Silo design codes: Their limits and inconsistencies

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Abstract

In order to structurally design a silo, an engineer must determine all loads that are likely to be applied to it. These include, among others, wind, seismic, external, and loads induced by the stored bulk solid. Numerous codes and standards specify means to calculate the latter (so-called solids-induced loads). Among them, the four most common in use in the world today are:

- American Concrete Institute ACI 313-97 “Standard practice for design and construction of concrete silos and stacking tubes for storing granular materials”

Unfortunately, guidance to the user is inconsistent between these codes. In addition, many common silo design conditions are not covered by any of them.

A brief description of each of these codes, their limitations, and common design conditions that are not covered are identified. Users of silo codes will find this information invaluable, as will code writers who will benefit by being given direction as to how to improve their codes to make them more useful.

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1. Introduction

A critical starting point when designing any structure involves determining the loads that are expected to act on it. Bins and silos used to store bulk solids are no exception. (NOTE: Various terms are used to describe a container for bulk solids, such as bin, silo, tank, bunker, vessel, elevator, etc. Since none of these terms has a commonly accepted definition, they are used interchangeably in this paper.) Unfortunately, the solids-induced loads that act on the walls and internals of such structures are not easily determined or understood. As a result, silos and bins fail with a frequency that 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. [1]

Given the importance of determining silo loads, the obvious question is, “Why isn’t this better understood?” Part of the problem lies in the lack of training in this subject. Many engineers when faced with the need to analyze a container storing a bulk solid wrongly assume that a flowing bulk material behaves like a flowing liquid. Nothing could be further from the truth! Solid particles can transfer shear stresses between each other and between themselves and silo walls even if there is no relative motion between them. In addition, the magnitude of these shear stresses is, for most bulk solids, independent of shear strain rate or velocity. Solids can form stable pile surfaces and sometimes stable flow interruptions known as arches and ratholes. Fluids do not exhibit any of this behavior. Therefore, using a fluids-based approach to calculate silo loads is doomed to produce unrealistic values. For example, a silo containing a fluid will have the highest wall pressure at the bottom, whereas the same vessel storing a bulk solid will almost always have the highest wall pressure somewhere near its mid-height.

2. History of silo codes

Various attempts have been made over the last 50 years to codify solids-induced pressures acting on silo walls. The first code to provide helpful rules to design engineers calculating silo loads was developed from the extensive testing performed by Pieper and his colleagues [2], who produced the German Standard DIN 1055 Part 6 “Design loads for buildings: Loads in silo bins”. This standard, which was first published in 1964, has been significantly revised and reissued twice -- 1987 and 2005.

Other groups in other countries have codified solids-induced silo wall pressures, and this process continues today.

Various terms are used to describe these documents: Standard, Code, Guidelines, Recommended Practice, Engineering Practice, etc. Documents titled “Code” or “Standard” require compliance, whereas those titled “Recommended Practice”, “Guidelines” or “Engineering Practice” might be considered recommendations only, not requiring mandatory compliance. While that may be true in a strict legal sense, this does not absolve an engineer from responsibility for what should be his/her primary focus: safety, regardless of pressure that may come from clients or others. Safety, and then economy, must determine the design. For practical purposes, “Guidelines”, “Recommended Practices” and “Engineering Practices” should be considered minimum mandatory standards. In other words, an engineer has the right to exercise independent engineering judgment when creating a design, and he/she may even go back to first principles. However, if a problem occurs and the engineer is required to justify the design, there will be a very strong presumption against the engineer that is very difficult to overcome in most cases if the engineer has not at least considered all applicable “Guidelines”, “Recommended Practices” and “Engineering Practices”. [3]

3. Silo design codes covered in this paper

The focus of this paper is limited to the four most commonly used silo design codes in the world today. Other, specialized codes exist, but, to the authors’ knowledge, they are not in general use.

Adopted by the European Committee for Standardization (CEN) in October 2005, this is the most modern and complete silo design code in use today [4]. It is commonly called “the Eurocode”, although that is like referring to “the ASTM Standard” as if there is only one. The formal designation for the English version of this code, which was published in May 2006, is British Standard BS EN 1991-4:2006 “Eurocode 1 – Actions on structures – Part 4: Silos and Tanks” (BS 2006). A German standard was produced from a late draft of this standard and published as DIN 1055-6:2005-03 “Actions on structures – Part 6: Design loads for buildings and loads in silo bins” in March 2005. This has been superseded by the mandatory DIN EN 1991-4 (2006), which is the German translation of the British Standard.

