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Indian Standard

CRITERIA FOR DESIGN OF STEEL BINS FOR STORAGE OF BULK MATERIALS

PART III  BINS DESIGNED FOR MASS FLOW AND FUNNEL FLOW

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(Continued on page 2)

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2
Page 31, clause 12.2.2.2, equation 10 — Substitute the following for the existing equation:

\[
P_{\text{st}} = P_{\text{ute}} + \frac{3.3 \left[ \frac{Q_s}{A} - \left( \frac{4}{\pi} \right)^{\frac{m}{2}} \cdot P_r \cdot w.d \right]}{(2 - 0.4 \sin \theta)^m \times (\sin \theta + \cos \theta \cdot \tan \delta h)} \quad \ldots \quad (11)
\]
Indian Standard

CRITERIA FOR DESIGN OF STEEL BINS FOR STORAGE OF BULK MATERIALS

PART III BINS DESIGNED FOR MASS FLOW AND FUNNEL FLOW

0. FOREWORD

0.1 This Indian Standard (Part III) was adopted by the Indian Standards Institution on 7 July 1980, after the draft finalized by the Structural Engineering Sectional Committee had been approved by the Structural and Metals Division Council and the Civil Engineering Division Council.

0.2 Bins are known as silos if they have circular or polygonal shape in plan. When square or rectangular in plan they are known as bunkers. In this standard, bin shall mean both silos and bunkers unless otherwise stated.

0.3 The functions of bins as storage structures are very important in power stations, fertilizer complexes, steel plants, cement plants and other similar industries for efficient storage and use of bulk material in both granular and powdery form. On the agricultural front bins are used to store food-grains for ensuring their supply throughout the year. Bulk storage of materials in bins has certain advantages over other forms of storage. An Indian Standard on this subject has, therefore, been a long felt need and this standard is aimed at giving the necessary guidance in the analysis and design of steel bins for storing various materials of different characteristics and flow properties.

0.4 Bins have been designed on the basis of Janssen’s Theory (with modifications to the original). From experimental investigations and a study of the performance of the existing bins, it has been noticed that the pressure distribution is influenced by the size and shape of the material to be stored (that is granular or powdery), moisture and temperature, bulk density, which, in turn, are affected by storage and flow characteristics. Besides, there is increase in the imposed loads during filling and emptying, the latter being more predominant.

0.5 For reasons mentioned above, in the bins designed by conventional methods, materials do not easily flow due to arching and piping. This
requires frequent poking — manually, pneumatically, with steam or by other mechanical means. With research data available, this problem has been successfully solved by adopting mass flow or funnel flow bins where the shape of the bin hopper and the size of the openings are based on the flow properties of the stored material.

0.6 In this part of the code the present thinking on the design of mass flow and funnel flow bunkers based on Jenike's work is explained. Further research in this field is continuing and it will not be possible to give a universal approach for all materials under varying service conditions. This standard has limitations which are explained in Appendix A with proper reference. It is, therefore, suggested that designers should consider all these aspects while adopting the recommendations given in this code.

0.7 In order to deal with the subject in an effective manner this standard has been prepared in three parts, namely,

Part I General requirements and assessment of loads.
Part II Design criteria.
Part III Bins designed for mass flow and funnel flow.

0.8 This standard keeps in view the practices being followed in India and elsewhere in the field. Assistance has also been derived from the following publications:

1. DIN 1055 (Sheet 6) Design loads for building bins, issued by Deutsche Normenausschuss.
3. Bins and bunker for handling bulk materials, Reisner, W., and Rothe, M E. Trane-Tech. Publication, Ohio, USA

0.9 Recommended literature for reference is given in Appendix B.

0.10 For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with
IS : 2-1960*. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

SECTION I  GENERAL

1. SCOPE

1.1 This standard (Part III) deals with the design of steel bins for storage of bulk materials ensuring satisfactory mass flow and funnel flow (plug flow) under gravity flow in the case of powdery and granular materials.

2. TERMINOLOGY

2.1 For the purpose of this standard, the definitions given in Parts I and II in addition to the following definitions shall apply.

2.1.1 Active Pressure Field — The field in which the major pressure is vertical or near vertical.

2.1.2 Arched Pressure Fields — In arched pressure fields major pressure lines arch across flow channels, synonymous with "passive pressure" in soil mechanics.

2.1.3 Charges — Deposition of bulk solid into a bin, usually by dropping in or blowing in from above.

2.1.4 Cylinder — Vertical part of a bin.

2.1.5 Draw — Withdrawal or feeding of bulk solids from a bin.

2.1.6 Flow Channel — Space through which a bulk solid is actually flowing during draw.

2.1.7 Flow Pressure — Pressure which the material exerts on the walls of a bin during flow.

2.1.8 Funnel or Plug Flow — The flow pattern in which the material flows primarily in the central region of the bin or hopper.

2.1.9 Initial Pressure — Pressure exerted by bulk solids on the walls of the bin during and after charging, but before any withdrawal of the material.

2.1.10 Mass Flow — Flow in which the entire mass of material flows without stagnation.

2.1.11 Passive Pressure Field — Field in which the major pressure is horizontal or near horizontal.

*Rules for rounding off numerical values (revised).
2.1.12 **Peaked Pressure Fields** — In peaked pressure fields major pressure lines from peaks at the centre of the bin, synonymous with "active pressure" in soil mechanics.

2.1.13 **Radial Pressure Field** — Field which occurs in the lower part of a hopper and in which pressures are proportional to the distance from the vertex of the hopper.

2.1.14 **Strain Energy** — The energy of a flowing mass of solid which could be recovered by a relaxation of boundary forces and displacements.

2.1.15 **Switch** — Region of change of an active pressure field towards a passive pressure field.

2.1.16 **Transition** — Joint between the cylinder wall and the conical flow channel in a funnel flow bin. In mass flow it is the joint between cylinder and hopper.

3. **NOTATIONS**

3.1 For the purpose of this standard the notations as given below shall apply:

- \( b_0 \) = Minor dimension of the outlet, m
- \( l_0 \) = Major dimension of the outlet or length of the opening (slot length), m
- \( d_0 \) = Diameter of the opening of hopper, m
- \( d \) = Diameter of a circular cylinder, that is, dia of vertical, portion of storage system, width of rectangular or square cylinder, m
- \( h \) = Height of the cylinder, m
- \( m \) = Coefficient, \( m = 0 \) for wedge hopper \( m = 1 \) for conical hopper
- \( r \) = Distance from the axis of symmetry, m
- \( w \) = Bulk density of the solid, kg/m\(^3\)
- \( A \) = Area of horizontal section of a cylinder, m\(^2\)
- \( B \) = Diameter of hopper, width of a hopper, m
- \( F \) = Unconfined yield force of bulk solid, kgf
- \( R \) = Hydraulic radius = \( A/U \)
- \( U \) = Perimeter of the cross-section of the stored material, m
- \( S \) = Shearing force, kgf
- \( J \) = Janssen's pressure line
- \( \zeta_i \) = Depth of the fill in the cylinder, m
- \( t_w \) = Frictional stress on the bin wall, kgf/m\(^2\)
- \( t_h \) = Frictional stress on the hopper wall, kgf/m\(^2\)
As

\[ A_0 = \text{Shear cell area (cross-sectional area of the test sample)}, \ m^2 \]

\[ R_i = \text{Radius of curvature at transition} \]

\[ f_i, f_{i+1} = \frac{V}{P} = \text{Flow factor of a channel (hopper)} \]

\[ V = \text{Major consolidating force, kgf} \]

\[ P = \text{Major force in a dome or a pipe (bulk material under flow), kgf} \]

\[ FF = \frac{V}{P} = \text{Flow function of bulk material} \]

\[ FF_o = \text{Instantaneous flow function of bulk solid} \]

\[ FF_t = \text{Time flow function of bulk solid stored for a period 't' before delivery starts} \]

\[ P_n = \text{Pressure normal to hopper or cylinder wall, kgf/m}^2 \]

\[ P_{nt} = \text{Initial pressure on a hopper wall at the vertex, kgf/m}^2 \]

\[ P_{nt} = \text{Peak pressure at the transition, kgf/m}^2 \]

