1-1-2008

Design of silos for flow and strength - the various contributors must communicate

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Design of Silos for Flow and Strength – The Various Contributors Must Communicate

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ABSTRACT: Too often in the design of silo systems for the storage and handling of bulk solids those involved in the various components of the design process do not communicate. The chemical engineers often have a range of desired outcomes that differ from those of the mechanical engineers and the mechanical and structural engineers are often not aiming for the same range of outcomes. Even if all the designers communicate well the overall result may disappoint if the project manager allows significant (but sometimes subtle) design variations during construction. The result can be a system that does not perform well. Had there been some consistent communication between the competing interests throughout the design and construction phases many of the limitations on performance would have been avoided. This paper will highlight some areas where lack of communication can have an adverse effect on good performance.

1 INTRODUCTION

The design and operation of silos for bulk solids can be an important activity of several engineering disciplines. It is unfortunate that the desired outcomes of the various disciplines do not always coincide. Often the chemical engineers are primarily interested in the associated processes and the silo and its feeding and conveying equipment are simply the devices that deliver bulk solids to a process or receive bulk solids from a process. The mechanical engineers may be interested in the silo geometry that will deliver a certain flow pattern together with designing/specifying the associated feeding and conveying equipment. The structural engineer is concerned with designing a silo structure that can contain the desired quantity of bulk solids.

Why then do silo systems too often:

- Deliver poor quality bulk solids to a process?
- Contain significant 'dead' regions and are not capable of delivering all their contents?
- Include equipment that is performing poorly and/or is underpowered?
- Suffer total structural failure?

While the principal reasons for these poor performance events can be many and varied it is also the case that, in far too many instances they are due to a lack of communication between the design contributors and a lack of appreciation how the actions of one group may adversely affect the design requirements of another group.

In this paper some of the issues raised in this introduction (especially the conflicts that can arise between those concerned with the flow of bulk solids and those concerned with design of structures) will be expanded upon.

2 BULK SOLIDS CHARACTERISATION

To design silos 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).

3 SELECTING THE TYPE OF BIN FLOW PATTERN

When determining an appropriate geometry for a silo and also when troubleshooting silo performance difficulties it is essential that due consideration be given to the type of flow pattern that will be or is being developed in the silo.

In selecting an appropriate flow pattern there are a number of issues that need consideration including:

- Should the flow pattern be mass-flow or funnel-flow or expanded-flow?
- Is the chosen flow pattern likely to be axi-symmetric or display significant non-symmetry?
- Will the silo be used as a batch container or a container to feed a downstream process continuously?
- Is the contained bulk solid free-flowing or cohesive?
- Is the contained bulk solid coarse or fine (and floodable)?
- Does the contained bulk solid have a definite shelf-life?
- Is it required that the silo be self cleaning or can some dead storage be tolerated?
- Is the contained bulk solid abrasive?
- How many outlets are contemplated?
- Are there likely to be any off-take chutes installed?
- What is the segregation potential of the bulk solid and is segregation likely to be an issue for the downstream equipment/processes?
- What is the charging method, is it single point or multiple point, is it central or offset, is it high velocity or low velocity?
- What type of feeder is contemplated? Is it an open or closed feeder? Will it be easy to interface with the hopper outlet(s) to avoid adversely influencing the flow pattern in the silo?

While the above list is not exhaustive it is hoped that it gives some indication that the selection of the appropriate flow pattern to be induced within a silo is not a straightforward matter.

If mass-flow is the flow pattern of choice then it is vital that the geometry is chosen to be as practical as possible. Sometimes this requires recognizing that wall friction varies with the consolidation stresses at the hopper walls and that this variation needs to be exploited (Arnold, 2002a). It is also vital that the internal surface of mass-flow hoppers maintain constant wall friction values over time and don't vary due to such effects as corrosion or wear. In addition for conical mass-flow hoppers it is vital that the internal hopper surface will display the assumed wall friction values from start-up and not rely on a wearing-in period. Normally if the bulk solid does not slide on the hopper walls at start-up then the wearing-in process is likely to be minimal.

While it is usually rather obvious that the outlet size for a mass-flow hopper has to be sufficiently large to prevent cohesive arching under all operating conditions, it may also be necessary to increase the outlet dimensions to enable wall friction to be lowered sufficiently to enable a practical hopper half-angle to be chosen. It may also be necessary to increase the outlet dimension if a fine powder is being discharged by gravity and flowrate limitations are likely. Of course the outlet dimension for gravity discharge may be so great that some form of discharger may be needed to assist gravity.

The selection of dischargers has not received a lot of scientific assistance. However, taking into account the flow properties of the bulk solid can often give a good indication of the type of discharger that should be selected (Arnold 2000).

