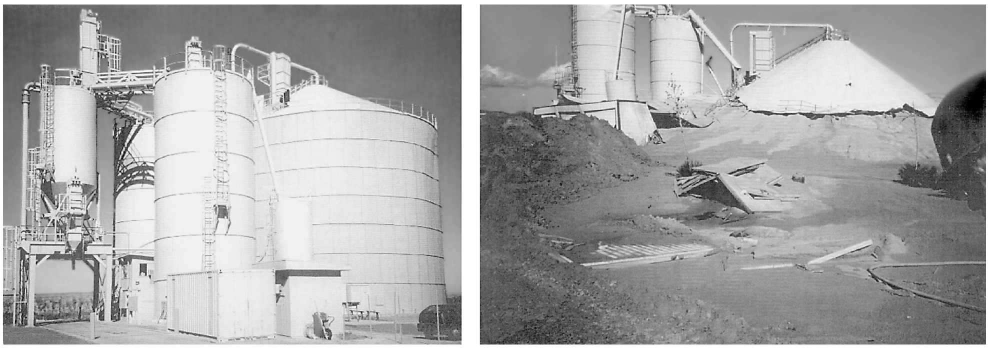

Figure 1. The brand new 9 000 ton bolted steel silo split apart about two weeks after it was first filled to capacity

settle as the silo expands. However, the material 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. The effect is repeated each day that the material sits at rest.

The investigation also revealed that some cost-cutting measures taken by the silo supplier during the construction of the silo contributed to the failure. The design specified that bolts of a particular classification, size, and strength be used in the construction. Bolts of the specified type have a distinct marking on their head which identifies that the bolts have been tested and meet recognized standards. Less than 1% of the bolts that were recovered from the failed fly ash silo had the specified marking and none of the marked bolts had been used in the critical vertical seams. Strength tests on the unmarked bolts revealed that some had tensile strengths less than the specified minimum.

Why did this silo collapse? The answer to this question is not straightforward. There were many contributing factors acting together and if any one had not been present the collapse of the silo might have been avoided. Had the potential for thermal ratcheting been recognized at the design stage and had correct design parameters been selected, the collapse may not have occurred. If proper bolts had been purchased and used, the silo collapse may have been avoided (Figure 2). If the silo had been inspected by an independent silo expert either during the construction or after construction was complete, perhaps the incorrect bolts would have been noticed and corrective action could have been taken. Had the operation of the silo been such that material was discharged more frequently, the condition of accumulated stresses that precipitated the collapse could have been prevented.

Hundreds of industrial and farm silos, bins, and hoppers, storing powders or bulk solids, experience some degree of failure each year [6–8]. In fact, silos and bins fail with a frequency which is much higher than that of almost any other industrial equipment.

Sometimes the failure involves complete and catastrophic collapse of the structure. In other cases, failure involves only distortion or deformation (Figure 3). A similar variation can be found in the severity of the consequences of structural failure. Whether it results in a loss of human life, downtime, or simply a need for repair, a structural failure is always costly. The owner faces the immediate expense of lost production and/or repairs; personnel in the vicinity are exposed to significant danger;

Figure 2. Less than 1% of the recovered bolts had specified marking

Figure 3. Silo deformation

and the design engineer and builder face possible litigation because of their liability exposure.

The life of a silo can be divided into three distinct phases: design, construction, and utilization. In each of these phases there are numerous opportunities for errors that can result in structural failure. As in the fly ash silo failure described above, the majority of structural failures of bins and silos can be attributed to a combination of several deficiencies or errors.

2. Design errors

Silo design requires extremely specialized knowledge. The design engineer must first gather a substantial amount of information and the functional design intent of the silo must be known. The latter includes geometrical information such as size and shape, operational information such as feed/discharge schedules, methods and rates, as well as bulk solid information such as how many and what type of bulk solids will be handled. The flow properties [9] for all of the bulk solids to be handled in the silo must also be known (Figure 4). Only once all of this information is compiled can proper attention be given to the structural design.