\[ P_{ntt} = \text{Initial pressure on a hopper wall at the transition, kgf/m}^2 \]

\[ P_{ntt} = \text{Radial pressure on a hopper wall at the transition, kgf/m}^2 \]

\[ P_{t} = \text{Peak pressure at an effective transition, kgf/m}^2 \]

\[ P_{t} = \text{Non-dimensional vertical force acting within a bulk solid at the level of the transition due to radial stresses in the hopper} \]

\[ P_{w} = \text{Vertical force developed in cylinder walls due to wall friction, kgf} \]

\[ P_{w} = \text{Pressure normal to cylinder wall, kgf/m}^2 \]

\[ Q_{c} = \text{Total vertical force acting within the bulk solid at the level of transition due to stresses in the cylinder, kgf} \]

\[ EYL = \text{Effective yield locus of the flow of bulk solid} \]

\[ WYL = \text{Wall yield locus of the flow of bulk solids for a particular hopper wall} \]

\[ \theta = \text{Hopper slope measured from vertical, deg} \]

\[ \theta_c = \text{Conical hopper slope measured from vertical, deg} \]

\[ \theta_p = \text{Plane flow hopper slope measured from vertical, deg} \]

\[ \theta' = \text{Slope of flow channel with respect to vertical, deg} \]

\[ H(\theta) = \text{A function depending on } \theta \]
IS 9178 (Part III) - 1980

\( \phi \) = Kinematic angle of internal friction of bulk solid, deg
\[ G(\phi) \] = A function depending upon \( \phi \)
\( \delta \) = Effective angle of wall friction of bulk solid on the walls of the bin, deg
\( \delta' \) = Kinematic angle of wall friction between bulk solid and wall of bin, deg
\( \delta_h \) = Angle of friction between bulk solid and hopper wall, deg
\[ G(\delta') \] = A function depending on \( \delta' \)
\( \mu \) = Coefficient of friction between the bulk solid and the cylinder wall
\( \lambda \) = Pressure ratio, that is, horizontal to vertical pressure
\( \sigma \) = Pressure, kgs/m².

4. DESIGN CONSIDERATIONS

4.1 In the design of bins for bulk storage, the two important considerations involved are:

a) flow characteristics, and
b) load distribution characteristics of the stored material.

4.1.1 The flow characteristics determine the slope of the hopper portion of the bin and the outlet dimensions which indirectly lead to the selection of shape and size of the bin. These are dealt with in detail in Section 2 and Section 3 of the code for mass flow and funnel flow respectively.

4.1.2 Load distribution characteristics give the actual loading condition on the walls of the bin and at the outlet. These govern the structural design of the bin as well as the selection of the feeder system to be incorporated at the outlet. This has been dealt with in detail in Section 4 of the code.

SECTION 2 DESIGN FOR MASS FLOW

5. GENERAL

5.1 In mass flow, the contents of the hopper move at all points and sliding takes place at the walls whenever any solid is drawn through the outlet of the bin. Inactive or dead regions are absent in the stored mass. Mass flow is a gravity flow without any flow promoting device.
5.2 Mass flow has the following characteristics which guide the selection of the design parameters:
   a) Channelling, hang-ups, surging and flooding are absent,
   b) Flow is uniform, and steady state flow can be achieved closely,
   c) Pressure throughout the mass and at the walls is relatively low, which results in low consolidation or packing,
   d) There are no dead regions within the bin; hence there is minimum of consolidation at rest.
   e) A first-in-first-out flow pattern may be obtained, if desired. This is useful in the storage of solids which either deteriorate with time or segregate during charging.
   f) By circulating a mixture around a suitable bin, blending may be attained.

5.3 Mass flow storage bins may be designed with a variety of hopper shapes listed below (see Fig. 1):
   a) Conical or pyramidal hoppers with circular or square outlet,
   b) Chisel hoppers with rectangular outlet or slot,
   c) Transition hopper with rectangular outlet,
   d) Wedge hopper with full slot or rectangular outlet.

5.4 This standard covers the various hopper shapes given in 5.3 under the following two distinct groups:
   a) Conical channel with square or circular outlet,
   b) Plane flow channel with rectangular or full slot outlet.

6. FACTORS INFLUENCING THE DESIGN

6.1 Flow Properties of Stored Bulk Solids — The flow properties of bulk solid stored in the bin is the principal factor affecting the design. These properties shall be determined under similar conditions of the bulk mass as it is stored in and delivered by the bin being designed. Factors affecting the flow properties are as follows:
   a) Particle size and shape,
   b) Bulk density and consolidation,
   c) Moisture content,
   d) Temperature,
   e) Surface finish of bin walls, and
   f) Period of storage.

   The flow properties shall be determined after considering these factors in the actual storage conditions. The flow properties thus
determined will help in determining the outlet size, the slope of hopper and the load distribution on the walls of the bin.

![Hopper Shapes for Mass Flow Bins](image)

**Fig. 1 Hopper Shapes for Mass Flow Bins**

**6.1.1 Slope of Hopper** — For a good design, the hopper slope angle shall be so selected (see 7.4) that the stored mass moves in a first-in-first-out fashion and each point of the mass moves when flow starts. The bin shall fully clear itself without any flow promoting device.
6.1.2 Outlet — For a satisfactory flow in a mass flow storage system, the outlet shall be large enough (see 7.5) so that plug flow, piping and doming do not occur and the flow continues without the aid of flow promoting devices.

6.2 Lump Size — The flow is also influenced by lump size with respect to a certain outlet size. For uninterrupted flow, the outlet shall be designed for an optimum lump size. Normally, the lumps are free flowing and are suitable for mass flow.

7. DESIGN PROCEDURE

7.1 Design procedure involves the following stages:
   a) Collection of information about the stored bulk solids and the wall material of the bin,
   b) Determination of the flow properties of the bulk material to be stored,
   c) Estimation of the hopper slope \( \theta \),
   d) Estimation of the size of outlet.

7.2 Collection of Information About the Stored Bulk Solids and the Wall Material of the Bin

7.2.1 The size, unpacked bulk density (aerated bulk density) and the lump size (if lumps are present) of the powdered and granular solid shall be determined.

7.2.2 The condition of the bulk solid to be stored shall be conformed. This requires information about the moisture content and temperature of the bulk material of actual service and the time period for which the bulk material is stored at rest in the bin.

7.2.3 The wall material and its surface condition (finish, lining finish) shall be determined or the information shall be obtained from the prescribed specifications of the bin.

7.3 Determination of the Flow Properties of Bulk Material

7.3.1 The bulk material shall be tested on a shear tester (flow factor tester) to obtain \( \phi \) distribution curve with respect to major consolidating force \( V \) and flow function \( FF \). The test shall be done with the sample of bulk material representing the actual material to be stored (size, moisture content, time period, temperature, etc, shall be similar). The \( \phi \) distribution with respect to various consolidation and wall yield loci (WYL) shall be determined (see Appendix C).

7.3.2 The values of shear cell area \( A_s \), mean values of \( \theta \) and \( \theta' \) at the outlet conditions shall be determined from the flow property data. \( \theta' \) shall be estimated from WYL (see Fig. C-3 of Appendix C).
7.4 Estimation of Hopper Slope Angle $\theta$

7.4.1 Flow factor ($f$) corresponding to the assumed $\delta$ and $\delta'$ values at outlet shall be estimated from the $f$ contours for conical and plane flow channel (see Fig. C-13 to C-15 of Appendix C). The $f$ values should be so selected that the point ($\delta$, $\theta$) is very close to the extreme boundary.

7.4.2 $\theta_0$ shall be selected from Fig. C-8 of Appendix C such that the point ($0_e$, $\delta'$) lies 5° within the boundary of the selected $f$ for the case of conical flow.

7.4.3 In the case of plane flow channels, $\theta_0$ shall be selected very close to the left of the dotted extreme boundary. In the case of a smooth transition zone (transition from vertical portion of storage equipment to the hopper) with a radius of curvature $R_t \geq d/3$, $\theta_0$ may be increased by 5° from the optimum value selected earlier.

