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Abstract

It has taken some time to obtain general acceptance but in recent times, at least in Australia, competent designers of mass-flow bins use techniques based on the traditional concepts of Jenike to determine the appropriate geometry for mass-flow hoppers to handle bulk solids reliably. While the traditional Jenike design concepts may appear straightforward experience dictates that some important considerations need to be exercised during the design process, especially when handling the more difficult bulk solids, to ensure that the final bin construction performs to expectations. Some of the important considerations that this paper will highlight include: • Appropriate bulk solids sampling for flow property testwork; • Interpreting flow property test results; • Applying flow property test results to determine appropriate hopper geometries; • Detail design issues; • Special requirements for particular circumstances (eg segregation, fine powders); • Design auditing.

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Determining the Geometry of Mass-Flow Bins Some Important Considerations

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It has taken some time to obtain general acceptance but in recent times, at least in Australia, competent designers of mass-flow bins use techniques based on the traditional concepts of Jenike to determine the appropriate geometry for mass-flow hoppers to handle bulk solids reliably.

While the traditional Jenike design concepts may appear straightforward experience dictates that some important considerations need to be exercised during the design process, especially when handling the more difficult bulk solids, to ensure that the final bin construction performs to expectations.

Some of the important considerations that this paper will highlight include:

- Appropriate bulk solids sampling for flow property testwork;
- Interpreting flow property test results;
- Applying flow property test results to determine appropriate hopper geometries;
- Detail design issues;
- Special requirements for particular circumstances (eg segregation, fine powders);
- Design auditing.

1. Introduction

It has taken some time to obtain general acceptance but in recent times, at least in Australia, competent designers of mass-flow bins use techniques based on the traditional concepts of Jenike to determine the appropriate geometry for mass-flow hoppers to handle bulk solids reliably.

While the traditional Jenike design concepts may appear straightforward experience dictates that some important considerations need to be exercised during the design process, especially when handling the more difficult bulk solids, to ensure that the final bin construction performs to expectations. This paper will explore some issues that may be relevant in ensuring that the bin design is practical and performs reliably.

2. Bulk Solids Characterisation

To design mass-flow bins for reliable flow with any degree of confidence to contain a bulk solid for which there is little or no prior experience, requires a reasonably well defined range of 'flow properties'. Generally the 'average' tabulated property values listed in codes and design guides (eg for belt conveyors) are usually of little value. Since the determination of flow properties is an experimental process it must be remembered that often such determinations are only as good as the sample on which they were made. What is desired is a test sample that reasonably represents conditions of worst handleability. It has to be conceded that in some instances obtaining reliable test samples is not possible and/or laboratories are not prepared to handle bulk solids that may, from an

OH & S point of view, be hazardous. Yet bulk solids handling plants are still being designed on the basis of very little reliable data on the flow properties of the bulk solid(s).

Assuming an appropriate sample of coarse cohesive bulk solid is available then when designing a mass-flow bin for the traditional range of flow properties determined via shear testing comprises:

(i) Flow functions FF for instantaneous and time storage conditions. These represent the strength versus consolidation occurring under storage and flow.
(ii) Effective angle of internal friction δ.
(iii) Wall friction angles ϕ for different bin wall materials and finishes.
(iv) Bulk density ρ as a function of consolidation.