BS EN 1991-4:2006 exploits extensive European research on silos over the past 30 years. It was extensively reviewed by civil, mechanical and chemical engineering specialists before it was adopted, and it is widely recognized as most advanced standard of its kind in the world.

The code divides silos into three classes – from simple, small structures (Action Assessment Class 1) to large and/or complex structures (Action Assessment Class 3). These distinctions permit appropriate procedures to be used for given conditions, and they eliminate debates on complexity vs. dangerous over-simplifications. Details of these three classes are provided in Table 1.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>&gt;10,000 tonne capacity or &gt; 1,000 tonne capacity if:</td>
</tr>
<tr>
<td></td>
<td>• Eccentric discharge with eccentricity greater than 25% of cylinder diameter</td>
</tr>
<tr>
<td></td>
<td>• Squat silo (cylinder height between 40 and 100% of cylinder diameter) with top surface eccentricity greater than 25% of cylinder diameter</td>
</tr>
<tr>
<td>2</td>
<td>All silos not in Class 1 or 3</td>
</tr>
<tr>
<td>1</td>
<td>Capacity &lt; 100 tonne</td>
</tr>
</tbody>
</table>

Silos are further classified by aspect ratio $h_c/d_c$, where $h_c$ is the height of the cylindrical section from the cylinder/hopper intersection to the centroid of the top pile, and $d_c$ is the cylinder diameter:

- **Slender** ($h_c/d_c \geq 2$)
- **Intermediate slenderness** ($1 < h_c/d_c < 2$)
- **Squat** ($0.4 < h_c/d_c \leq 1$)
- **Retaining** ($h_c/d_c \leq 0.4$)

Each geometry has special loading features with different conditions being critical for design, and each class blends smoothly with the next.

Design conditions depend on silo geometry, the stored bulk solid, and conditions of filling and discharge. This is the first silo design code to identify so many different conditions and regulate how each should be treated. It allows careful identification of requirements according to safety implications.

This code recommends that the three key material properties ($\mu$ -- coefficient of wall friction between the stored bulk solid and the wall surface, $\gamma$ -- bulk density, and $k$ -- lateral pressure ratio) be determined by tests, which are detailed in Annex C. Recognizing that variations occur when the same bulk solid is tested repeatedly, the code recommends a procedure by which upper and lower characteristic values can be obtained.
Eccentric loads cause more silo failures than any other condition, and this is the first standard to provide rational treatment of this phenomenon, adopting the simple model proposed by Rotter [5,6]. The complexity of treatment depends on the Action Assessment Class, with “patch loads” used to deal with smaller eccentricities.

This is the first code to recognize and fully treat the fact that characteristic actions for different parts of a silo are controlled by different ends of the statistical distribution of values of properties of the stored bulk solid. When calculating maximum lateral pressures in a silo’s cylindrical section, a combination of minimum coefficient of wall friction, $\mu$, with maximum lateral pressure ratio, $k$, is specified. This calculation is what usually dictates silo wall thickness when hoop tension governs, e.g., a thick-walled silo. On the other hand, if vertical buckling dictates wall thickness (such as for a thin-walled metal silo), a combination of maximum coefficient of wall friction with maximum lateral pressure ratio is used, since this results in maximum frictional drag. As a result, a significant reduction in empirical over-pressure factors is possible.

3.2 ACI 313-97 “Standard practice for design and construction of concrete silos and stacking for storing granular materials”

The current version of this U.S. publication was adopted in January 1997 [7]. Unlike EN 1991-4:2006 which has broad applicability, this document is focused solely on methods to calculate pressures exerted on the walls of concrete silos, although one could argue that the calculation methods – not the values used in the equations – should be independent of a silo’s material of construction.

Consistent with EN 1991-4:2006, this publication correctly recognizes that the three key bulk solid properties almost always vary for a given bulk solid, and that this variation should be taken into account depending on the calculations that one is performing. In all cases bulk density is to be taken at its maximum value, since solids-induced pressures vary linearly with bulk density. The coefficient of wall friction, $\mu$, is determined by test or reference to tabulated values.