7.5 Estimation of Outlet Size

7.5.1 The estimated flow factor $f$ (see 7.4.1) shall now be plotted against flow function $FF$ of the bulk solid $FF$ is a plot of $V$ and $F$ with $V$ as abscissa and $F$ as ordinate, whereas $f$ is the plot of $V$ and $F$ with $V$ as ordinate, scale of $V$ and $F$ being same for the plot.

7.5.2 $H(\theta)$ corresponding to the estimated $\theta$ for the selected shape of outlet is determined from Fig. C-12 of Appendix C.

7.5.3 If there is no intersection of $f$ with $FF$, and $FF$ lies below $f$, it shows that the material stored is free flowing and any dimension of outlet based on the rate of discharge and lump size shall be sufficient. An outlet size $b_0 = 6 \times (\text{maximum lump size})$ or the size based on discharge whichever is greater shall be selected. The following relation yields the value of $V$ at the outlet condition:

$$V = \frac{b_0 w A_y}{H(\theta)}$$

When $P$ so determined is located on $f$ line, $V$ at the outlet is also obtained.

7.5.4 If $FF$ lies above $f$, it means that the solid will not flow in a channel with flow factor assumed. If lower values of $f$ are available and if an intersection can be obtained, the new flow factor $f$ shall be selected. Based on this modified $f$, the intersection point ($V$, $P$) is noted.

7.5.5 If there is an intersection of $f$ with $FF$, it shows that the bin of a particular slope and outlet size can be designed for mass flow. The intersection point ($V$, $P$) is noted.
7.5.6 After plotting \( f \) over \( F F_0 \) and \( F F \), if it is found that the \( f \) line lies between \( F F_0 \) and \( F F_t \), that is, \( f \) is above \( F F_0 \) but below \( F F_t \), the stored material shows a tendency of consolidation with time. In these cases, vibrators are specified, so that the flow may be started, and the outlet is designed with a factor of safety to allow for any unfavourable effect of vibration. This shall be accomplished by so selecting \( \bar{V} \) that at outlet \( \bar{V} = 1.5 \bar{F} \).

7.5.7 From 7.5.3 to 7.5.6 according to the case faced in design \( \bar{V} \) shall be selected and \( H ( \theta ) \) shall be revalued from Fig. C-12 of Appendix C if any modification in \( \theta \) has been done during the location of \( ( V, \bar{V} ) \).

7.5.8 Minimum outlet dimensions, \( b_0 \) shall be calculated from the following formula:

\[
b_0 = \frac{-F, H ( \theta )}{L_s \omega}
\]

7.6 Check for Estimated Design Data

7.6.1 Corresponding to the \( V \) value obtained under 7.5.3 to 7.5.6, \( \delta \) shall be read from plot \( \delta \) and \( V \). This value of \( \delta \) will determine the \( EYL \) of the stored mass at outlet conditions.

7.6.2 The Mohr's semicircle shall be drawn through \( ( V, \theta ) \) such that it shall be tangential to \( EYL \). The \( WYL \) shall then be drawn over this Mohr's semicircle. The point of intersection shall determine \( \delta' \) at outlet. This should check with the estimated \( \delta' \).

7.6.3 If the estimated \( \delta' \) does not tally with the check value of \( \delta' \), a further estimation of \( f \) and \( \delta' \) shall be done, so that the check value of \( \delta' \) is closely reached.

7.7 Recalculation for Slope of Hopper and Outlet Size on Basis of Corrected Data

7.7.1 The corrected values of \( f \), \( \delta \) and \( \delta' \) shall be noted and the corresponding \( \theta \) (hopper slope) shall be obtained from Fig C-13 to C-15 of Appendix C. \( H ( \theta ) \) shall be obtained from Fig C-12 of Appendix C. \( V \) is obtained in the manner shown under 7.5.3 to 7.5.6. The outlet size \( b_0 \) shall then be obtained according to 7.5.3.

7.7.2 A check is done once again to ascertain the recalculated values in a similar way as shown in 7.6.1, 7.6.2 and 7.6.3.

7.7.3 The check and recalculation shall be continued until corrected and check values of \( \delta' \) are equal.
7.8 Adopted Values of Outlet Size and Slope of Hopper for Design

7.8.1 The hopper slope angle shall be equal to or less than the calculated values. It shall not exceed the calculated value in any case.

7.8.2 In the case of conical hoppers or steep pyramidal hoppers, the outlet shall be circular or square. The diameter of the circular outlet or the side of the square outlet shall not be less than the calculated minimum dimension $b_o$.

7.8.3 In the case of plane flow hopper, the outlet shall be rectangular or full slot. In the case of rectangular opening, the small side shall not be less than $b_o$. In case the stored solid contains lumps, the smaller side shall be at least four times (preferably six times) the maximum lump size. The greater side of the rectangular outlet shall not be less than three times the smaller side. In the case of full slot opening, the width of opening shall be greater than the calculated $b_o$. For lumpy stored solid, it shall always be more than four times (preferably six times) the maximum lump size. The length of slot shall be at least six times the width of slot ($l_o \geq 6b_o$).

7.8.4 A recommended calculation sheet is given in Appendix D for the design of bins for mass flow, including determination of outlet size and slope of hopper.

SECTION 3 DESIGN FOR FUNNEL OR PLUG FLOW

8. GENERAL

8.1 In funnel flow (plug flow), the bulk solid flows towards the outlet of the bin in a channel formed within the mass, while the mass around the channel remains stationary (see Fig. 2). It is a gravity flow without any flow promoting devices.

8.2 Funnel flow bins are used for storage when segregation is unimportant and there is no problem of deterioration with time of the stored material. Since there is little wear in the hopper walls during service, this storage system is useful for the storage of hard, abrasive and lumpy solids.

8.3 Funnel flow bins (Fig. 3) may be classified in the following types:

a) Flat, bottom bins without hopper,

b) Bins with conical hopper, or

c) Bins with pyramidal hopper.

8.4 The shape of the outlet may be circular, square or rectangular.
**Fig. 2** Plug Flow

**Fig. 3** Plug Flow Bins

(a) Flat Bottom  
(b) Conical  
(c) Pyramidal
9. FACTORS INFLUENCING DESIGN

9.1 Flow Properties of Stored Bulk Solid — The flow properties of bulk solids stored in the bin is the principal factor affecting the design. These properties shall be determined under similar conditions of the bulk mass as it is stored in and delivered by the bin being designed. The factors affecting the flow properties are as follows:

   a) Particle size and shape,
   b) Bulk density and consolidation,
   c) Moisture content,
   d) Temperature,
   e) Surface finish of bin walls,
   f) Time period of storage.

The flow properties thus determined will help in arriving at the outlet size, the slope of hopper and the load distribution on the walls of the bin.

9.1.1 Outlet — For a satisfactory flow in funnel flow bins, the outlet shall be large enough so that piping and doming do not occur and the flow continues without any flow promoting device.

9.1.2 Slope of Hopper — The hopper slope shall be so selected that the moving channel of the mass attains a maximum possible size and there is no possibility of piping and doming.

9.2 Lump Size — The flow is also influenced by lump size with respect to a certain outlet size. For uninterrupted flow, the outlet shall be designed for an optimum lump size.

10. DESIGN PROCEDURE

10.1 Collection of Information about the Stored Bulk Material and Wall Material of the Bin

10.1.1 The size, aerated bulk density and packed bulk density of the powdered and granular solid shall be determined. The lump size (if lumps are present) shall also be determined.

10.1.2 The condition of the bulk solid to be stored shall be confirmed. This requires information about the moisture content and temperature of the bulk material at actual service and the time period for which the bulk material is stored at rest in the bin.

10.1.3 The bin wall material and its surface condition (finish, lining finish) shall be determined or the information shall be obtained from the specification sheet of the bin.
10.2 Determination of the Flow Properties of Bulk Material

10.2.1 The bulk material shall be tested on a shear tester (flow factor tester) to obtain \( \delta \) distribution curve with respect to major consolidating force, \( V \), and flow function \( FF \). These tests shall be conducted with the sample of bulk material representing the actual material to be stored (size, moisture content, time period, temperature, etc., shall be similar). The \( \phi \) distribution with respect to various consolidation shall also be determined (see Appendix C).

10.2.2 The values for shear cell area \( A_s \), mean values of \( \delta \) and \( \phi \) shall be determined from the flow property data.

