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Contributions of Different Standards and Codes for the Design of Silo: A Review

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***Abstract* - Determination of loads play significant role in the design of silo. The silo is a structure used for storage of bulk materials, in which the loads due to stored materials has to be taken into account in addition to wind load and seismic load. The various codes and standards stipulate guidelines for the silo design. The four codes studied and compared in this paper viz., a) Indian Standard IS 4995 - 1974 b) American Concrete Institute ACI 313 – 97 c) German Standard DIN 1055 – 6: 2005 – 03 and d) British Standard BS EN 1991-4: 2006. Though, the analysis and design of silo cannot be performed using single code, the lack of compatibility among various codes makes the designers difficult in designing the silo. The consideration of minor modifications in the analysis and design of silo makes it possible to construct and operate safe and economical silo. The aim of this paper is to compare and briefly describe about the superiority and limitations of four codes.**
***Keywords* : Silo design codes and standard; Silo classification; Material induced loads; Flow pattern; Hopper geometry.**

I. INTRODUCTION

Silos and bunkers are the structures meant for storing materials like food grains, cement, coal, ore, crushed stone, gravel, clinker etc., in large quantities. The bunker is a shallow structure whereas the silo is a tall structure. In general, bunkers or bins are used to store gravel, stone and coal whereas cement and grains are stored in silos [1]. They can be constructed as either ground supported or elevated. With the advent of green revolution, there is a need for the proper storage of huge quantity of crops for future use after it has been harvested. To fulfill this demand of storing crops and grains, the construction of silos became essential. The silo plays a vital role in agricultural, industrial and military domain for the purpose of storing materials. Before 1960's, people stored the materials in bins which was designed by guessing. The research of Andrew W.Jenike in 1960's has provided the base for the bin design. The silos designed by traditional techniques are inadequate due to the application of simplified methods in the complex situations [2].

The materials for construction of silos comprises of steel or reinforced concrete. The silo mainly consists of bin and hopper for storing and discharging materials respectively. For the purpose of self cleaning and emptying, the silo is supported on a number of columns. The bin is covered by a roof with suitable man hole. The foundation of the silo may be mat, raft or pile based on the soil condition.

Silos are considered as special structures as its design is based on the properties of materials stored. In addition to the loads that are acting on the normal structures such as wind, seismic and external loads, the silos are specially designed for the loads that are induced by the stored materials. Engineers ensure that the silo is built to be strong and stable enough to resist structural loads and loads due to materials stored. The pressure exerted by the stored material on the side of a bin varies with the processes and arrangements of filling and emptying operations. Due to this variation, it is extremely difficult to analyze the pressure exerted on the walls of the bins. The approximate methods suggested by Janssen are commonly followed for the calculation of pressure in most cases [3]. Based on the types and properties of the stored materials, the loads imparted by the stored materials on the bins may vary. The silo walls are subjected to horizontal, vertical and frictional shear. The magnitude and distribution of these shears and pressure over the height of the bin depends on the properties of the materials and its filling conditions (i.e. filled or discharged).

During the design process, the loads such as wind and seismic loads, stress due to temperature difference, potential expansion of the material stored and the settlement of the foundation are to be considered [4].

II. CODES CONSIDERED IN THE STUDY

A. Indian Standard - IS 4995 : 1974

The guidelines recommended by the Bureau of Indian Standard for the design of reinforced concrete silos were explained in 'Criteria for Design of Reinforced concrete bins for the storage of Granular and Powdery materials'. The silos load determination is described in Part 1 – General Requirements and assessment of Bin loads. The criteria for the design of the silo are given in Part 2 – Design Criteria. In 1968, this standard was published by considering the requirements of structural design for food grain storage bins (silos) [5]. In the year 1974, the revision was adopted to design silo for storing all kinds of materials in addition to food grains. The physical nature of the materials to be stored in the bins are taken into account and the code classified the stored materials as granular and powdery materials as shown in Table1.

TABLE 1 CLASSIFICATION OF MATERIALS

Materials	Particle size
Granular	> 0.2 mm
Powdery	< 0.06 mm

The Part 1 of this standard has given the guidelines for the assessment of bin loads exerted by the stored material based on the different treatments taking into account the granular or powdery nature of the material. This standard deals with various types of bins namely circular, polygonal or interstice bins. The definition of terms such as silo, bunker and interstice bins is presented in Table 2.