In an attempt to cover the many unknowns when calculating silo wall pressures, the writers of this publication specified the use of a large factor-of-safety, specifically:

4.4.2.2 Concentric flow -- The horizontal wall design pressure above the hopper for concentric flow patterns shall be obtained by multiplying the initial filling pressure….by a minimum over-pressure factor of 1.5.

Eccentric loads are treated poorly, providing practically no guidance to the design engineer:

4.4.2.3 Asymmetric flow -- Pressures due to asymmetric flow from concentric or eccentric discharge openings shall be considered.

The Commentary provides little additional guidance on this topic:

R4.4.2.3 Asymmetric flow can result from the presence of one or more eccentric outlets or even from non-uniform distribution of material over a concentric outlet.

Methods for evaluating the effects of asymmetric flow have been published. None of these methods has been endorsed by the Committee.

Thirteen publications are referenced.

Unlike EN 1991-4:2006, which includes patch loads to cover non-uniform silo wall pressures that are known to develop even in silos with concentric fill and discharge [8] (Ooi et al 1990), ACI 313-97 makes no mention of patch loads.

As with almost all silo design codes, this publication includes a table of example physical properties of common bulk solids. However, Table 4-A in this Standard Practice’s Commentary is more simplistic and therefore more dangerous than most. For example, the value given for coefficient of wall friction for bituminous coal against steel is a single value, 0.3. There is no indication of the type of steel (e.g., carbon steel or stainless steel) or its surface finish (hot rolled, cold rolled, polished, corroded, etc.), nor any suggestion that the coal’s moisture, ash or other variables have any effect on wall friction. The footnote to this table

The properties listed here are illustrative of values which might be determined from physical testing. Ranges of values show variability of some materials. Design parameters should preferably be determined by tests and the values shown used with caution.

This footnote is meant to provide a warning to the reader, but it is easily overlooked.

The latest version of this Engineering Practice was adopted by ASAE in December 1988 and approved by the American National Standards Institute (ANSI) in September 1991. It was reaffirmed yearly thereafter and revised editorially by ASAE in March 2000. The current version was reaffirmed by ANSI in February 2011 [9].

As its title indicates, this publication was developed solely for vessels storing free-flowing, agricultural whole grain. Furthermore, its application is limited to a silo flow (i.e., discharge) pattern classically called “funnel flow”, although in this publication that term is restricted to a flow pattern in which the flow channel does not intersect the cylinder wall. (NOTE: Funnel flow is defined as a flow pattern in which some of the stored bulk solid is stationary while the rest is moving.) It states that this flow pattern “will normally occur in silos which have H/D ratios less than 2.0.” (NOTE: H is total height of material from lowest point of discharge, i.e., including hopper section, to one-third height of pile surcharge at top surface, D is bin diameter.) If the flow channel were to open up more than about 14° (from vertical) it would intersect the cylinder wall. This Engineering Practice calls this condition “plug flow” and specifies that an over-pressure factor, F, equal to 1.4 be used when calculating silo wall pressures.

For coefficient of wall friction a simplistic table of values similar to that in ACI 313-97 is included, but the numbers are different, as shown in Table 2:

<table>
<thead>
<tr>
<th>Wall surface</th>
<th>ANSI/ASAE EP433 2011 Table 1</th>
<th>ACI 1997 Table 4-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0.30</td>
<td>0.26 -0.42</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.40</td>
<td>0.29 – 0.47</td>
</tr>
</tbody>
</table>

This publication is limited to silos that are centrally loaded and unloaded, so eccentric loads are not included. Patch loads are also not included, even though it is well recognized that non-uniform wall pressures develop during symmetric fill and discharge.

3.4 AS 3774-1996 “Loads on bulk solids containers”

The first Australian publication on solids-induced pressures on silo walls was titled “Guidelines for the assessment of loads on bulk solids containers”. It was published in 1986 by a working party on bins and silos of the Australian Institution of Engineers’ National Committee of Structural Engineering. This was followed by Australian Standard AS 3774, which was first published in 1990 and then revised in 1996. [10] This standard can be considered one of the precursors of EN 1991-4:2006, since Michael Rotter was the lead author of both documents.