Generally these parameters are summarised in graphical form as in Figs. 1 and 2

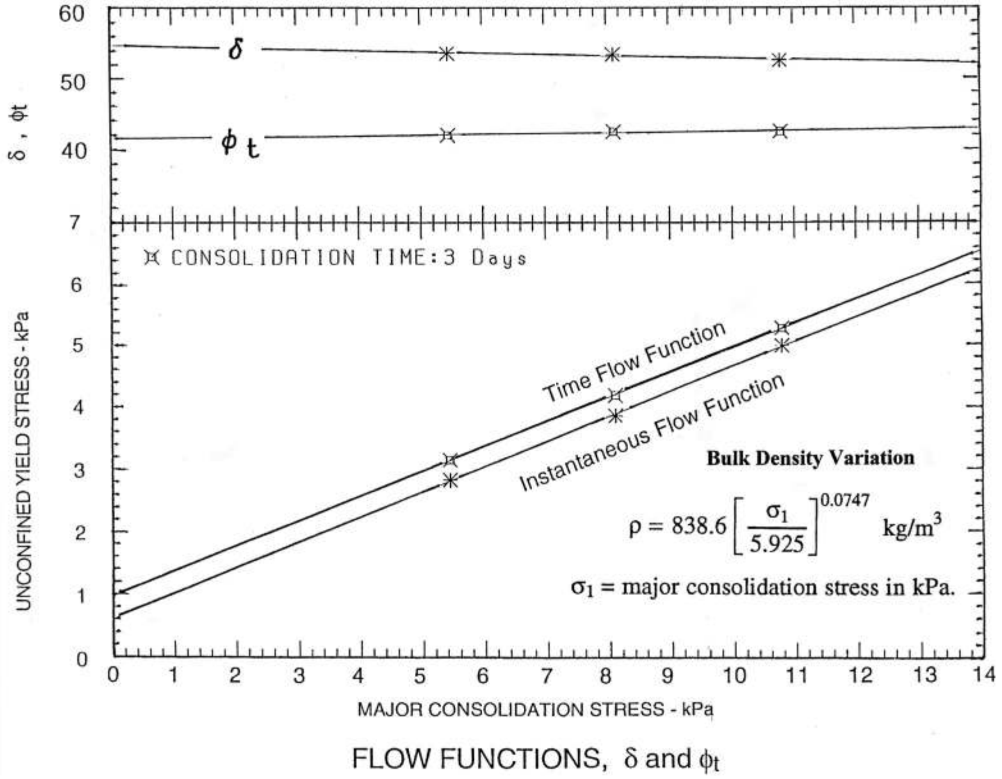


Fig 1 Traditional Flow Property Data in Graphical Form
(Flow Functions, Effective Angle (δ) and Static Angle (ϕ_t) of Internal Friction
plus Bulk Density Variation Represented by a Power Law)

Flow property testing can be both time consuming and expensive so frequently one should question whether this range of flow property testing should be always undertaken irrespective of the bulk solid(s) involved? For example, if the geometry of a mass-flow bin to replace an existing, but poorly performing, bin is all that is required then maybe only the variation, with major consolidation stress, of wall friction angles and bulk density are all that is required. In principle, these two measurements can be made without employing expensive and complicated shear testing machines.

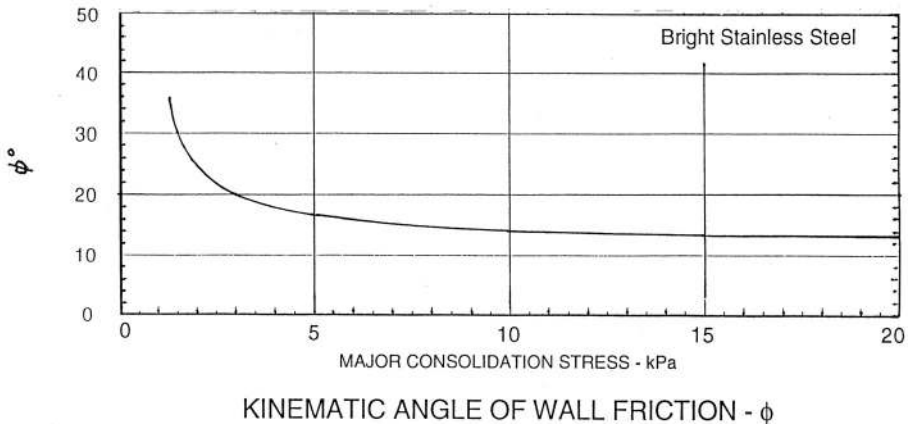


Fig 2 - Variation of Wall Friction Angle (ϕ) with Major Consolidation Stress (σ_1)

Wall friction and bulk density are all that is needed if a mass-flow bin is required for a bulk solid that is virtually free-flowing or simple (ie the flow functions pass through the origin in Figure 1). This is particularly the case if the effective wall friction angle is variable. In situations where the wall friction angle ϕ reduces significantly with major consolidating pressure σ_1, then there is often considerable advantage to be gained by knowing how the hopper half angle α varies with the hopper outlet dimension B (or with the hopper span).