10.3 Determination of Hopper Slope Angle \( \phi \)

10.3.1 Flow factor \( \tilde{f} \) corresponding to the average \( \delta \) and \( \phi \) shall be fixed with reference to Fig. C-9 of Appendix C. The value of \( \tilde{f} \) shall not be less than 17.

10.3.2 Referring to Fig C-10, the hopper slope may be fixed corresponding to the average \( \delta \) and the \( \tilde{f} \) obtained under 10.3.1. The maximum \( \theta \) values for conical and plane flow channels shown in Fig. C-10 of Appendix C shall not be exceeded if doming is to be avoided.

10.3.3 In the case of plane flow (rectangular outlet) hoppers, the slope \( \theta_p \) shall always be more than 30°, if \( \delta \) is greater than 40°, which represents the majority of bulk solids. In the case of pyramidal hoppers, the slope angle refers to the valley angle.

10.3.4 The conical channels for plug flow are usually very steep and this leads to the adoption of flat bottom bins in place of a conical channel.

10.4 Determination of Outlet Size

10.4.1 The flow factor \( \tilde{f} \) determined as per 10.3.1 is plotted against the flow function \( FF \) of the bulk material. \( FF \) is a plot of \( V \) and \( F \) with \( V \) as abscissa and \( F \) as ordinate, whereas \( \tilde{f} \) is the plot of \( V \) and \( \tilde{V} \) with \( \tilde{V} \) as ordinate, scale of \( V \) and \( F \) being the same. The intersection of \( \tilde{f} \) with \( FF \) yields a point \( (V, \tilde{V}) \).

10.4.2 Functions \( G(\phi) \) and \( H(\theta) \) are evaluated from Fig. C-11 and Fig. C-12 respectively of Appendix C.

10.4.3 If the outlet shape selected for design is square or circular, the major dimension of the outlet will represent the side of square or diameter of circular opening. The major dimension, \( l_0 \) for rectangular or \( d_0 \) for circular opening shall be calculated by the following formula:

\[
l_0 \text{ or } d_0 = \frac{\tilde{V} G(\phi)}{A_8 . \omega}
\]

17
10.4.4 If the outlet is rectangular in shape, the minor dimension $b_o$ of the outlet (apart from the major dimension $l_o$) shall be obtained to avoid any doming. $b_o$ is calculated by the following relation:

$$b_o = \frac{\sqrt{H(\theta)} \cdot w}{A_s}$$

10.4.5 The dimension of the rectangular outlet is given by $b_o \times l_o$. The dimension $l_o$ shall be so adopted that is always greater than three times $b_o$.

10.5 Adopted Values of Outlet Size and Slope of Hopper

10.5.1 Adopted values for the outlet dimensions shall be larger than the calculated values to accommodate the uninterrupted flow of lumps also. The dimension of outlet shall be at least six times the diameter of the size of lump being handled.

10.5.2 Adopted slope of the hopper shall be equal to or smaller than the calculated value. It shall not exceed the calculated value in any case.

10.6 A recommended calculation sheet is given in Appendix E for the design of bin for funnel flow.

SECTION 4 LOAD DISTRIBUTION FOR DESIGN OF BULK STORAGE BINS

11. INITIAL AND FLOW PRESSURES

11.1 The method of calculation is based on the principle of minimum recoverable strain energy (For full details of the concept and pressure distribution, reference may be made to the papers 'Bin Loads Part II concepts; Part III — Mass flow bins and Part IV — Funnel flow bins' by A. W. Jenike, J. R. Johanson and J. W. Carson, published in the Journal of Engineering for Industry of ASME, February 1978). There are certain limitations of this theory as pointed out by different research workers which are outlined in Appendix A. The procedure for determining pressure distribution as given in this section may be adopted subject to these limitations. The loads which act on the bin walls are different during the initial stage of charge into a bin and during the flow stage from a bin, because the deformations which the stored materials undergo during these two stages are different. In the initial stage when the bulk material is charged into an empty bin with the discharge gate closed or the feeder at rest, the bulk material settles down as the head of bulk material rises. During this process, the material contracts vertically in the cylinder as also in the hopper. The major pressure tends to align with the direction of contraction of the bulk material. Hence, these initial pressures are close to vertical throughout the bin thus forming a "peaked" pressure field.
This initial pressure corresponds to load calculated by Janssen's method in the cylindrical part of the bin and by a linear distribution in the hopper. This assumes that the bulk materials are not charged with significant impact and the bulk storage materials in powder form are charged at sufficiently low rate so that they deaerate. If granular bulk materials are to be dropped from some height the bins have to be designed with safety for impact and wear in impact areas. Powdery material when charged at high rate may develop close liquid pressures on the walls. Also, it should be ensured that the storage materials are sufficiently free flowing without obstruction; otherwise, stable arches of the stored materials may form. When this arch collapses, a large amount of bulk material falls and induces dynamic loads in the bin.

11.2 When the gate is open or the feeder is started, the stored material starts flowing out to the outlet, and in this case, a vertical expansion of solid takes place within the flow channel. The minor pressures may tend to align with the direction of expansion of the stored material. As a rule, the flow channel diverges upwards from the outlet. Hence, the flowing mass of stored material also contracts laterally. The major pressures within the flow channels tend to align with the lateral contractions. Hence, major pressures are essentially lateral, minor ones are vertical and the pressure field is arched.

11.3 The region of switch from peaked to arched fields originates at the outlet of the bin when the gate is first opened or the feeder is started and rapidly travels upwards into the bin as the stored material is withdrawn from the bin. At the level of the switch, the equilibrium of the mass imposes a sharp overpressure on the walls of the flow channels. This overpressure travels upward with the switch at least to the level at which the channel intersects the cylindrical part of the bin to the level of the transition in mass flow bins and effective transmission in the case of funnel flow bins. In a cylinder, above a transition, experimental data indicate wide oscillation of low pressure with time and this along with the peaks need be predicted. This has been analysed as a strain energy, based on the second law of thermodynamics and the pressure distributions for the mass and funnel flow bins are worked out.

11.4 The procedure for load distributions suggested in this code may be applied to bins designed for mass and funnel flow.

12. PROCEDURE FOR CALCULATION OF LOAD DISTRIBUTION IN MASS FLOW BINS

12.1 Initial Pressure

12.1.1 Cylinder — Initial pressure \( P_h \) on the walls of cylinder is:

\[
P_h = \frac{w R}{\mu} \left[ 1 - e^{-\frac{\mu \lambda Z_1}{R}} \right]
\]
and the hydraulic radius \( R = \frac{d}{2(1 + \frac{m}{2})} \) ... (2)

where

\( m = 1 \) for circular bin,  
\( m = 0 \) for long rectangular or square cylinder, and  
\( \lambda = 0.4 \).

In the cylinder, the frictional stress \( t_w \) is related to normal pressure \( P_h \) by

\[ t_w = \mu P_h \] ... (3)

12.1.2 Hopper — The surcharge, due to the stored material in the cylinder, exerts a vertical load \( Q_o \) (see Fig. 4) on the stored material of the hopper. This force becomes maximum when the cylinder wall pressure is minimum (Janssen's distribution). This is given by

\[ \frac{Q_o}{A} = \frac{wR}{\mu \lambda} \left[ 1 + c \left( \frac{-\mu \lambda h}{R} \right) \right] \] ... (4)

Values of \( \frac{Q_o/A}{wR} \) are plotted in Fig. 5.

The initial pressures perpendicular to the hopper wall are assumed to vary linearly from the apex to the transition, as shown in Fig. 4. The value at the apex, \( P_{n1} \) is given by

\[ P_{n1} = \frac{w.d}{2(\tan \theta + \tan \delta_h)} \] ... (5)

The initial pressure at the transition, \( P_{n1} \), is given by

\[ P_{n1} = \frac{Q_o}{A} \left( \frac{2 + m}{1 + m} \right) \cdot \frac{\tan \theta}{\tan \theta + \tan \delta_h} \] ... (6)

The parameter \( m \) is 0 for long edged shape hopper and 1 for conical hopper.