TABLE 2 DEFINITIONS OF TERMS

Silo	Bunker	Interstice bins
Bins of circular or polygonal in plan	Bins of square or rectangular in plan	Bin formed out of space enclosed by battery of interconnected bins

The governing factors for the computation of bin loads are bulk density W, angle of internal friction Φ, angle of wall friction δ and pressure ratio λ. The values of W and Φ are based on the type of the stored material. The δ and λ values depend on the physical nature of the material and it's filling conditions (i.e. filling or discharged). The bin loads are categorized as a) Horizontal load or horizontal pressure (P_h), b) Vertical load or vertical pressure (P_v) and c) Frictional wall load or frictional wall pressure (P_w).

In general, the Janssen's theory is used for the assessment of bin loads. The maximum value of the above mentioned pressures (P_h, P_v & P_w) exerted by the stored material during normal filling and emptying operations is calculated. The condition of homogenization, rapid filling and pneumatic emptying is to be considered, when the powdery materials are to be stored in the bin. During homogenization condition, the lateral and vertical pressures depend on the volume of empty space in the bin. Therefore, the following condition is adopted.

$P_h = P_v = 0.6\ WZ$, which should not be less than the pressures evaluated for normal filling and emptying.

The lateral pressure during rapid filling and pneumatic emptying of a silo is calculated. In the unloading stage, the eccentric emptying of bin causes increase in bin loads. The following loading conditions and effects are considered while designing the various components of silo namely roof, bin walls, ring girder, hopper bottom, supporting columns and foundation.

1. Dead load of the structure
2. Superimposed loads due to material handling & transportation machinery
3. Bin loads as specified under Part I of IS 4995 - 1974
4. Live load (for roof only) recommended as per IS: 875-1964
5. Wind load recommended as per IS: 875-1964
6. Seismic loads recommended as per IS: 1893-1975
7. Thermal load

The effect due to temperature variation is considered in the design of silo in IS codal provision only. This has two positive impacts. First, this consideration is highly beneficial for the silo design located in India with varying climatic conditions throughout the country. Secondly, if the thermal variation due to the material to be stored is considered, some minor problems can be avoided. For instance, if cement is stored in the silo, the heat released from cement leads to cracking of silo wall due to thermal effect. The walls of the circular bins, polygonal bins and interstice bins are designed considering the stress, wall thickness and the crack width. As per Indian standard codal provisions, it is possible to design hoppers of any shape like conical, pyramidal etc.

B. American Concrete Institute - ACI 313 : 1997

ACI 313 – 91 was superseded by ACI 313 – 97 which was adopted as a standard of the American Concrete Institute on January 7, 1997[6]. The material, design and construction requirements for the concrete silos are covered in ACI standard. The recommendations for the cast-in place or precast silos are also mentioned. This standard provides the static and dynamic loading cases from funnel flow, mass flow, concentric flow and asymmetric flow in the silos.

The loads to be considered while designing the silos are dead load, live load, wind load, seismic load, thermal loads, external loads and the force due to differential settlement of foundations. The reinforcement details such as diameter of bars and spacing of bars in the vertical and horizontal direction, lap splices and provisions of dowels are thoroughly explained in ACI standard. The reinforcement detail to be provided at the wall openings due to the existence of pressure zone is also described clearly. The above recommendations are highlighted in ACI standard and it helps the users in the effective design of silos.

As per this code, the pressure due to initial filling, air pressure and pressure during discharge of stored materials are computed against silo walls and hoppers. While determining the pressures and loads on walls, the flow pattern like concentric flow pattern and asymmetric flow pattern are considered as the concentric flow pattern arises during the initial filling and the asymmetric flow pattern arises during the discharge of materials.

The pressures are also calculated for funnel flow hoppers, mass flow hoppers, flat bottom and homogenizing silos. The direct hoop tension due to horizontal pressures along with combined tension and bending due to non uniform pressures are taken for the design of circular silo walls in the pressure zone. The combined tension, flexure and shear due to horizontal pressure are considered for the walls of square, rectangular or polygonal silos. As the walls below pressure zone are subjected to vertical and lateral loads, it is designed as bearing walls. The circumferential and meridional tensile membrane forces are acting on the conical hopper walls whereas the combined tensile membrane forces, flexure and shear are acting on the pyramidal hopper walls. The foundation is designed as per ACI 318 "Building Code Requirements for Structural Concrete and Commentary".