3. Determining Appropriate Hopper Geometries

For the flow properties given in Figs. 1 and 2 the traditionally computed critical hopper geometry parameters for mass-flow using the Jenike procedure, Jenike [1], for instantaneous and time consolidation conditions and for a hopper with an internal surface of bright stainless steel are:

<u>Axisymmetric</u> (Conical)
Instantaneous $\alpha_c = 8.0°$ $B_c = 345$mm
Time $\alpha_c = 21.0°$ $B_c = 605$mm
<u>Plane Flow</u> (Wedge)
Instantaneous $\alpha_p = 17.0°$ $B_p = 175$mm
Time $\alpha_p = 30.0°$ $B_p = 280$mm

Taking the conical hopper as an example it is obvious that to design the hopper based on instantaneous conditions is not a practical solution.

However, in situations where the wall friction angle ϕ reduces significantly with major consolidating pressure σ_1, (ie as it does in Figure 2) then there is often considerable advantage to be gained by knowing how the hopper half angle α varies with the hopper outlet dimension B (or with the hopper span). For the set of flow properties shown in Fig. 1 and 2 plus the bulk density variation, the resulting α versus B graph for bright stainless steel is given in Fig. 3.

It will be noted that the traditional hopper geometry parameters listed above all lie on the α versus B curves as indicated in Fig. 3.

For time conditions an outlet diameter of at least 605 mm is required with a hopper angle α_c of 21.0°. While this is a feasible solution, maybe the bin is to be a train loading bin fitted with a 1400 mm square flood loading chute. From Fig. 3 it can be seen that for an outlet size of 1400 mm, α_c

may be increased to 28°. The saving in height compared with using the critical time value of α_C of 21.0° is 362 mm/meter of hopper span