The frictional stress \( t_h \) is related to normal pressure \( P_n \) by

\[ t_h = P_n \tan \delta_h \] ... (7)
FIG. 4 INITIAL Pressures in a CONICAL HOPPER
12.2 Flow Pressures

12.2.1 Cylinder — The pressures exerted by a mass of stored material in a cylindrical vessel are governed by

- Slight deviation in shape of the vessel from cylindrical, and
- thin stable or unstable boundary layers of solid which forms at the wall of the cylinder.

As a result, only bounds on wall pressures can be established. Janssen's formula nearly gives the lower bound and the upper bound is calculated by the consideration of strain energy of the mass of stored material.

An example of the loci of maximum cylinder pressure computed from strain energy and modified for the hopper effect is plotted in non-dimensional form \( \frac{P_{h/wd}}{wR} \) in Fig. 6. These pressures are a function of the distance from the top of cylinder and the product \( \mu \lambda \), Janssen pressures are also plotted as a reference.
The vertical force $P_w$ caused by the frictional stress $\tau_w$ and Pressure $P_h$ is computed from

$$\frac{P_w}{\pi d} = \left[ \frac{P_w}{(w d^2)} \right]_{\text{max}} \times \frac{wd^2}{\pi} \quad \ldots \quad (8)$$

Typical results in non-dimensional form $\left( \frac{P_w}{wd^2} \right)_{\text{max}}$ are represented in Fig. 7 for circular cylinders.
FIG. 7 (a) $(P_{w/nd^2})_{max}$ FOR CIRCULAR CYLINDERS $h/d = 3$

FIG. 7 (b) $(P_{w/nd^2})_{max}$ FOR CIRCULAR CYLINDERS $h/d = 5$
12.2.2 Hopper — Flow pressure variation in a mass flow hopper consists of a pressure peak at the transition, then a linear decrease to an intermediate value and another linear decrease to zero at the apex (see Fig. 8).

![Diagram of flow pressure in a conical hopper]

**Fig. 8 Flow Pressure in a Conical Hopper**

12.2.2.1 The radial pressure component at the transition $P_{ntr}$ is given by

$$P_{ntr} = \left( \frac{\sigma}{wB} \right) \cdot w.d.$$  \hspace{1cm} (9)

Typical plots of $\left( \frac{\sigma}{wB} \right)$ as a function of $\theta$ and $8h$ are given in Fig. 9 and Fig. 10 for conical channels and symmetric plane flow channels respectively.
\[ \frac{\sigma}{wB} \] Contours for Conical Channels, \( \delta = 30^\circ \)

\[ \frac{\sigma}{wB} \] Contours for Conical Channels, \( \delta = 40^\circ \)
Fig. 9(c) $\frac{\sigma}{w_B}$ Contours for Conical Channels, $\beta = 50^\circ$

Fig. 9(d) $\frac{\sigma}{w_B}$ Contours for Conical Channels, $\beta = 60^\circ$
Fig. 9(e) $\frac{\sigma}{w_B}$ Contours for Conical Channels, $\delta = 70^\circ$

Fig. 10(a) $\frac{\sigma}{w_B}$ Contours for Symmetric Plane Flow Channels, $\delta = 30^\circ$
Fig. 10(b) $\frac{\sigma}{w_B}$ Contours for Symmetric Plane Flow Channel, $\delta = 40^\circ$

Fig. 10(c) $\frac{\sigma}{w_B}$ Contours for Symmetric Plane Flow Channel, $\delta = 50^\circ$
Fig. 10(d) $\frac{\sigma}{wB}$ Contours for Symmetric Plane Flow Channel, $\delta = 60^\circ$
The peak pressure $P_{nt}$ can be calculated from

$$P_{nt} = P_{nt} + \frac{3}{3} \left[ \left( \frac{Q_e}{A} - \frac{4}{\pi} \right)^m \right] \cdot \frac{P_{T \cdot w.d.}}{2 - 0.4 \sin \theta} m \left( \sin \theta + \cos \theta + \tan \delta h \right)$$  

... (10)
This equation is based on the overpressure at the transition being distributed over 0.3 d of the hopper wall. The value of \( \frac{Q_c}{A} \) is computed from Eq. (4). Typical plots of \( P_r \) contours are given in Fig. 11 and Fig. 12 for conical channels and symmetric plane flow channels respectively.

**Fig. 11(a)** \( P_r \) Contours for Conical Channels, \( \delta = 30^\circ \)

**Fig. 11(b)** \( P_r \) Contours for Conical Channels, \( \delta = 40^\circ \)
Fig. 11(c) $P_r$ Contours for Conical Channels, $\delta = 50^\circ$

Fig. 12(a) $P_r$ Contours for Symmetric Plane-Flow Channels, $\delta = 30^\circ$
Fig. 12(b) $P_f$ Contours for Symmetric Plane-Flow Channels, $\delta = 40^\circ$

Fig. 12(c) $P_f$ Contours for Symmetric Plane-Flow Channels, $\delta = 50^\circ$
12.3 Appendix F may be referred to for a typical procedure for the application of the above-mentioned method for calculating load distribution in mass flow bins.

13. PROCEDURE FOR CALCULATING THE LOAD DISTRIBUTION IN FUNNEL FLOW BINS

13.1 In tall funnel flow bins, the flow pressures are larger than the initial Janssen's pressure. Hence, for design purposes flow pressures have to be used. Fig. 13 shows the general bin configuration and some of the useful variables.

![Figure 13: Funnel Flow Bin Pressures](image)

13.2 Cylinder — The loci of $(P_{h}/w/d)_{max}$, the maximum non-dimensional horizontal wall pressures exerted by a mass of stored materials on the walls of a vertical cylinder are drawn in Fig. 14 for different $h/d$ ratios with $\frac{z_1}{d}$ as y-axis. These pressures are a function of the height from the top of the cylinder and the product $\rho \lambda$. A value of 0.4 is taken for $\lambda$.

13.2.1 The equations on the basis of which the figures for different values of $h/d$ may be drawn are given in clauses 13.2.2 to 13.2.4.

Note — For a height to diameter ratio less than 2, it is suggested that Janssen's equation may be used, for the flow channel seldom intersects the cylinder wall.
Fig. 14(a) \((P_h/wd)_{\text{max}}\) for circular cylinders, \(h/d = 2\)

Fig. 14(b) \((P_h/wd)_{\text{max}}\) for circular cylinders, \(h/d = 3\)
FIG. 14(d) \( (P_{h/wd})_{\text{max}} \) FOR CIRCULAR CYLINDERS, \( h/d = 5 \)

FIG. 14(c) \( (P_{h/wd})_{\text{max}} \) FOR CIRCULAR CYLINDERS, \( h/d = 4 \)

FIG. 14(e)

\[ \mu \alpha = 0.02 \]
\[ \mu \alpha = 0.05 \]
\[ \mu \alpha = 0.10 \]
\[ \mu \alpha = 0.15 \]
\[ \mu \alpha = 0.20 \]

\[ \lambda \alpha = 0.02 \]
\[ \lambda \alpha = 0.06 \]
\[ \lambda \alpha = 0.10 \]
\[ \lambda \alpha = 0.15 \]
\[ \lambda \alpha = 0.20 \]

\[ A = 0.02 \]
\[ A = 0.06 \]
\[ A = 0.10 \]
\[ A = 0.15 \]
\[ A = 0.20 \]
13.2.2 Figure 15 shows the equilibrium at an effective transition.