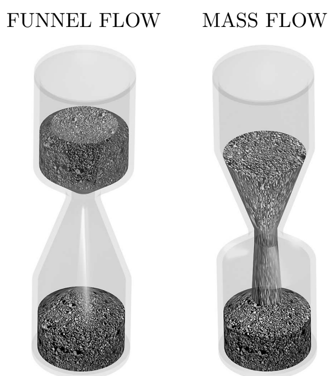

Figure 4. Material flow properties and flow pattern strongly affect the loads that will be imposed on a silo

Having established the design criteria, a competent design has to follow. Here the design engineer must have a full appreciation of load combinations, load paths, primary and secondary effects on structural elements, and the relative flexibility of the elements [10, 11]. Consideration must be given to issues such as flow channel geometry, flow and static pressure development, and dynamic effects like rathole collapse and self-induced silo vibration. The design engineer must be alert to the possibility of unexpected loading cases such as non-uniform and/or thermal loads and their potential effects. The design should also consider construction and fabrication details, making use of standard methods whenever possible. Special attention must be given to how the most critical details in the silo and its supporting structure will be constructed so that the full intent of the design will be realized. Six of the most commonly overlooked design considerations are discussed below. The structural design engineer must understand the effect that the material's flow properties and the resulting flow pattern can have on the structure.

2.1. Design errors: material flow properties and flow patterns

The functional design requirements will dictate the flow pattern, either mass flow or funnel flow [9], that is required. It is then the job of the design engineer to ensure, through the selection of geometry and materials of construction, not only that the selected flow pattern occurs, but also that the structure is capable of withstanding the loads induced by that flow pattern.

As is illustrated in Figure 5, the pressure distribution for mass flow is significantly different than for funnel flow. If mass flow develops in a silo which has been structurally designed for funnel flow, or if the location of the local pressure peak that develops where a funnel flow channel intersects a silo wall is different than that assumed in the design, the result can be devastating [11].

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 design engineer 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, or ash content, the type of steel, its surface finish, *etc.* If the actual wall friction angle is lower than the selected design value, less vertical load will be transferred, through friction, to the cylinder walls, and the wall pressures in the hopper will be significantly larger than was expected. This effect can be seen in Figure 6. Alternatively, higher wall friction results in higher compressive loads in cylinder walls, which can cause buckling. These examples clearly illustrate the importance of knowing the material's flow properties.

Quick tips

- Know your material's flow properties, and the type of flow pattern that is likely to develop in your silo [13].
- If the flow properties are likely to vary (due, for example, to changes in moisture, particle size, temperature, suppliers), make sure that the silo is designed to handle this variation.

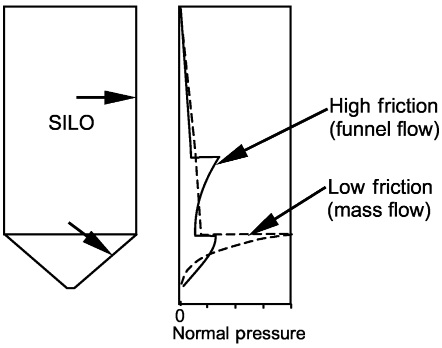

Figure 5. Pressures normal to walls; mass flow compared to funnel flow

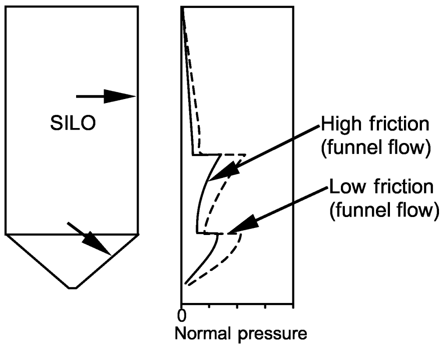

Figure 6. Pressures normal to walls; high compared to low wall friction in funnel flow

- 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.
- Buyer 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 be used only 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.