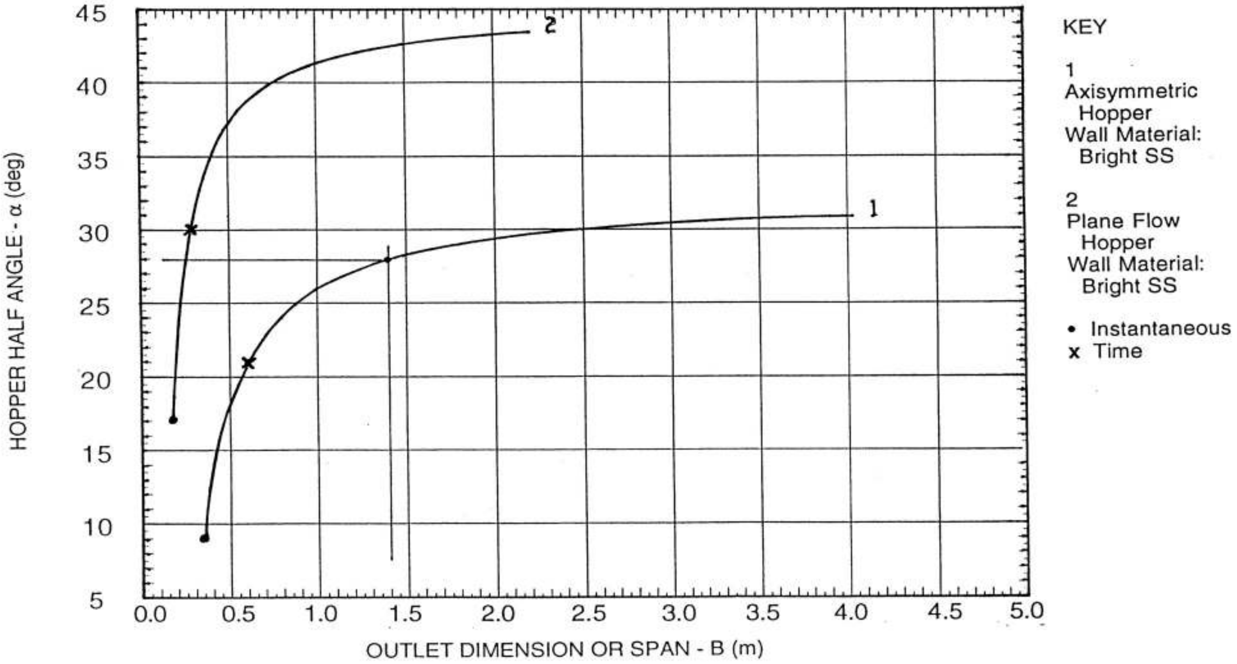


Fig 3 - Hopper Half Angle versus Hopper Outlet Dimension or Span

Particular care in using traditional flow functions needs to be exercised in situations where the flow functions (FF) are steep, Figure 4. This type of flow function indicates that the bulk solid gains considerable cohesive strength with relatively small increases in consolidation stress. It is noted that the flow factor (ff) intersects the FFs at a very acute angle suggesting that the resulting hopper arching dimensions are very sensitive to accuracy and should be given a significant safety margin. In many instances experience indicates that the critical cohesive arching dimensions calculated are too small to be adopted in the final design.

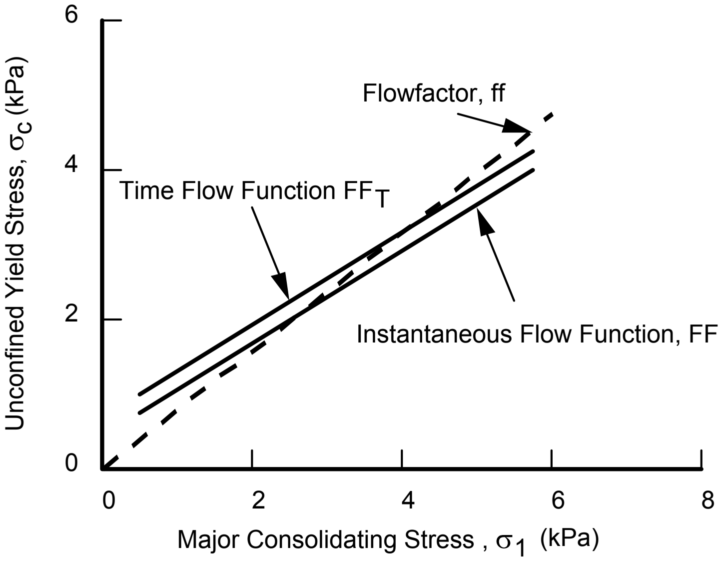


Fig 4 – Utilising Steep Flow Functions Requires Particular Care

Design problems can also arise with wall yield loci that do not pass through the origin but show a positive intercept on the shear stress axis. The resulting plot of wall friction angle versus major consolidation stress shows a marked increase in wall friction angle for small values of major consolidation stress as indicated in Figure 2. With particularly cohesive bulk solids on smooth wall materials this increase in wall friction angle can be rather extreme. Generally in such instances it is impossible to calculate hopper outlet dimensions based on cohesive arching and resorting to a hopper half angle versus outlet dimension plot such as shown in Figure 3 is needed to determine if a practical mass-flow hopper is possible for the bulk solid/wall material combination being considered. In such circumstances it is not surprising if simple conical mass-flow hoppers prove to be completely impractical especially if gravity alone is being relied upon for reliable discharge. Even a simple wedge hopper may have limited practical application.

Fortunately, considerable advances have also been made in the development of alternative mass-flow hopper arrangements beyond the traditional cones and wedges. Two of these advances are the cone-in-cone insert and the Diamondback Hopper.

Inserts inside bins have been described in the literature for more than 30 years [5-7]. The original conical insert has largely been superseded by the cone-in-cone insert or Binsert™, Fig 5.