Unlike EN 1991-4:2006 this standard does not include Action Assessment Classes, but it does include upper and lower characteristic values of key material parameters. It includes four classifications of loads (dead loads, normal service loads, environmental loads and accidental loads) and a table describing load combinations that must be considered. Some often-overlooked conditions such as permissible geometric deviations in silo geometry and effects of wall flexibility are described.

Even though it includes methods to calculate wind and seismic loads, this is perhaps best handled using the most up-to-date general design code such as the Universal Building Code (UBC).

4. Load conditions

Table 3 summarizes various load conditions covered by these four codes.
Table 3. Load conditions covered by various codes

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hopper geometry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Symmetric single cone</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>- Square pyramid</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>- Wedge with vertical end walls</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Fill and discharge conditions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Patch loads</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>- Eccentric fill and discharge</td>
<td>Yes</td>
<td>Poorly</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>- Mass flow</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>- Funnel flow</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>- Pipe flow</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>- Mixed flow</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>- Expanded flow</td>
<td>No</td>
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</tr>
<tr>
<td>- Impact loads on filling</td>
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<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>- Silo quaking</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Internals</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Thermal Ratcheting</strong></td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Grain swelling</strong></td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Effects of gas pressures</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Completely fluidized contents</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>- Partially fluidized contents</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>External equipment</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

4.1 Hopper geometries

Only a few, common hopper geometries are covered by all four codes. In industrial practice many other hopper geometries are commonly used, including transition, chisel, non-symmetric pyramid, wedge with non-vertical end walls, asymmetric cone, multiple hoppers joined together one above the other (e.g., a cone below another cone, etc.) (Fig. 1). None of these geometries is covered by any of these codes. EN 1991-4:2006 notes that there are problems in some of these cases, but it simply requires a rational analysis to be used in addressing them.
4.2 Patch loads

Even the simple case of symmetric fill and discharge involves accidental asymmetries that can result in non-uniform pressures around the circumference of a silo [11, 12]. EN 1991-4:2006 handles this issue by requiring use of patch loads.
4.3 Flow patterns

Only two of these codes (EN 1991-4:2006 and AS 3774-1996) cover the flow pattern call mass flow, which occurs when a silo’s hopper walls are sufficiently smooth and steep that all the material is in motion whenever any is withdrawn.

Funnel flow occurs with less steep or less smooth hopper walls, which results in some of the material remaining stagnant while the rest (directly over the outlet) is flowing. These four codes use somewhat different terms to describe this flow pattern. EN 1991-4:2006 and AS 3774-1996 use the term mixed flow to describe the condition of the flow channel intersecting the silo wall, whereas ANSI/ASAE EP433 calls this plug flow. EN 1991-4:2006 and AS 3774-1996 use the term pipe flow to describe the condition when the flow channel does not intersect the silo wall.

None of these codes covers expanded flow, which is a combination of mass flow and funnel flow.

4.4 Internals

Structures are often placed within a silo in an attempt to alter the flow pattern, facilitate introduction of a gas into the bulk solid for processing, heating, cooling, etc., reduce pressures on silo walls, or to reduce loads on the outlet region. These structures include so-called Chinese hats, cone-in-cone inserts, and cross beams as shown in Fig. 2. Loads on such internal structures can be extremely high, and many have failed or caused silos to fail. They also alter the pressure distribution on silo walls in the vicinity of the insert. Only AS 3774-1996 addresses loads on such internals, but the calculations are rather simplistic and do not include the effects of internals on the silo wall. EN 1991-4:2006 identifies these problems and requires a rational analysis to be used in addressing them.
Anti-dynamic tubes are sometimes used to convert a silo’s flow pattern to last-in-first-out, thereby eliminating pressure increases on silo walls that develop during discharge. Only ANSI/ASAE EP433 covers the loads acting on such tubes.

4.5 Material properties

All four codes start with the premise that the stored bulk solid is free flowing. Unfortunately the vast majority of bulk solids are not in this category. Both EN 1991-4:2006 and AS 3774-1996 note that it can be used when “the stored solid can be guaranteed to flow freely within the silo container as designed”, but neither ACI 313-97 nor ANSI/ASAE EP433 provides any guidance on how to design storage vessels for non-free-flowing bulk solids.