Assuming that the ratio of horizontal to vertical pressure at an effective transition, $\lambda_1$, is equal to that ratio in the radial stress field, lower in the conical channel, the peak pressure at an effective transition is given by

$$P_t = \lambda_1 \frac{wR}{\mu \lambda_g} \left[ 1 - e^{-\mu \lambda_g \frac{Z_1}{R}} \right]$$

... (11)

**FIG. 15 EQUILIBRIUM AT AN EFFECTIVE TRANSITION**

13.2.3 Considering the radial stress field, $\lambda$ is to be determined as given in Eq. (12) after establishing

a) a relationship between $\sigma$ and $P_h$, assuming that the wall of the flow channel to be a velocity characteristic, and

b) a relationship between $\sigma$ and $P_r$:

$$\lambda = \frac{\{24 \tan \theta' + \pi P_r\} (1 - \sin \delta \cdot \tan \theta')}{16 \{ \sin \delta + \tan \theta' \}}$$

... (12)

Value of $P_r$ and $\theta'$ as function of $\delta$ can be determined. By taking $\lambda = \lambda_1$, $P_t$ can be calculated from Eq. (11).
13.2.4 Frictional stresses accompany $P_h$ and are computed from the following:

$$t_w = \mu P_h$$

These stresses cause vertical force $P_w$ in the walls and are the same as those worked out for mass flow bins. The vertical force per unit length is calculated from the equation:

$$\frac{P_w}{\pi d} = \frac{(P_w)}{(wd^3)_{\text{max}}} \cdot \frac{wd^3}{\pi} \quad \text{... (13)}$$

13.3 Hopper — The pressure field computed for the cylinder is assumed to extend into the hopper. The normal stress $P_n$ and shear stress $t_h$ on the hopper walls are computed from the equations:

$$P_n = P_h \left[ \left( \frac{\sin^2 \theta}{\lambda} + \cos^2 \theta \right) + \frac{2r}{d} \mu \left( 1 + \frac{1}{\lambda} \right) \sin \theta \cos \theta \right]$$

and

$$t_h = P_h \left[ \left( \frac{1}{\lambda} - 1 \right) \sin \theta \cos \theta + \frac{2r}{d} \mu \left( \cos^2 \theta - \frac{\sin^2 \theta}{\lambda} \right) \right] \quad \text{... (14)}$$

The variable $r$ is defined in Fig. 13.

For a flat bottomed bin, the above equations reduce to:

$$P_h = P_h/\lambda$$

$$t_h = \frac{-2r \mu P_h}{d \lambda} \quad \text{... (15)}$$

13.4 Reference may be made to Appendix G for a typical procedure for the application of the aforementioned method for calculating load distribution in funnel-flow bins.

APPENDIX A

(Clause 0.6)

LIMITATION OF JENIKE'S THEORY

A-1. Experimental evidence reveals overdesign of the critical outlet widths in mass flow hoppers when the standard Jenike's method is followed (1)*. This is due to the fact that Jenike does not account for the possibility that an arch across the outlet may slide along the wall (2) and for the fact that the arch in addition to its own weight will have to sustain the weight of the powder above.

*Number in parenthesis refer to the literature given in 0.8.
A-2. Arching just below the transition is frequently reported (3). This does not seem to cover that.

A-3. Actual stresses close to the transition zone between parallel part of the silo and the hopper section deviate strongly from those predicted by the radial theory (1).

A-4. It does not adequately allow for the impact loading which often occurs on filling and can easily cause arching (3). This is believed to be a major reason for the discontinuity of flow that commonly occurs in bunkers designed based on Jenike's method.

A-5. Jenike's shear cell which is the main tool in finding out the design parameters of the bulk materials used in this theory (which has been described in Appendix A of the draft code) could be used only in the case of samples with particles top size of only about 1-6 mm and is subjected to the following limitations (4).

A-5.1 The limited shear displacement available makes necessary a rather arbitrary and laborious preparation of the sample prior to the shear consolidation.

A-5.2 To obtain design data for hoppers with outlets less than about 1 metre across requires knowledge of material characteristics at major principal stresses of less than 70 kg/m². At the low normal loads required for this, lifting or pivoting of the cell lid, associated with non-uniform stress distribution becomes noticeable.

A-5.3 The tensile strength of material may be measured in the annular shear cell designed by Walker and Carr (5) instead of a split Jenike-type cell as recommended by Ashton, Farley and Valentin (6).

A-5.4 Professor Schwedes (7) points out that in the flow factor tester of Jenike, the state of stress cannot be determined completely and assumptions regarding the positions of slip planes are necessary to evaluate the test results.

A-6. Other research work has been in progress and the relevant references are included (8).

Conclusions: The theories presented by Walkar (9), Walkers (10-12) and Enstad (1) are meant to cover the limitations of Jenike's theory but they are approximate a fact also pointed out by the authors themselves.

Reference to the work done by Docksen (13) may be made for the precautions that have to be observed while designing the bins.
APPENDIX B

( Clause 0.9 )

RECOMMENDED LITERATURE FOR REFERENCE

1. Enstad

2. Molerus, O and Schoneborn, P. R.

3. Wright, H.

4. Walker, D. M.

5. Carr, J. F.
   and Walker, D. M.

6. Ashton, M. D.
   Farely, R. & Valentn
   F. H. H.

7. Schwedes, J.

8. Proposed, ACI Standard

9. Walker, D. M

10. Walters, J. K
APPENDIX C

PROCEDURE FOR TESTING OF FLOW PROPERTIES OF BULK SOLIDS

C-1. The tests for determination of flow properties are performed on the flow factor tester which consists of a shear cell with cover and arrangement for applying normal and shearing load on the sample packed in the shear cell. The normal load is applied through the hanger and weights and the shearing load is applied gradually by an advancing screw stem operated by an electric motor, causing a stem displacement of 0.9 mm/min. The shear load is measured by a proving ring placed between the screw stem and shear cell [see Fig. C-1 (a)].

The inside diameter of shear cell is 63 mm, and the height is 38 mm, which yields the shear cell area,

\[ A_s = 0.00312 \text{ m}^2 \]
Fig. C-1 Determination of the Flow Properties Using a Flow-Factor Tester
C-1.1 Shear cell which is the main tool in finding out the design parameters of the bulk materials used in this theory could be used only in the case of samples with particle top size of 1.6 mm.

C-2. Bulk density of the aerated bulk material is determined without any packing. Thereafter, the bulk densities of packed bulk solids shall be recorded as further tests proceed under various consolidating loads. Typical curves giving bulk density at different consolidating loads are given in Fig. C-2 for gypsum, triple superphosphate and pulverised coal. Similar curves should be drawn for the material to be stored.

C-3. The bulk solid to be tested is placed in the cell set-up shown in Fig. C-1 (b) for preconsolidation. One layer after another is packed up to the top of the mould and excess material is scraped off. The twisting top is placed over the packed solid. A normal load is applied on the top with the help of hanger and weights. A number of oscillating twists are applied to the top by means of a special wrench. This completes the preconsolidation.

C-4. The load applied for preconsolidation is removed and the twisting top and the mould is removed with precaution so that the base and ring of the shear cell are not disturbed. The excess material over the ring is scraped off with the top of ring. The test cover is placed over the material and the consolidation load is applied to the cover. The screw stem (shearing device) is advanced against the bracket so that the shear of the layer of material starts. The shear load attains a steady maximum value for a certain consolidation normal load. This completes the consolidation and shear yielding of the bulk solid. The values of normal loads and shear load are recorded.

C-5. The shearing of the material is done at various normal loads under the same consolidation. This is done by consolidating the test sample following the same procedure as under C-4 shearing until 95 percent of the maximum shearing force as obtained under C-4 is reached. At this point, the normal consolidation load is replaced by smaller normal loads for further shearing of the sample. The maximum steady shear force values thus obtained shall be recorded.

C-6. Yield locus shall be plotted by locating various normal load vs shear load values for a particular consolidation load. A number of suitable consolidation loads selected shall yield a family of yield loci. Mohr's circles, when drawn, yield major consolidating force $V$ and unconfined yield force, $F$. These plots shall also give kinematic angle of internal friction and effective angle of friction of the bulk solid.

C-7. Plots of Wall Yield Locus — The shear cell shall be arranged as shown in Fig. C-1 (c). The sample of wall material is placed as the base, representing the actual material and surface condition of the bin.
or hopper wall. The bulk material is placed inside the ring up to the top. The cover is placed and normal load is applied on the cover. The maximum steady shearing forces are recorded for various normal loads yielding the points on wall yield locus (WTL). A typical WTL for coal on structural steel is plotted in Fig C-3.

C-8. The charts and curves given in Fig. C-2 to C-15 are based on the tests explained in this appendix and they apply for typical bulk solids. They are given for information only. Such data should be worked out for each of the stored materials for which the bins are to be designed.

Note — To convert consolidating load to consolidating pressure (kgf/cm²) divide by 30.2.