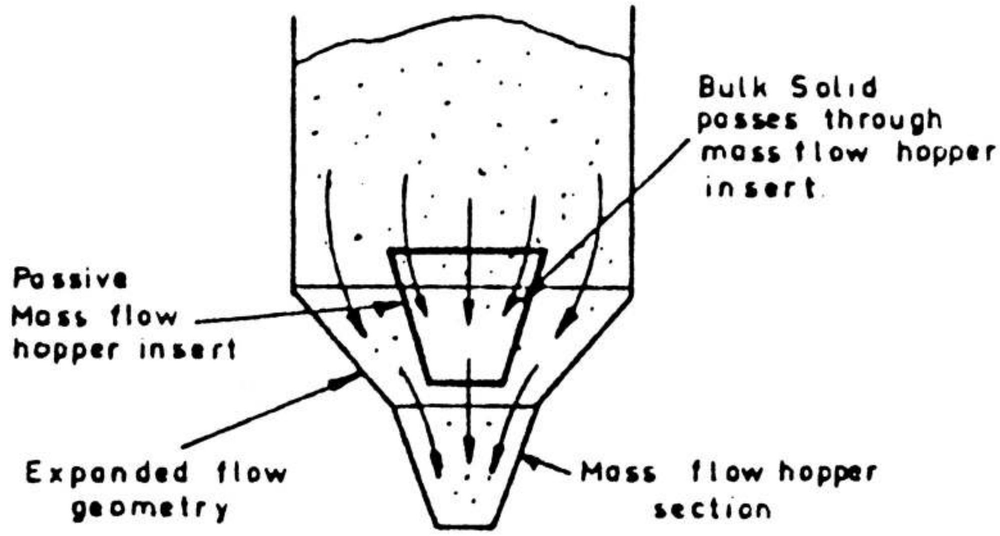


Fig 5 – Cone-in-Cone Insert

The inner cone is sloped at the traditional conical mass flow hopper half angle while the outer cone can have a hopper half angle up to twice the traditional value. Properly sized this arrangement can promote a wide range of flow patterns from the normal mass flow pattern to mass flow patterns where there is a significant velocity distribution across the bin diameter. In this second scenario conditions ideal for in-bin blending can be generated. The cone-in-cone insert can be used to minimise the influence of a number of segregation mechanisms.

The principal limitations of the cone-in-cone insert are the bin size in which the insert can be fitted, and the level of the cohesion that the bulk solid can display (effectively twice the cohesive arching dimension for a normal cone is required). Considerable care has to be taken to ensure that the insert is properly sized and located.

Since the Binsert first appeared other variations of insert have also been promoted, for example, the Lynsert mass flow generator [5, 6], Fig 6.

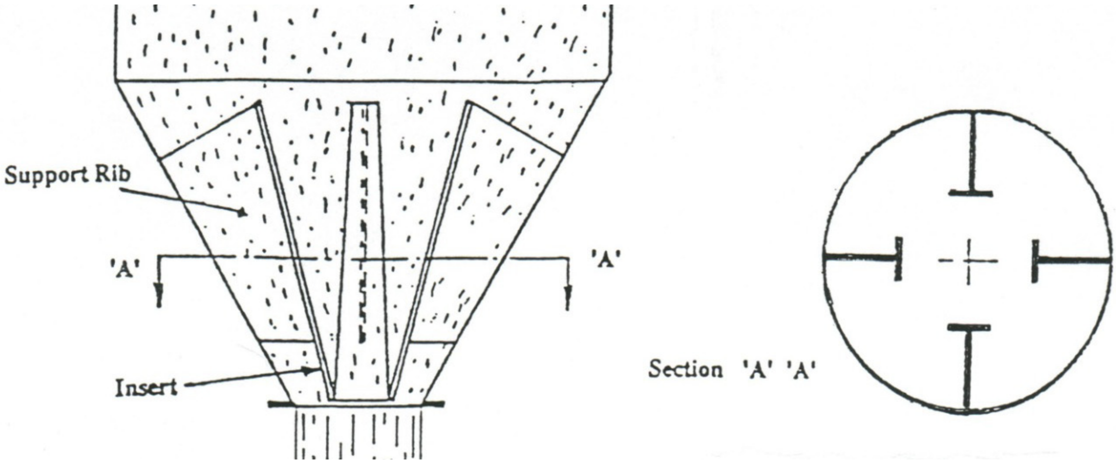


Fig 6 – The Lynsert

Hopper shapes have undergone some significant developments in recent years. No longer should we consider mass flow hoppers to be shaped either as cones or wedges.