2.2. Design errors: out-of-round bending of circular walls

Out-of-round bending of a circular wall can result when material is not withdrawn on the vertical centerline of a circular silo [14, 15]. If the eccentric 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 7. Many silo design engineers incorrectly account for these non-uniform pressures by increasing only hoop tension [16, 17].

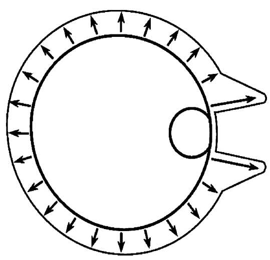

Figure 7. Non-uniform pressures caused by eccentric withdrawal

Eccentric withdrawal is one of the most common causes of silo structural problems, because it is often overlooked. There are several situations which can result

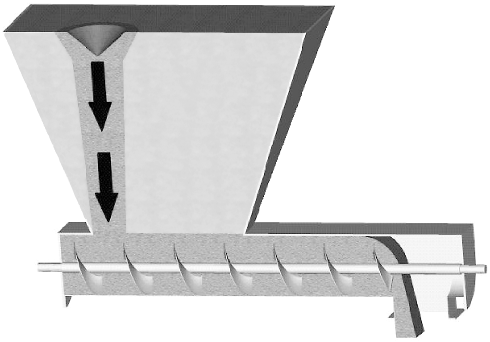

Figure 8. Constant pitch screw feeder causes eccentric withdrawal

in eccentric withdrawal. For example, the flow channel will be eccentric when only one (or in fact, any number less than the total) of the hopper outlets in a multiple hopper silo is used at a time. It can also occur when an off-center bypass chute in the hopper or cylinder walls allows an alternate path for material to discharge from the silo. Improper feeder design can also lead to eccentric flow channels. If the entire outlet of the hopper is not activated by the feeder [18, 19] an eccentric flow channel will develop. Figure 8 shows an eccentric flow channel resulting from an improperly designed screw feeder. Note that the result will be similar for other improperly designed feeders such as belt feeders or rotary valves, or even flow aids such as vibrating dischargers.

Quick tips

- Whenever possible, design your silo for center fill and center withdrawal.
- Consider non-uniform pressures in your design. Leaks due to wall erosion or abrasion or seemingly minor retrofits such as a bypass chute can cause non-uniform load cases to develop after a silo has been in use for many years.
- If multiple outlets are required, consider splitting the discharge stream outside of the silo below the main central withdrawal point.
- Be aware of the potential effects of the feeder type and design. In the case of 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 a vibrating discharger is used but not cycled on-off on a regular basis, an eccentric flow channel may develop, particularly if a pantleg chute is below the outlet.
- Consider non-uniform pressures when designing silos with blend tubes.

2.3. Design errors: 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. If an internal is to be used (and/or retrofitted into an existing silo), the design engineer must be aware of the high bending stresses that are applied to the silo walls at the support points. It should also be noted that an internal will often create a "hopper like" convergence that will be accompanied by a local pressure peak against the silo walls.

Quick tips

- Don't ignore loads on inserts, since they can be extremely large [20].
- Be aware that when internals are used, non-uniform pressures may develop if the resultant flow pattern 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 a case such as this, the vertical load greatly exceeds the dead weight of the material inside the insert and the surcharge of material above it.
- Be aware that inserts can be accompanied by a local pressure peak against the silo walls.
- The design engineer should carefully specify the desired construction method in order to fully realize the design intent.

2.4. Design errors: specific requirements for structure type

During the course of any silo design, the structure type and construction materials and methods must be determined. When deciding on the structure type there are many factors to consider, such as cost, construction methods, and availability of materials. Specific requirements associated with the selected design must be considered.

For example, many silos are constructed of bolted metal panels (usually steel or aluminum). With such silos, consideration must be given to how the loads in each panel are transferred through the bolts into adjacent panels. 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 of these modes governs the design will depend on many factors [21–23]. Compressive buckling must also be considered, particularly if the bolted silo has corrugated walls.