C. German standard - DIN 1055 – 6: 2005 – 03

The German standard DIN 1055 – 'Actions on structures, Part - 6 - Design loads for buildings: Loads in Silo bins' was recommended by Pieper and his colleagues after performing extensive research in this area. This standard was first published in 1964 and revised twice in the year 1987 and 2005 [7]. The German standard DIN 1055 was the first code to provide helpful rules to design engineers for calculating silo loads as the effect of stored materials on the silo walls were included in the load calculation. The German standard was produced from the late draft of the British standard BS EN 1991 – 4 : 2006 and published as DIN 1055 – 6: 2005 – 03.The German translation of the British standard DIN EN 1991 – 4(2006) has superseded the DIN 1055 – 6: 2005.

Generally, the material stored in the silo was considered as Bulk material and the particle size less than 0.05mm was particularly referred as powdery bulk material. The type of materials to be stored in the silo is not given much importance. The following limitations are provided in the design rules of silos such as a) geometric limitations, b) limitations on the stored bulk materials and c) limitations on the filling and discharge arrangements.

The classifications of silos are described below:

a. Based on the aspect ratio hc/dc (i.e. slimness)

   1. Silo with braced wall, $h_c/d_c \leq 0.4$
   2. Low silo, $0.4 < h_c/d_c < 1.0$
   3. Silo of medium slimness silo, $1.0 < h_c/d_c < 2.0$
   4. Slim silo, $h_c/d_c \geq 2.0$

b. Based on the wall thickness

   1. Thick walled silo , $d_c/t < 200$
   2. Thin walled silo , $d_c/t > 200$

c. Based on the wall surface

   1. Polished (D1),
   2. Smooth (D2),
   3. Rough (D3),
   4. Corrugated (D4).

Where,

h_c – height of vertical walled segment of silo from the transition to the equivalent surface
d_c– characteristic dimension of silo interior cross section
t – silo wall thickness

The classification of the dimensioning conditions based on the silo capacity is given in Table 3.

TABLE 3 CLASSIFICATION BASED ON SILO CAPACITY

Standardized Categories	Description
Category 3	Silos capacity > 10000 tonnes
Category 2	All silos not covered in another class
Category 1	Silos capacity < 100 tonnes

The values of the solids properties such as the Specific gravity γ, coefficient of wall friction μ, horizontal load ratio K and angle of internal friction Φ are considered in the evaluation of loads. The flow pattern during discharge which may be categorized as follows should be considered in the design given in Figure 1[7].

1. Mass flow
2. Funnel flow
   a. Internal Parallel funnel flow
   b. Internal convergent funnel flow
   c. Eccentric parallel funnel flow
   d. Eccentric convergent funnel flow
3. Mixed flow
   a. Concentric mixed flow
   b. Fully eccentric mixed flow
   c. Partially eccentric mixed flow

The actions on silos are classified as

1. Variable actions
   a. Loads due to stored particulate solids
2. Variable stationary actions
   a. Symmetric loads
   b. Gas pressure loads by pneumatic conveying
   c. Eccentric loads
3. Variable free actions
   a. Reference Surface loads
4. Extra ordinary actions
   a. Loads due to dust explosions

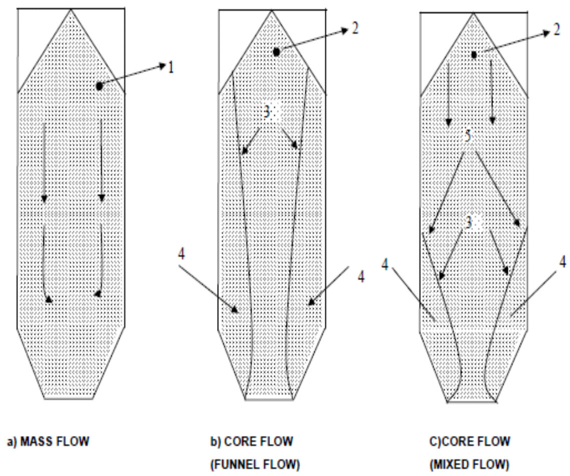

Fig.1 Basic flow Profiles

The actions on the silo should be evaluated by taking the range of particulate solid properties, variation in the surface friction condition, silo geometry and the methods of filling and discharge. The symmetric load and reference surface load should be calculated for filling and discharging conditions for the different silos (i.e. silos based on slimness and wall thickness). The loads on the vertical walls of the silos, silo hoppers (shallow or flat inclined) and silo bottoms (flat) are also evaluated. The hopper design was applicable for conical and cuneiform shaped hoppers.