All four codes recommend that the stored material’s relevant properties be determined by tests, if possible. However, they all provide a table of typical values. These must be used with caution, particularly the tables in ACI 313-97 and ANSI/ASAE EP433, as noted above. All four codes warn against over-reliance on tabulated values, but the warnings can be easily overlooked.

4.6 Thermal ratcheting

Thermal ratcheting is a condition in which successive temperature cycles cause increasing pressures on metal silo walls. Metals have a higher coefficient of thermal expansion than bulk solids, and metal silo walls react more quickly to ambient temperature changes than the stored bulk solid. Thus metal walls expand with increasing temperature, and the stored material settles (assuming no discharge). When the ambient temperature drops, the walls attempt to contract, but the bulk solid could only be pushed upward to its previous level if the direction of friction in the solid and between the walls and solid were reversed. This causes stresses within the wall to increase significantly [13], and the phenomenon may continue (“ratcheting”) with each succeeding temperature cycle.

ANSI/ASAE EP433 provides an estimate of this effect on silo walls in 4.4.1, but notes in the Commentary that this estimate is based on laboratory studies using steel model circular silos. It notes that qualitative results collected from full size silos are available in the literature, but that “quantitative results needed for design purposes are not available from large silos”.

AS 3774-1996 and EN 1991-4:2006 cover this phenomenon much more completely than ANSI/ASAE EP433, while ACI 1997 does not address it at all.

4.7 Grain swelling

This is a known cause of a number of silo failures. ANSI/ASAE EP433 notes in 4.4.2.1 that “moisture increases during storage of 4% or more can cause lateral pressures to increase several times static load conditions.” It notes in the Commentary:

5.4.2 Stored grains are hygroscopic; that is, they absorb moisture from liquid sources and from the atmosphere. When grains absorb moisture, they expand. When grains are confined within a structure, the expansion is restrained. The consequence is an increase in bin wall pressure.

It notes that data on this subject in the literature is limited in number and scope, but that some studies have reported that lateral pressures increased by a factor of six as grain moisture increased by 4%, and by a factor of ten for a 10% increase in grain moisture content [13].

AS 3774-1996 also covers this phenomenon, but neither of the other two codes covers it.

4.8 Effects of gas pressures

Sometimes gas is added to storage vessels to cause or suppress chemical reactions, cool or heat the bulk solid, etc. If sufficient gas is added, a completely fluidized condition develops, and the wall pressures change to essentially hydrostatic. ACI 313-97, EN 1991-4:2006 and AS 3774-1996 provide guidance on this condition.
If less gas is added, the effect is not as dramatic as a fluidized column, but the wall loading can certainly be affected in a major way. Sometimes the entire vessel is operated at above-atmospheric pressure, while at other times it is close to atmospheric but differential gas pressures are present. None of the four codes address such conditions.

4.9 External equipment

External equipment such as electric or pneumatic vibrators, vibrating bin discharger (bin activator), localized aeration devices, and air cannons impart significant forces to a silo structure that must be taken into account. They can also affect the stored bulk solid in such a way that its properties change, resulting in different silo loads. AS 3774-1996 provides some limited guidance on this phenomenon, but it does not cover loads acting on external equipment itself by the stored bulk solid. The other three silo design codes do not cover this at all.

Feeders and gates are also critical to a safe and properly functioning silo. AS 3774-1996 provides guidance regarding loads imposed on them, but the other three codes do not.

5. Conclusions

Knowledge of the loads applied to the walls and internals (if any) of a silo is extremely important. Such loads must not be ignored if a stable, safe silo is to be designed.

Much progress has been made in the last 50 years in providing silo load guidance to design and structural engineers. EN 1991-4:2006 is a significant advance over all previous codes, but even it does not cover many common load cases.

For load cases not covered by the codes, the design/structural engineer is left with two choices:

- Be extremely conservative in estimating applied loads. This approach can be quite expensive and yet still may not be conservative enough to prevent the silo from failing.
- Rely on design engineers who have significant experience in calculating silo loads.

Acknowledgements

The authors are indebted to Michael Rotter for his insight and useful discussions on the topic of this paper.

References