If funnel-flow is the desired flow pattern then consideration of potential stable ratholing becomes an important design consideration. The prediction of the critical rathole diameters for a bulk solid is still rather primitive but it has received some useful updating in recent times (Roberts et al. 2007). A bulk solid does not need to be particularly cohesive before its critical rathole dimensions become prohibitively large. Remembering that the 'diameter' of a stable rathole is generated by the size of the outlet over which it forming then funnel-flow silos can easily become impractical if self-cleaning is a requirement or if dead regions are to be controlled. In such situations expanded-flow silos or funnel-flow silos with multiple outlets and good control over rathole stability become important design considerations.

It has been appreciated by researchers that the prediction of silo flow patterns is not as straightforward as it may appear. For example, Sugden (1980) from his own work and from reviewing the work of others observed that 'for flat bottom bins there is no unique flow pattern for a particular material in a particular silo bin. The flow pattern is extremely sensitive to the initial density of the ensiled material'. It is known that packing densities can be influenced by charging regimes. These regimes can influence the degree of over-consolidation of the bulk solid and hence the extent to which a bulk solid has to dilate before it will flow. This in turn can have a significant influence on the flow channels that influence the bin flow pattern; this is especially the case with flow patterns that are of the funnel-flow type.

In work on full scale silos Rotter et al. (1993) have shown that flow patterns that were expected to be symmetrical were shown to have significant non-symmetry. While Rotter et al. did not identify the causes of the non-symmetry, this author believes it is likely that the charging protocol was a prime influencing factor.

In funnel-flow bins where the outlet dimension is significantly smaller than the critical rathole diameter of the bulk solid then the flow pattern that would be exhibited would be quite different to the flow pattern that a free flowing bulk solid such as grain would develop in a bin of the same geometry.

4 DESIGNING THE SILO STRUCTURE

Structural Engineers are normally responsible for the design of the silo structure for strength and stability. The loads exerted by the bulk solid on the silo walls are usually estimated via a loading code (eg the Australian Standard 1996 or the more recent Eurocode 2007). It helps the overall design outcome significantly if the structural designer is aware of the flow patterns that can develop within the silo and in particular the flow pattern assumed by the designer who specified the silo geometry.

It can materially assist the overall design outcome if the structural designer of silo has an appreciation of the importance of the flow patterns within silos and how the flow patterns may be affected (often adversely) by the structural designer's actions.

While there are widely varying approaches to the problem of predicting wall loads on bulk solids containers, one thing is clear - 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. Yet we find non-symmetrically located hopper outlets and/or eccentrically placed out-loading chutes still being responsible for many silo structural failures. Sadler (1980) 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. Ooms & Roberts (1985) have shown how the use of the Tremie Tube concept can allow out-loading chutes to be employed while still retaining symmetric flow patterns.

5 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. Often this situation is exacerbated by the practice to separate contracts at the outlet of the bin and have the bin and feeder designed and supplied by different interests. This practice often promotes poor design and allows each contractor to blame the other for the poor performance of the total system. Unfortunately, the user often is so ill-informed about the operation of bins and feeders and their mutual interaction that they are in no strong position to arbitrate and end up having to pay extra costs for redesigning and/or retrofitting to correct the situation.

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. Especially in situations where the bin and feeders are supplied under different contracts, the geometry of the interface connecting the hopper outlet to the feeder is the responsibility of no-one in particular, yet it is vital that the interface receives careful consideration at the design stage and also during construction.

More detail and relevant case studies illustrating the importance of well designed interfaces between hopper outlets and feeders can be found in Arnold (1995) and Arnold (1998).

6 SELECTING DISCHARGERS

While the discharge of bulk solids from bins under the influence of gravity may be a desirable objective, situations frequently arise where gravity forces alone are insufficient to allow reliable and/or desirable discharge and additional assistance is required. In many instances the additional assistance is in the form of some external energy input (e.g. vibratory, mechanical, pneumatic) to overcome problems of cohesive arching or stable ratholing. The aim of the extra energy input is to augment the gravity forces and overcome these common obstructions to flow.

In assessing strategies for improving the reliability of discharge from bins consideration should also be given to solving the problems by, for example:

- Modifying the bin flow pattern to eliminate stable ratholing.
- Enhancing gravity forces by modifying adverse interstitial void pressures.
- Removing the high consolidation stresses at the exit end of the slotted outlet of a wedge shaped hopper.
- Reducing the consolidation stresses exerted on a bulk solid (and hence reducing its cohesive strength) as it flows through a hopper.