D. British Standard - BS EN 1991 – 4: 2006

The Eurocode was published in October 2005 which was adopted by the European Committee for standardization (CEN) [8].The British standard BS EN 1991 – 4: 2006 'Eurocode 1 – Actions on Structures' was the English version of the Eurocode. The Part 4: Silos and Tanks of this standard cover the design of the silos and tanks.

The terms mentioned in DIN 1055 – 6: 2005 – 03 and BS EN 1991 – 4 : 2006 with more or less same meaning is given in the Table 4.

TABLE 4 TERMS MENTIONED IN CODES

DIN 1055 – 6: 2005 – 03	BS EN 1991 – 4: 2006
Bulk material	Stored solids
Slimness	Slenderness
Silo with braced wall	Retaining silo
Low silo	Squat silo
Silo of medium slimness	Intermediate slenderness silo
Slim silo	Slender silo
Thick walled silo	Thick walled circular silo
Thin walled silo	Thin walled circular silo
Specific gravity	Bulk unit weight
Horizontal load ratio	Lateral pressure ratio
Funnel flow	Pipe flow
Reference Surface Load	Patch Load
Variable stationary actions	Variable Fixed actions
Extra ordinary actions	Accidental actions
Flat inclined hopper	Steep hopper
Cuneiform hoppers	Wedge shaped hoppers

III. SUMMARY

The four codal provisions for the design of silo are described individually and the comparison between them is presented in Table 5.

TABLE 5 COMPARISON OF FOUR CODES

	IS 4995 - 1974	**ACI 313 - 97**	**DIN 1055 -6: 2005 - 03**	**BS EN 1991 – 4: 2006**
Materials stored is defined as	Granular & Powdery	Granular	Bulk material	Stored solids
Silo Classification	No	No	Based on slimness & wall thickness	Based on slenderness & wall thickness
Vital Parameters	Bulk Density W, Angle of internal friction φ, Angle of wall friction δ, Pressure ratio λ	Weight per unit volume γ, Lateral pressure ratio k, Coefficient of friction μ'	Specific Gravity γ, Coefficient of wall friction μ, Angle of internal friction ϕ, Horizontal load ratio k	Bulk unit weight γ, Coefficient of wall friction μ, Angle of internal friction ϕ, Lateral pressure ratio k
Numerical Values of Solids properties	Directly given for each materials	No values	Obtained from tests & provided as lower and upper limit value	Obtained from tests & provided as lower and upper limit
Loads during filling & discharging	Horizontal load, vertical load & Frictional load	Horizontal load, vertical load & Frictional load	Symmetric load & Reference surface load	Symmetric load & Patch load
Computation of Loads	Based on materials	Based on materials	Based on Silos	Based on Silos
Limitations	No	Effect of hot stored material is not considered	Geometric, Materials, Filling & discharging arrangements.	Geometric, Materials, Filling & discharging arrangements.
Classification of action assessment	No	No	Based on Capacity of stored material	Based on Capacity of stored material
Flow Pattern during discharge	No	Walls – Concentric and Asymmetric flow, Hoppers – Funnel and Mass flow	Mass flow, Funnel flow and Mixed flow	Mass flow, Pipe flow and Mixed flow
Applicable hopper shapes for design	All shapes	Conical and Pyramidal hoppers	Conical and Cuneiform hoppers	Conical and Wedge shaped hoppers
Pressure zone consideration	No	For calculation of wall pressure	No	No
Crack Width calculation	Check and limitations are given	Calculation given	As per DIN 1045 – 1	As per EN 1992
Particle size	No limitation	No limitation	$\ngtr 0.03\, d_c$	$\ngtr 0.03\, d_c$
Reinforced details, Column & Foundation design	Mentioned	Mentioned	No	No