FIG. C-2 CONSOLIDATING LOAD VERSUS BULK DENSITY CURVES FOR GYPSUM, TRIPLE SUPERPHOSPHATE AND PULVERISED COAL
Fig. C-3  Wall Yield Locus (Coal on Structural Steel)

Fig. C-4  Angle of Repose Versus Compressibility
(Packed Bulk Density — Aerated Bulk Density)

Packed Bulk Density

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Note — Similar charts for various other materials should be drawn.
Fig. C-5  Solid Flow Function FF and Hopper Flow Factor ff

Fig. C-6  Typical Yield Loci for Four Classes of Powder
HOPPER SLOPE ANGLE, $\theta$. DEGREES

Fig. C.8 Range of Conical and Flow Plane Flow

Fig. C.7 Range of Mass Flow and Funnel Flow in Conical Hoppers

15 : 9178 (Part III) - 1980

48
**Fig. C-9** \( f_w \)-Flow-Factor for No Piping
FIG. C-10  ff-Contours for Doming in Plug Flow
KINEMATIC ANGLE OF INTERNAL FRICTION OF BULK SOLID, $\phi$, DEGREES

**Fig. C-11** Function $G(\phi)$
Fig. C-12  Function $H(\theta)$

Fig. C-13(a)  Contours for Conical Channels, $\delta = 30^\circ$
Fig. C-13(b) Conours for Conical Channels, $\delta = 40^\circ$

Fig. C-13(c) Conours for Conical Channels, $\delta = 50^\circ$
Fig. C-13(d) *ff Contours for Conical Channels, δ=60°*
**Fig. C-13(c)** *ff Contours for Conical Channels, $\delta = 70^\circ$*

**Fig. C-14(a)** *ff Contours for Symmetric Plane-Flow Channels, $\delta = 30^\circ$*
Fig. C-14(b) *Contours for Symmetric Plain-Flow Channels, $\delta = 40^\circ$*
FIG. C-14(d)  *ff Contours for Symmetric Plane-Flow Channels, $\theta = 60^\circ$*
FIG. C-14(e) Contours for symmetric plane-flow channels, \( \theta = 70^\circ \)
Fig. C-15(a)  \textit{Contours for Asymmetric Plane-Flow Channels with One Vertical Wall, }\delta=50^\circ, \phi_v=20^\circ
Fig. C:15(b) Iso Contours for Asymmetric Plane-Flow Channels with One Vertical Wall, $\delta=50^\circ$, $\phi_v=30^\circ$
Fig. C.15(c) Contours for Asymmetric Plane-Flow Channels with One Vertical Wall, $B=50^\circ$, $\phi=10^\circ$. 

$\theta_p$, DEGREES

$\theta$, DEGREES
APPENDIX D
(Clause 7.8.4)

RECOMMENDED CALCULATION SHEET FOR DESIGN
OF BINS FOR MASS FLOW

D-1. DESIGN WITH CONICAL (SQUARE/CIRCULAR) OUTLET

a) Bulk Material
   i) Material:
   ii) Size:
   iii) Condition:
   iv) Average Bulk Density \( \rho \):

b) Hopper Wall
   i) Material:
   ii) Finish:

c) Flow Properties of Bulk Material
   i) Shear Cell Area, \( A_s \):
   ii) Estimated \( \delta \) at outlet:
   iii) Estimated \( \delta' \) at outlet:

d) Estimated Hopper Slope Angle \( \theta_0 \)
   i) Estimated \( \delta \):
      (Fig. C-13)
   ii) Estimated \( \theta_0 \):
      (Fig A-3, stay 5° within boundary)

e) Estimation of Outlet Dimensions:
   i) \( H (\theta_0) \):
      (Fig. C-12)
   ii) Estimated \( \delta \)

   ii) For no interaction of \( \delta \) with \( FF \):
       Case 1: \( FF \) lies below \( \delta \)
       (free flowing material)
       \[ b_o = \frac{\bar{V} \cdot H (\theta)}{A_s \cdot \rho} \]
       Case 2: \( FF \) lies below \( \delta \)
       Select lower \( \delta \) for an intersection if possible,
       Selected \( \delta \)

       \( \delta \) (correction if any):
       Intersection \( \delta \) with \( FF \) of
       stored material (\( V, \bar{P} \)):

   ii) For \( \delta \) lying between \( FF_0 \) and \( FF_c \):
       Select a point (\( V, \bar{P} \)) on
       \( \delta \) such that \( \bar{V} = 1.5 \ F \)
       (\( V, \bar{P} \)):
       (\( V, F \)):
       \[ \bar{P} = \text{Min outlet dimension} \]
       \[ H (\theta_0) = \quad b_o = \frac{\bar{V} \cdot H (\theta_0)}{A_s \cdot \rho} \]
f) Check

\( V = \) Corresponding \( \delta = \)

By drawing Mohr's semicircle through \( (V, \theta_c) \) and tangential to \( ETL \) and its intersection with \( WYL \).

\( \delta \) at outlet =

Corrected \( \delta = \)

Corrected \( \theta_c = \)

\( H (\theta_c) = \)

\( V = \)

Minimum outlet dimensions, \( b_0 = \frac{V . H (\theta_c)}{A_s \cdot w} \)

g) Adopted Values for Design

Hopper slope angle \( \theta_0 = \)

Outlet dimensions \( B_0 = \) Circular/Square

D.2. DESIGN WITH PLANE FLOW CHANNEL — Rectangular/full slot outlet

a) Bulk Material

i) Material:

ii) Size:

iii) Condition:

iv) Bulk density \( w \):

b) Hopper Wall

i) Material:

ii) Finish:

c) Flow Properties of Bulk Material

i) Shear cell area, \( A_s = \)

ii) Estimated \( \delta \) at outlet =

iii) Estimated \( \delta' \) at outlet =

d) Estimated Hopper Slope Angle \( \theta_p \)

i) Estimated \( \theta' \)

\( ( \text{Fig. C-14 or Fig. C-15} ) \)

ii) Estimated \( \theta_p = \)

\( ( \text{Fig. C-8} ) \)

e) Estimated outlet Dimensions

Estimated \( \theta' \)

i) \( H (\theta_p) = \)

ii) Estimated \( \theta' \)
Case 1: \( FF \) lies below \( \beta \) (Free flowing material)

\[
b_o = \frac{\bar{V} \cdot H(\theta)}{A_s \cdot w}
\]

Case 2: \( FF \) lies Select lower \( \beta \) above \( \beta \) for an intersection, if possible

\[
= \beta_1
\]

\( \beta \) (Correction, if any):

Intersection of \( \beta \) with \( FF \) of bulk material \( (V, \bar{V}) \) =

ii(b) For \( \beta \) lying between \( FF_o = \) and \( FF_t \)

Select a point \( (V, \bar{V}) \) on \( \beta \) such that \( \bar{V} = 1.5F \)

\[
(V, \bar{V}) =
(V, F) =
\bar{V} =
H(\theta_p) =
\] (Correction if any)

Min outlet dimension \( b_o = \frac{\bar{V} \cdot H(\theta)}{A_s \cdot w} \)

1) Check

\( V = \), Corresponding \( \delta = \)

By drawing Mohr's semicircle through \( (V, O) \) and tangential to \( EYL \) and its intersection with \( WYL \).