One interesting development is the Diamondback Hopper® developed by JR Johanson. Johanson [7] claims that the optimum hopper shape must provide:

- Convergence in only one direction at a time.
- A circular or straight line cross-section to allow rigid body movement with a minimum of internal energy dissipation.
- Diverging, or at the minimum, vertical walls in some part of the cross-section.
- Low friction coefficient between the walls and the bulk solid.

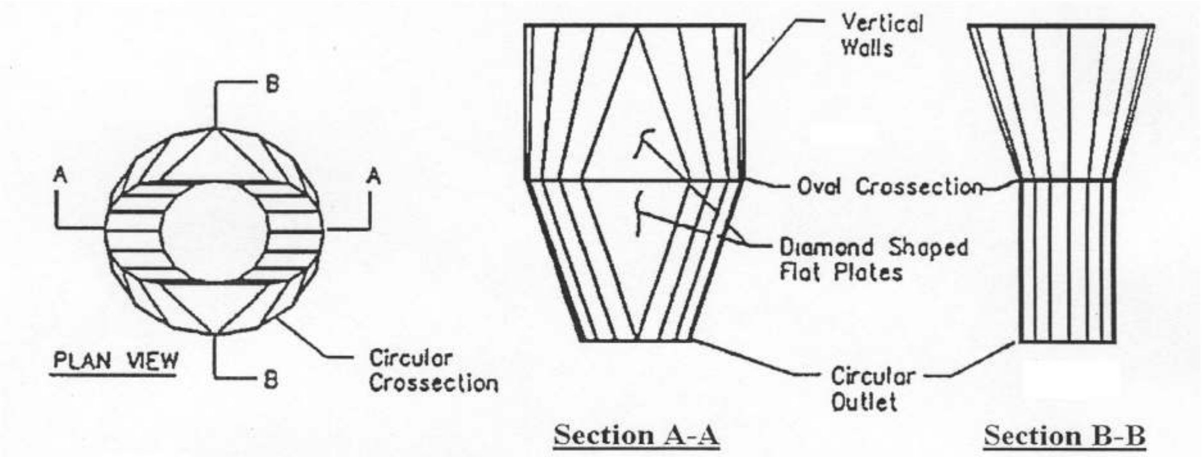
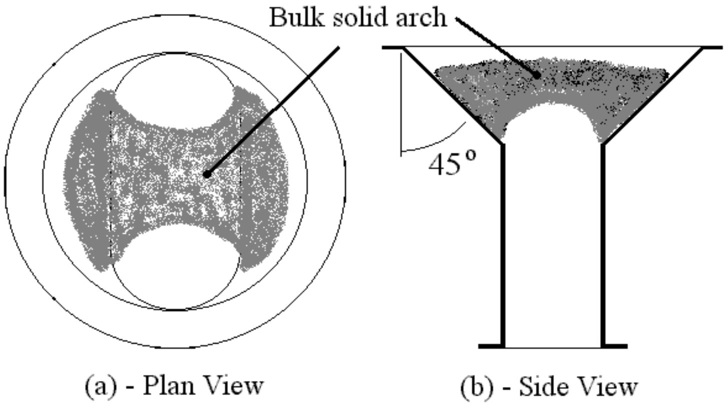


Fig 7- The Diamondback Hopper®

It is claimed that the Diamondback Hopper, Fig 7, has all of these qualities. Johanson indicates that the Diamondback Hopper can arch if the bulk solid is cohesive enough and that the most likely location for that arch is at the centre of the mid oval section. Drinkwater [8] undertook some preliminary studies into the performance of the Diamondback Hopper and confirmed that this was the likely location, Fig 8. Ratholing in the Diamondback Hopper is minimised by the requirement to have diverging, or at the minimum, vertical walls in some part of the cross-section. This requirement inhibits the development of continuous hoop stresses found in stable ratholes. Other advantages claimed for the Diamondback Hopper include the ability to provide a first-in-first-out flow sequence, limiting powder flow rates approximately double that achieved with a conventional conical mass flow hopper and an inherent ability to limit flooding and flushing.