IV. GENERAL DISCUSSION ABOUT THE CODES

A. Solids Properties

The material properties will dictate the silo bin design. The important solids properties considered for the design of the silo are bulk density, wall friction, angle of internal friction and pressure ratio. All the four codes mentioned the solids properties. The wall friction is adopted for calculating hopper angles for mass flow and internal friction. The bulk density is used in the design of feeder and also in the calculation of the pressures and bin loads. The cohesiveness of the material is used in the analyses of arching and ratholes behavior. The arches prevent the material to discharge by forming obstructions whereas the ratholes cause erratic discharge. But the cohesive strength consideration is not provided in the codes.

B. Material

For the design of silo, the codes suggested that the material should be coarse, free flow and non degradable. The particle size greater than 3 mm are considered as coarse. The free flow for bulk materials cannot be expected in various materials in all the cases. It is to be noted that, no arching or ratholes should be formed in the free flowing material. The DIN 1055 – 6: 2005- 03 and BS EN 1991 – 4: 2006 provided the limitation for the material stored in bins, such that it must be the free flowing material. As per this limitation, the silo cannot be designed for non free flowing material.

C. Bin Geometry

The primary design objective when determining the bin geometry is to ensure that bulk solid will flow with the effects of gravity and without flow obstructions [7, 9, 10]. In general, all codes recommended that, the bin may be circular, square or rectangular in shape. The square or rectangular straight sided wall has large cross sectional area compared to the circular wall bin. They are easy to fabricate. The drawback of the straight sided flat walls is suspected to bending due to pressure. But the circular wall cylindrical bin resists internal pressure through hoop tension. The provision of thinner walls and less reinforcement is enough for the cylindrical bins. The round bins tend to empty more easily due to lack of corners for the stored material to become wedged and encrusted.

D. Hopper Shape

The majority of the weight of the stored solids is act on the hopper, so that the design of hopper is difficult in filling stage than the discharging stage [1, 11-20]. The conical or wedge shaped hoppers are recommended as per the codes. The term wedge shaped hoppers as mentioned in BS EN 1991 -4:2006 are referred as cuneiform hoppers in DIN 1055 – 6: 2005 – 03 and pyramidal hoppers in IS 4995 - 1974. The hopper angle depends on the friction of the material. The steep hopper angle is provided for the high friction material and shallow hopper angle for the low friction material. The angle of the wedge shaped hoppers is 10-12º less than the conical hopper angle (i.e.) wedge shaped hoppers have steep hopper angle. The outlet diameter of the conical hopper is twice the outlet width of the wedge shaped hopper. The length of the wedge shaped hopper is three times its width and it has maximum flow rate.

E. Flow Pattern

The flow pattern of the material depends on the internal friction and friction between the materials and hopper walls. The material flows without obstructions are referred as mass flow. In funnel flow, some of the material moves in the center of the hopper whereas, the rest of the material remains in the hopper along its walls. The bulk solids are discharged for most of the bins with the funnel flow pattern. The flow obstructions occur when the forces opposing motion exceed the forces due to gravity. The arches and ratholes are obstructions formed in the funnel flow pattern. Due to this, the material caking and segregation are found to occur. The bin may fail due to material caking which cause unexpected structural loading. Also, there is no chance for fluidized powders to deaerate. The problems experienced in the funnel flow pattern can be rectified in mass flow pattern. The mass flow pattern is the best suited flow pattern for cohesive materials and powders. Almost all the codes, except IS 4995 – 1974 had given the description about flow pattern.

V. CONCLUSION

This paper looks over the superiority and limitations of the four codes namely Bureau of Indian Standard (BIS), American Concrete Institute (ACI), German Standard (DIN) and British Standards Institution (BSI). For the sake of complete, logical and relevant analysis, this study has been divided into two parts. In the first part, each code was thoroughly studied and the basic concepts behind each code were explained. The second part presents the comparison and discussion of similarities and dissimilarities of each code and the analysis of the parameters involved in the design of the silo. The insight of loads exerted by the stored materials and external forces to the silo is significant for designing the safe silo. A slight modifications in the parameters, namely the effect of the thermal variation and the properties of stored materials, if taken into account in the analysis of silo, the discrepancies associated with various codes can be further reduced.

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