Reinforced concrete construction presents different problems [24, 25]. Concrete is strong in compression but very weak in tension. For this reason, 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 collapse.

Quick tips

- In the case of bolted steel design, consider all the various modes by which a bolted joint can fail, ensure that the design can withstand compressive buckling, and follow recognized design procedures.
- Determine the likelihood of eccentric fill or discharge and design accordingly. In particular, do not use only a single layer of reinforcement in reinforced concrete silos if eccentric loading is possible.

- Be wary of novel, unique, unproven structural details whose sole purpose is to reduce costs [26].

2.5. Design errors: temperature and moisture effects

Unusual loading conditions can also occur as a result of temperature and/or moisture effects. As was explained in the fly ash silo failure description above, temperature fluctuations, such as would occur from daytime to nighttime, can lead to much higher hoop stresses than would otherwise be expected.

A similar phenomenon can occur if the bulk solid being stored is moist and has a tendency to expand with increased moisture content. Temperature fluctuations and other mechanisms may cause moisture to migrate between stagnant particles or masses of stagnant particles, causing some to expand. If this occurs while material is not being withdrawn, upward expansion is greatly restrained. Therefore, most of the expansion must occur in the horizontal direction, which will result in significantly increased lateral pressures on, and hoop stresses in, the silo walls. The authors are aware of a case in which the lateral pressures on a silo wall were increased by more than a factor of five. If it is possible for this phenomenon to occur, the larger pressures and stresses must be accounted for in the design.

Quick tips

- Include factors of safety in the design of outdoor metal silos to account for the effects of thermal ratcheting [27].
- Assess the likelihood of significant moisture migration occurring while the bulk solid is stationary, and design accordingly.

3. Construction errors

Mistakes that can lead to structural failure can also be introduced during the construction of the silo and its supporting structure. Discretion must be used in the selection of the construction team, who must be cognizant of the importance of their role. Poor quality workmanship is the most common way in which construction related mistakes are made. 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. Design specifications must be carefully followed and if any situation arises during construction that requires design modifications the structural design engineer should be consulted.

If design specifications, with respect to materials of construction, placement, and type of reinforcing steel, construction sequence, and other details are not followed, the full intent of the design will not be realized.

3.1. Construction errors: poor quality workmanship

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.* The design engineer should have a representative on site, during construction, to ensure that the correct procedures are followed and that events are properly sequenced.

Quick tips

- Use only qualified suppliers and contractors.
- Make sure that specifications are clear and tightly written [28].
- Use an experienced construction team that understands the specifications and recognizes the potential consequences of poor quality work.
- Carefully and frequently inspect the installation.

3.2. Construction errors: unauthorized design changes

As with most structures, the construction of a silo requires careful planning and scheduling. The availability, cost, and delivery times of the specified materials of construction can often be such that design changes are warranted. It is imperative that if, for any reason, design changes are necessary the structural design engineer be consulted before they are implemented. 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.

Quick tips

- Make sure that both the silo builder and design engineer carefully consider and approve any changes in details, material specifications, or erection procedure.
- Closely inspect all construction.

4. Utilization errors

A properly designed and properly constructed silo should have a long life. Unfortunately the incidence of silo failure is quite high. Even silos that have been well designed and constructed can fail. Specific parameters are used in the design of a silo and if any of the actual parameters are different than those used in the design, the silo may fail. To ensure a silo's long and safe life, it is imperative that it be used only for the purpose for which it was designed and that appropriate inspection and maintenance programs be implemented and executed.

4.1. Utilization errors: improper usage

Improper usage of a silo can result in failure (Figure 9). This can occur, for example, if a silo is being used differently than the design engineer intended.

Flow properties of the bulk solid being handled can be different than expected for a number of reasons. For example, the material being stored may be purchased from several sources depending on availability and economics or the original source could dry up. Alternatively, the silo's purpose could change at some point in its life, necessitating that it be used to handle a completely different material.