In many instances these changes can be effected through static devices which require no continuous form of additional energy input. Not only do these solutions lead to reduced energy consumption but they often lead to reduced noise emissions, avoid structural failures, eliminate problems due to flow property changes resulting from the heat generated as the additional energy is absorbed. In many instances they may be simpler and/or cheaper to implement. Arnold (2002b) considers some of these static devices and examines their range of application together with their advantages and limitations.

The selection of bin dischargers requiring some form of additional energy input (e.g. by vibration or aeration) remains a rather empirical exercise. Generally, the choice relies heavily on previous experiences. Extrapolation from the behaviour of a bulk solid that has been handled before to predict the behaviour another bulk solid for which there is no prior experience, is still commonplace; such extrapolations can be very dangerous. Erroneous conclusions and poorly performing equipment often result. In addition, care must be exercised to ensure that the employment of these devices does not lead to the development of non symmetric flow patterns in bins and silos that are geometrically symmetric.

Traditional flow properties determined to aid in the design of bins, feeders and chutes can also be used with some confidence, to aid in the selection of bin dischargers. Arnold (2000) explores the application of flow properties as an aid in selecting dischargers that rely on vibration or aeration to ensure reliable flow of bulk solids from storage bins and hoppers.

7 DETAILED DESIGN

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 silo systems.

7.1 *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.

7.2 *Maintenance of a Minimum Level in a Mass-Flow Bin*

It is important to always maintain a 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.

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.

7.3 *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.

7.4 *Minimisation of Wear*

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. The discharge end of belt conveyors feeding material to the top of the bin should be positioned so that the trajectories followed by lumps of material falling into the bins do not allow contact with the walls. If necessary, an impact baffle plate should be fitted at the conveyor outlet to eliminate the horizontal component of the discharge velocity, thus allowing the material to fall vertically into the bin.

A disadvantage of mass-flow hoppers is that the bulk solids sliding along the walls may cause wear with abrasive materials. It is essential, therefore, that adequate wall liners be included in the design. Wall liners are also often used 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. The selection of wall lining materials is usually a compromise between the requirements for low friction and adequate wear resistance. Many lining materials will exhibit good abrasive wear resistance but poor impact wear resistance. It is vital that the design take account of the fact that 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.

It should be noted that under normal circumstances the flow pressures at the wall of a mass-flow hopper are low; this, coupled with the low velocity of the fully developed flow across the total opening, will ensure that wear is minimised. In this regard, good feeder design is essential.

More serious wear problems will occur during funnel-flow where the flow channel or pipe is not fully contained in the bulk solid itself but may incorporate part of the hopper or bin wall. Problems of this nature may occur when bins with eccentric discharge are used, particularly when the bin opening is located near a side wall. On other occasions a badly designed feeder may cause material to rathole adjacent to the hopper wall. Ratholes of this nature give rise to high velocity flow against the wall, resulting in accelerated wear.

Often side delivery chutes are incorporated in bins for the purpose of off-loading bulk materials into trucks. Side delivery chutes create undesirable flow patterns in bins, leading to accelerated wear of the bin wall in the region of the chute intake as well as in the plates above the chute. This wear is caused by both abrasion and impact. Abrasive wear results from the high velocity of the material during chute discharge, the flow following a funnel-flow pattern. After using the chutes the surface of the material in the bin is left with the surface sloping steeply downward towards the chute intake. Subsequent filling of the bin will result in large lumps of material bounding off the surface and striking the bin wall above the chute. This action aggravates the wear in the plates and in view of the likelihood of buckling, the bin, as a structure, will ultimately be weakened.

It should be noted that despite the fact that side delivery chutes are used intermittently, the wear rate during operation can be considerable. It is, therefore, most desirable that side delivery chutes be avoided, and off-loading be incorporated via a transfer conveyor operating from the main bin discharge. If side delivery chutes are used, such as in existing installation, it is essential that the bins be lined with wear plates in the region of the chute intakes as well as above the chutes.

7.5 *Prevention of Shock Loads*

Where a storage bin operates under funnel-flow and discharge is sporadic due to the formation of pipes, when pipes collapse either spontaneously or as a result of the application of flow promotion, severe impact loads are experienced. Often the amount of material falling may be a major proportion of the total bin contents and there is a distinct danger of significant structural damage. The seriousness of this type of problem reinforces the need for correct bin design which takes into account the relevant bulk solid flow properties.

7.6 *Care of Wall Lining Materials*

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.

7.7 *General Maintenance and Safety*

It is vital that any storage bin be monitored continuously for wear and deterioration such as that caused by corrosion. Problems of corrosion are likely to be more serious in funnel-flow bins where there are dead regions of material, the problem being aggravated at higher moisture levels. Operator awareness of likely problems is essential in order that problem areas can be detected early. It is important that regular inspections and maintenance of storage and handling plant be undertaken.