(a) - Plan View (b) - Side View

Fig 8 - Bulk Solid Arch in a Diamondback Hopper [9]

4. Some Design Issues

4.1 The Importance of Flow Patterns

It is important that the bin designer is aware of the flow patterns within bins and silos and how the flow patterns may be affected (often adversely) by their actions.

The loads exerted on the walls of a bin or silo under operating conditions are directly related to the flow pattern which the contained bulk solid exhibits when flowing into and, more importantly, when flowing out of the bin. The importance of appreciating the flow pattern has been understood by many practitioners for many years. Symmetric bin shapes should be chosen to try to ensure that the flow pattern within the bin is symmetric. However, non-symmetrically located hopper outlets and/or eccentrically placed out-loading chutes are still being utilized and found responsible for many silo structural failures. Sadler [2] in his litany of silo problems that lead to structural failures identified non-symmetric draw-off patterns as the prime cause of many of the problems and indicated that the solution centred on converting the draw-off pattern from an eccentric to a concentric pattern.

4.2. Feeders and Feeder Interfacing

Associated with the discharge of bulk solids from most bins are one or more feeders to provide control over the discharge rate. In far too many instances there is a failure to realise that the design and selection of feeders for removing bulk solids from storage are critical and the feeder and hopper from which it is reclaiming must be designed as a complete unit. A well designed hopper may be prevented from working properly if the feeder is poorly designed and/or selected and vice versa.

In many instances the poor performance of a bin/feeder system stems from the lack of attention paid to detailing the geometry of the connection between the hopper outlet and the feeder. It is vital that the interface receives careful consideration at the design stage and also during construction since poorly designed feeders and/or feeder interfaces can be responsible for turning a mass-flow bin into a funnel-flow bin.

More detail and relevant case studies illustrating the importance of well designed interfaces between hopper outlets and feeders can be found in Arnold [3] and Arnold [4].

4.3 Design Detailing and Operational Issues

In order that the bin and feeder design procedures achieve their full potential in practice it is important that proper attention be paid to the detailing of the design and to certain aspects of bin operation. The reader may feel that the application of a bit of common sense would avoid most of the problem areas outlined below, however, it is amazing how often one finds that these problem area receive little or no attention throughout the design, construction and/or operation of bin and silo systems.

(a) Elimination of Valley Angles and Other Obstructions

Pyramidal and rectangular mass-flow hoppers of necessity have valley angles. When handling cohesive bulk solids these valley angles promote material hang-up and create a 'rough' wall with high friction. In-flowing valleys should be generously radiused or plated-in with substantial fillet plates.

Flow blockages can easily occur if protruding ledges, bolt heads, structural members, wall stiffeners, incompletely opening outlet gates, access ladders, etc. are allowed inside the bin. Bin walls should be kept 'clean' and free from such obstructions, as they allow pockets of bulk solid to form which create 'rough' wall conditions and promote the formation of arches. Special care should be taken with the top edges and horizontal joins in wall lining materials; ledges should be eliminated by butting linings together or overlapping them 'shingle-style' and care should be taken to prevent an ingress of bulk solid or moisture behind the linings. Should a slotted outlet be used with any hopper configuration, then tie beams must be kept to a minimum, be spaced at not less than 3 times the slot width and be steeply capped and lined to ensure that their obstruction to flow is minimised.

(b) Maintenance of a Minimum Level in a Mass-Flow Bin

It is important to always maintain buffer storage in a mass-flow hopper to:

- prevent damage to the special hopper lining surfaces during filling;
- reduce the load exerted on the feeder and to prevent impact forces damaging the feeder. being damaged by impact loading by providing the cushion of bulk material.

The minimum level must, therefore, be maintained above the top of any special hopper wall lining material. This requires that an effective non-intrusive type bin level indicator be used to control the minimum bin level.