If the flow properties of the bulk solid being handled in a silo are different than or have wider variations than those 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. Sometimes these obstructions will clear by themselves, but, more often, operators will have to resort to various and sometimes drastic means (*e.g.*

Figure 9. When mass flow develops in a funnel flow silo, the results can be catastrophic

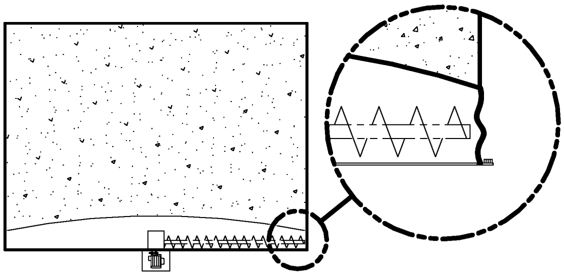

Figure 10. Buckling of unsupported wall due to an arch forming in the cylinder section above a sweep arm unloader

dynamite) to clear them. No matter which method is used, the resulting dynamic loads when an arch or rathole fails can collapse the silo [29].

There are many other results of different than anticipated flow properties. For example, if mass flow develops when funnel flow was expected, dramatically different wall pressure loading will result, particularly at the top of the hopper section. (The opposite – funnel flow in a silo designed structurally for mass flow – can also occur but this generally is not as serious a problem.) Other effects include self-induced silo vibrations which can result in significant dynamic loads that most silos are not designed to withstand [30, 31]. Zones of stagnant material can lead to a fire if the material is pyrophoric. In some cases, if the material is also dusty, an explosive condition will develop. Few if any silos can withstand the loads imposed by an explosion.

Changing the operational parameters of the silo also can lead to structural failures. For example, if the length of time between discharging batches is longer than was expected, it could lead to an explosive condition if the material is both pyrophoric and dusty or it could result in the bulk solid gaining sufficient strength to form an obstruction to flow.

The dangers associated with flow obstructions are not limited to the dynamic loads of collapse. Consider what happens if an arch forms across a silo's cylinder section, and material below it is withdrawn. The full weight of the silo contents above the arch, as opposed to just a portion of it, is transferred to the region of the silo walls below the arch. Buckling failure is likely when this occurs, particularly if the silo is of bolted construction. The likelihood of buckling is increased by the silo's reduced ability to resist it because the normal restraining effect of a bulk solid against a silo's wall (increased pressures in areas where the walls are deforming inward, decreased pressures where the walls are expanding) is lost by the absence of material below the arch. Figure 10 illustrates this mode of failure.

Physical changes to a silo also can radically change the load distribution. Over time, the interior surface of the hopper can become polished, particularly with abrasive bulk solids. Alterations to the outlet geometry, including the addition of secondary outlets, also can change the load distribution. This effect is particularly pronounced if an off-centered outlet is added to a center discharge silo or if a flow-controlling insert or constriction is added.

Quick tips

- Know the flow properties that were used to design your silo. Before putting bulk solids with different flow properties into your silo, determine the new material's flow properties and know how they will affect the silo loads.
- Avoid materials and/or conditions that could result in a flow pattern for which the silo was not designed. Note that polishing marks on the hopper walls in a funnel flow silo are a possible indication of mass flow.
- The design engineer or a silo expert should be consulted regarding the effects of any changes before they are implemented.
- Extreme caution should be exercised when attempting to restore obstructed flow. An investigation into the cause of the flow stoppage should be undertaken before any attempt is made to restore it. Under these circumstances personnel should not be allowed to be in proximity to the silo. Consideration should be given to top reclaim using experts trained in this technique.
- 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.

4.2. Utilization errors: improper maintenance

As with any structure, a silo must be properly maintained if it is to have a long, useful, and safe life. Maintenance of a silo is the owner's or user's responsibility and must not be neglected.

Two types of maintenance work are required. The first is the regular preventative work, such as the repair of the walls and/or liner used to promote flow, protect the structure, or both. Other examples of preventative maintenance items include periodic inspection of roof vents, level probes, feeders, dischargers, and gates.