The importance of good bin operating practice and regular maintenance, when viewed from the aspect of safety, cannot be over-emphasised. In the past, there have been a considerable number of bin failures; through better design and more informed operating procedures it is expected that such failures could have been avoided.

8 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 (e.g. Enstad 2001, Carson et al. 1986, Johanson 1988). The recent publication by Bates (1998) is of particular note.

9 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 silo 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 silos 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 detailed in Section 7. As a reminder some of the issues to focus upon are:

- 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.

10 CONCLUDING REMARKS

The necessity of taking a cooperative approach to the design of bulk solids handling plant cannot be overemphasised. Developments in technology have lead to significant advances being made in the processes involving the production and utilisation of bulk solids. In the design process considerable attention and a large component of the budget is expended on ensuring that the processing units perform their proper function. Budget overruns on the processing units often means that materials handling systems which link the total system together are the targets for cutting expenditure. This cost cutting usually results in inferior materials handling plant being designed and installed. As the total system is normally a series linked system with the processing units linked by materials handling components then the end result is that the total system has severe weak links. As these weak links begin to fail they cause serious and costly loss of productivity. Under such circumstances it becomes obvious, even to the 'bean counters' that the money saved on the inferior materials handling plant was a false economy.

It is also vital that the structural engineers are aware that the silo structures they design are to contain bulk solids. The interaction of the bulk solid with the silo structure needs to be constantly born in mind so as to aid in avoiding silos structures that fail and/or perform their storage and handling functions poorly.

REFERENCES

Arnold, P.C. 1991. The influence of segregation on the flow pattern in silos. *Bulk Solids Handling* 11 (2): 447-449.

Arnold, P.C. 1995. Interfacing feeders to bin outlets - A neglected area of design. *Mech. Trans., IEAust*, ME20 (3): 171-177.

Arnold, P.C. 1998. Feeding Bulk Solids from Bins: The Interface Factor. *Australian Bulk Handling Review.* 3 (2): 32-41.

Arnold, P.C. 2000. Some observations on the relevance of flow properties in the selection of bin dischargers. *Powder Handling and Processing* 12 (4): 371-374.

Arnold, P.C. 2002a. Some considerations to assist in improving the practicality of mass-flow bins. Paper (Paper No 432 on CD-ROM) presented at *World Congress on Particle Technology 4*, IEAust, Sydney Australia 21-25 July.

Arnold, P.C. 2002b. How Do Static Flow Promotion Devices Stack Up – The Pros and Cons. *Australian Bulk Handling Review* (7) 4: 61-66.

AS3774 1996. Loads on Bulk Solids Containers. Australian Standard, Standards Australia, Sydney.

Bates, L. 1997. *User Guide to Segregation*. Marlow UK: British Materials Handling Board.

Carson, J.W., Royal, T.A. & Goodwill, D.J. 1986. Understanding and Eliminating Particle Segregation Problems. *Bulk Solids Handling* 6 (1): 139-144.

EN 1991-4 2007. Eurocode 1; Basis of Design and Actions on Structures, Part 4 – Silos and Tanks, Eurocode 1 Part 4, CEN Brussels.

Enstad, G.G. 2001. Segregation of Powders - Mechanisms, Processes and Counteraction. In A Levy & H Kalman (eds) *Handbook of Conveying and Handling of Particulate Solids*: 589-602 Elsevier Science.

Johanson, J.R. 1988. Solids Segregation: Causes and Solutions. *Powder and Bulk Engineering*, August: 13-19.

Ooms, M. & Roberts, A.W. 1985. The reduction and control of flow pressures in cracked grain silos. *Bulk Solids Handling* 5 (5): 1009-1016.

Roberts, A.W, Wiche, S.J. & Krull, T. 2007. Review of rathole determination in relation to draw-down and live capacity of gravity reclaim stockpiles. *Proc. 9th intn. conf. Bulk Materials Storage, Handling & Transportation*, Newcastle, Australia, 9-11 October: on CD.

Rotter, J.M., Ooi, J.Y., Lauder, C., Coker, I., Chen, J.F. & Dale, B.G. 1993. A study of the flow patterns in an industrial silo. *Proc. intn. symp. on Reliable Flow of Particulate Solids II*, Oslo, Norway, 23-25 August: 517-524.

Satler, J.E. 1980. Silo problems. Paper presented at *intn. conf. on Design of Silos for Strength and Flow*, Lancaster, UK, 2-4 September.

Sugden, M.B. 1980. Effect of initial density on flow patterns in circular flat-bottomed silos. Paper presented at *intn. conf. on Design of Silos for Strength and Flow*, Lancaster, UK, 2-4 September.