\( \delta' \) at outlet =
Corrected \( \delta = \), Corrected \( \delta' = \)
Corrected \( \beta = \), Corrected \( \theta_p = \)

\( H(\theta_p) = \bar{V} = \)

Minimum outlet dimensions, \( b_o = \frac{\bar{V} \cdot H(\theta_p)}{A_s \cdot w} \)

g) Adopted Values for Design

Hopper slope angle \( \theta_p = \)

Outlet dimensions = (Circular, Square)

( Rectangular \( i \gg 3b_o \), Full slot \( t_o \gg 6b_o \) )

64
APPENDIX E

( Clause 10.6 )

RECOMMENDED CALCULATION SHEET FOR THE DESIGN OF BINS AND HOPPERS FOR FUNNEL FLOW

a) Bulk Material
   i) Bulk size:
   ii) Average bulk density:
   iii) Lump size:
   iv) Condition:

b) Hopper Wall
   i) Material:
   ii) Finish:

c) Flow Properties of Bulk Material
   i) Shear Cell area, $A_{s}$
   ii) Average $\delta$ =
   iii) Average, $\phi$ =

d) Hopper Slope Angle, $\theta$
   i) Flow factor, $f_f$ =
      (see Fig. C-9 of Appendix C)
   ii) $\theta_b$ or $\theta_h$ =
      (see Fig. C-10 of Appendix C)

e) Outlet Dimensions
   i) $f_f$ =
   ii) Intersection of $f_f$ with flow function of bulk material
      $(V, V) =$
   iii) $V =$
   iv) $G(\phi)$ (see Fig. C-11 of Appendix C)
   v) $H(\theta)$ (see Fig. 12 of Appendix C)
      Major dimension of outlet, $d_o$
      $d_o$ or $l_o = \frac{V \cdot G(\phi)}{A_s \cdot w}$
      Minor dimension of outlet,
      $b_o = \frac{V \cdot H(\theta)}{A_s \cdot w}$
      Square outlet side, $b_o = l_o \sqrt{2}$
      Circular outlet Diameter, $d_o =$
      Rectangular outlet Smaller side, $b_o =$
Adopted outlet dimensions =
(Circular/square/rectangular)
(Minor dimensions $\geq 6 \times$ maximum lump size)
Adopted slope of hopper =
($\theta_0$ or $\theta_p$)

APPENDIX F
(Clause 12.3)

PROCEDURE FOR CALCULATING LOAD DISTRIBUTION
IN MASS FLOW BINS

Step 1 — Define the bin geometry and the flow properties of the stored material
\(d, h, \theta, m, \mu, \delta_m, \delta, \text{and } w\).

Step 2 — Calculate \(h/d\) and \(\mu \lambda\) (use \(\lambda = 0.4\))

Step 3 — Calculate initial and maximum cylinder wall pressure \(P_b\) and
friction stress \(t_w\) using Fig. 6 for \((P_b/\rho_d)_{\text{max}}\) and Eq. (3) for \(t_w\).

Step 4 — Calculate maximum vertical force \(P_w\) and force per unit
length of circumference developed in walls using Fig. 7 for
\((P_w/\rho_d^2)_{\text{max}}\) and Eq. (8)

Step 5 — Calculate \(R\) from Eq. (2)

Step 6 — Calculate average vertical pressure \(Q_c/A\) at transition from
Fig. 5.

Step 7 — Calculate initial pressure in hopper from Eq. (5), (6) and (7).

Step 8 — Calculate the radial component of pressure \(P_{mR}\) from Eq. (9)
and Fig. 9 or Fig. 10 as appropriate for \((a/\rho d^2)\).

Step 9 — Calculate peak pressure \(P_{mR}\) at the transition from Eq. (10) and
Fig. 11 or Fig. 12 as appropriate.

Step 10 — Calculate the slant height \(0.3 \cdot d\) over which the overpressure acts.
APPENDIX G
( Clause 134 )

PROCEDURE FOR CALCULATING LOAD DISTRIBUTION
IN FUNNEL FLOW BINS

Step 1 — Define the bin geometry and flow properties
h, d, m, δh, λ, θ, w, and μ

Step 2 — Calculate the maximum cylinder wall pressure \( P_b \) and friction
wall stress \( t_w \) using Fig. 14 for \( \frac{P_b}{wd} \) and Eq. (3).

Step 3 — Calculate the normal stress \( P_n \) and shear stress \( t_h \) for the hopper
wall by Eq. (14) or (15) as the case may be.

Step 4 — Calculate the maximum vertical force \( P_w \) and force per unit
length of circumference of the cylinder wall by Fig. 7 for mass
flow bins and Eq. (13).
INDIAN STANDARDS
ON
STRUCTURAL ENGINEERING

Structural Section

IS:

808-1964 Rolled steel beam channel and angle sections (revised)
808 (Part I) -1973 Dimensions for hot-rolled steel beams: Part I MB series (second revision)
811-1965 Cold formed light gauge structural steel sections (revised)
1252-1958 Rolled steel sections bulb angles
1730 (Part I) -1974 Dimensions for steel plate, sheet and strip for structural and general engineering purposes: Part I Plate (first revision)
1730 (Part II) -1974 Dimensions for steel plate, sheet and strip for structural and general engineering purposes: Part II Sheet (first revision)
1730 (Part III) -1974 Dimensions for steel plate, sheet and strip for structural and general engineering purposes: Part III Strip (first revision)
1852-1973 Rolling and cutting tolerances for hot-rolled steel products (second revision)
2713-1969 Tubular steel poles for overhead power lines (first revision)
3908-1966 Aluminium equal leg angles
3909-1966 Aluminium unequal leg angles
3921-1966 Aluminium channels
3954-1966 Hot rolled steel channel sections for general engineering purposes
5384-1969 Aluminium I beam
6445-1971 Aluminium tee sections

Codes of Practise

800-1962 Use of structural steel in general building construction (revised)
801-1975 Use of cold formed light gauge steel structural members in general building construction
802 (Part I) -1977 Use of structural steel in overhead transmission line towers: Part I Loads and permissible stresses (second revision)
803-1976 Design, fabrication and erection of vertical mild steel cylindrical welded oil storage tanks (first revision)
805-1968 Use of steel in gravity water tanks
806-1968 Use of steel tubes in general building construction (revised)
807-1976 Design, manufacture, erection and testing (structural portion) of cranes and hoists (first revision)
3177-1977 Electric overhead travelling cranes and gantry cranes other than steelworks cranes (first revision)
4000-1967 Assembly of structural joints using high tensile friction grip fasteners
4014 (Part I) -1967 Steel tubular scaffoldings: Part I Definitions and materials
4014 (Part II) -1967 Steel tubular scaffoldings: Part II Safety regulations for scaffolding
IS:

4137-1967  Heavy duty electric overhead travelling cranes including special service machines for use in steel works
6533-1971  Design and construction of steel chimneys
7205-1973  Safety code for erection of structural steelwork
8147-1976  Code of practice for use of aluminium alloys in structures
8640-1977  Recommendations for dimensional parameters for industrial buildings

General

804-1967  Rectangular pressed steel tanks (first revision)
7215-1974  Tolerances for fabrication of steel structures
8081-1976  Slotted sections

Handbooks for Structural Engineers

No. 1  Structural steel sections
No. 2  Steel beams and plate girders
No. 3  Steel columns and struts
No. 4  High tensile friction grip bolts
No. 5  Structural use of light gauge steel
No. 6  Application of plastic theory in design of steel structures
No. 7  Simple welded girders
# INTERNATIONAL SYSTEM OF UNITS (SI UNITS)

## Base Units

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<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Symbol</th>
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<tr>
<td>Length</td>
<td>metre</td>
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<tr>
<td>Mass</td>
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</tr>
<tr>
<td>Time</td>
<td>second</td>
<td>s</td>
</tr>
<tr>
<td>Electric current</td>
<td>ampere</td>
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<tr>
<td>Thermodynamic temperature</td>
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<tr>
<td>Luminous intensity</td>
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<td>cd</td>
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<tr>
<td>Amount of substance</td>
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## Supplementary Units

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<td>Solid angle</td>
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## Derived Units

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<td>Force</td>
<td>newton</td>
<td>N</td>
<td>1 N = 1 kg m/s²</td>
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<tr>
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<td>J</td>
<td>1 J = 1 N m</td>
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<tr>
<td>Power</td>
<td>watt</td>
<td>W</td>
<td>1 W = 1 J/s</td>
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<tr>
<td>Flux</td>
<td>weber</td>
<td>Wb</td>
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<td>tesla</td>
<td>T</td>
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<tr>
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<td>hertz</td>
<td>Hz</td>
<td>1 Hz = 1 c/s (s⁻¹)</td>
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<tr>
<td>Electric conductance</td>
<td>siemens</td>
<td>S</td>
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<tr>
<td>Electromotive force</td>
<td>volt</td>
<td>V</td>
<td>1 V = 1 W/A</td>
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<tr>
<td>Pressure, stress</td>
<td>pascal</td>
<td>Pa</td>
<td>1 Pa = 1 N/m²</td>
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