(c) Problems of Prolonged Storage Times

It is usual to design a storage bin to hold the bulk material for a nominated storage time which, in some cases, may be for a maximum period of two or three days. The cohesive strength of many bulk solids will increase a very considerable amount under prolonged storage times at rest. It is essential that the plant operator be aware of the storage time limitations of the bin so that in the event of any abnormal period of shut-down the necessary steps can be taken to either empty the contents of the bin into a ground stock-pile or be prepared to employ some form of flow promotion when the material in the bin is ultimately to be used.

(d) Minimisation of Wear and Other Issues with Hopper Liners

The principal causes of wear in a bin are due to impact and abrasion; in designing and detailing the bin and feeder it is important that wear is minimised and not, as so often happens, aggravated. It is important that the internal surfaces of the bin, particularly the hopper, be protected from damage due to impact of materials during filling.

A disadvantage of mass-flow hoppers is that the bulk solids sliding along the walls may cause wear with abrasive materials. Wall liners are usually selected to provide a hopper wall with a sufficiently low friction coefficient to ensure mass-flow without having to resort to wall slopes which are so steep as to be impractical. However, if liner wear is likely to be an issue, the selection of wall lining materials needs to be a compromise between the requirements for low friction and adequate wear resistance. The design should take account of the fact that a lining may have a definite life. When it is known (or suspected) that wear will be an issue the design must allow for inspection of linings and ensure that it is possible to replace them periodically.

Special care should be paid to preserving the surface finish of special hopper linings. Any surface imperfections such as weld spatter, grinding marks, protruding bolt heads, geometric distortions, paint runs etc. will alter the friction characteristics and the laboratory data will not be representative of the finished product.

5. Segregation Effects

The phenomenon and degree of segregation present in the operation of a bin can influence significantly and often adversely the flow pattern exhibited in a bin or silo. Potentially mass-flow bins can exhibit funnel-flow and vice versa. Symmetric bins can display severely non-symmetric flow patterns. Bins which are charged pneumatically can cause particular problems.

Often when troubleshooting bin and silo performance issues it is segregation which has a significant influence on the problems being experienced. One must continually be aware of the propensity of bulk solids to segregate and realise that there are several mechanisms of segregation. Identifying the dominant segregation mechanism(s) contributing to the performance difficulties is not always straightforward.

A considerable literature exists on the topic of segregation, the various mechanisms of particle segregation and how they may be minimised is handling plant [eg. Refs 9-11]. The recent publication by Bates [12] is of particular note.

6. Design Auditing

An element of the overall design process that is often non-existent is the auditing of the final design of materials handling elements by a team competent in bulk solids handling. It is desirable that this auditing process take place before irreversible decisions are taken. There are many examples where the performance of a bin would have been greatly enhanced had a column been moved so that the feeder could fully activate the hopper outlet or had tie beams across a slotted outlet been spaced correctly and steeply capped so that potential ratholes merged and were unstable rather than form stable individual ‘structures’. It is important to ensure that hopper linings conform to the recommendations of the hopper geometry designer; bright cold rolled stainless steel is likely to have much better wall friction characteristics compared with hot rolled stainless steel of the same chemistry! Often the location of the inflowing charging stream(s) for bins is given little attention which can lead to uneven wall loadings and/or non symmetrical flow patterns.

If possible the design auditing function should be extended into the construction phase to try to avoid seemingly trivial issues such as:

- ledges and other protrusions especially within hoppers and chutes;
- fixing procedures and details for liners;
- interfaces between hoppers and feeders;
- protrusions due to types of aeration systems and/or level indicators, employed;
- protrusions due to access ladders and access holes.

7. Concluding Remarks

Determining the appropriate geometry for mass-flow hoppers to handle bulk solids reliably using techniques based on the traditional concepts of Jenike remains an acceptable design approach in many instances.

While the traditional Jenike design concepts may appear straightforward experience dictates that some important considerations need to be exercised during the design process, especially when handling the more difficult bulk solids, to ensure that the final bin performs to expectations. In such circumstances to traditional design concepts need to be augmented by such procedures as the determination of hopper half angle versus hopper outlet dimension or span relationships.

In addition, careful scrutiny of the flow property design information needs to be made to ensure that the design outcomes predicted are practical and/or realistic. In short, the design science is of great assistance to the decision-making processes but the science still has not replaced completely the art!

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