When abrasive and/or corrosive bulk solids are being handled, the silo wall thickness may be reduced by erosion, corrosion, and/or a cyclic combination of both. Walls that have been thinned by these processes are less capable of resisting applied loads. Combining the effects of abrasion with corrosion, such as can occur when an abrasive and moist bulk solid is stored in a silo with carbon steel walls, significantly accelerates the problem. Accelerated wear can also result when using special aging steels for wall construction. Abrasive wear causes the surface layer to be removed, thereby exposing new material. The obvious consequences of this type of problem, if left unchecked, tend to be catastrophic.

It should be noted that corrosion, caused by weather, of the outside of the silo walls or horizontal external structural members can also result in significant damage. Another mechanism that can create a corrosive environment is material buildup, combined with moisture from the air. Local corrosion on the outside of a silo wall can result in small holes in the wall. The holes alone may not be enough to cause a failure; however, they present the opportunity for the cyclic abrasion/corrosion process inside the silo by providing a possible entrance for water.

Silo failures often cause significant damage and sometimes result in death. Often failures can be prevented or damage can be minimized with information that could have been gained through routine inspection. For example, it is possible to prevent corrosion/erosion failures by regularly inspecting the silo, paying particular attention to the walls, both inside and out, and watching for signs of distress. The owner or user should be aware of what the minimum wall thickness requirements are, and should, as part of the regular inspection program, compare the actual measured values to the requirements.

The second area of maintenance involves looking for signs of distress (*e.g.*, cracks, wall distortion, tilting of the structure) and properly reacting to them [32]. If evidence of a problem appears, expert help should be summoned immediately. An inappropriate response to a sign that something is going wrong can cause a failure to occur with greater speed and perhaps greater severity.

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. Cracks in a concrete wall, or dents in a steel shell, though they may seem insignificant, are danger signals which indicate that corrective measures are probably required. Another common reaction is curiosity. People have lost their 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.

Quick tips

- Carefully inspect, both internally and externally, your silos on a regular basis [32]. In the case of a reinforced concrete silo, look for any signs of corrosion, exposed rebar, unusual cracking, or spalling of concrete. In the case of a bolted metal silo, pay particular attention to the bolted joints near the top of the hopper and look for waviness along the edges of the sheets, elongation of bolt holes, or cracks between bolt holes. Buildup of material which could trap moisture on the exterior of outdoor silos should be removed.
- Determine the minimum wall thickness required for structural integrity and compare to the actual wall thickness.
- Perform a detailed structural inspection of your silo before designing modifications to it, and before using it after any unusual event, such as a storm with very high winds or an earthquake.
- At the first sign of silo distress, cease discharging immediately and assess the integrity of the structure. Limit access to the area surrounding the silo. Investigate the cause of the distress. Ensure that the staff who are dealing with the silo have the education and experience to safely deal with the situation. Retain experts with knowledge of silo structures to assist in the investigation.

5. Summary

As in the fly ash silo failure described at the start of this paper, the majority of structural failures of bins and silos can be attributed to a combination of several deficiencies or errors made during one or more of the three stages in a silo's life: design, construction, and utilization.

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 only following a code of practice. Compliance with the locally applicable code is, of course, essential, but it should never, by itself, be regarded as a sufficient condition to the performance of a satisfactory design. It is the responsibility of the design engineer 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.

The construction of a silo, bin, or hopper should be executed by a qualified and experienced team that understands the specifications set out in the design and the consequences of not following them to the letter. It is the joint responsibility of the design engineer, builder, and owner that construction be 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.

As the saying goes: "If it is worth doing, it is worth doing right". This applies to the design, construction, and utilization of a silo. At all phases, it should be borne in mind that if a silo is designed, built, and operated properly it will have a long and safe life. It should also be remembered that in the event of a failure, the cost of repairs or rebuilding, litigation, and insurance almost always add up to several times the cost of doing the job properly in the first place.

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