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# Predicting Powder Flow from Containers with Flexible Walls


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## 1.0 Background

Flexible Intermediate Bulk Containers (FIBC) are used in many applications for the transport and storage of Bulk Materials. The containers are very effective in the handling of non-cohesive, granular free flowing materials in that they can be discharged with relatively few problems.

However, in the case of the storage of cohesive bulk materials, in most cases powders, significant discharge problems can occur due to the internal strength that can be developed by the powder under consolidating loads generated by filling and transport. There is also the potential for the flexible walls of containers to impose significant additional loads on the powders leading to an increase in the bulk strength of the powder. This in turn leads to significant discharge problems due to potential bridging and ratholing within the discharge flow channel.

In rigid silos, the geometry of the converging hopper section is critical in determining the discharge flow regime. Mass flow discharge is the preferred flow regime for cohesive bulk solids to avoid the barriers to flow caused by ratholing and bridging. However, this requires that the geometry of the hopper section (hopper half angle and outlet dimension) is specified based on the flow properties of the bulk solids (powders) to be handled and the wall friction developed between the material of construction and the bulk solid. As is often the case, the storage height is limited requiring the storage capacity to be accommodated laterally. This gave rise to the Expanded Flow Bin which operates by funnel flow and mass flow in series. The upper main storage section operates by funnel flow designed with the required opening dimension and geometry to ensure that the upper funnel-flow section completely discharges into the lower mass-flow hopper section, thus ensuring controlled discharge. Expanded flow is not limited to bins and hoppers. It also applies to gravity reclaim stockpiles in which the storage bin is replaced by a laterally unconstrained heap of material. The importance of the gravity reclaim mass flow hopper(s) in this case is highly significant.

Noting that the project will focus on FIBC containers of varying geometrical proportions ranging from squat to tall, the possibility of variations in mass-flow such as encompassed by the label “intermediate flow” will need to be considered. In such cases the surcharge load acting on the stored product may not be sufficient to enforce fully developed mass-flow. Rather, the flow regime results in a 2-zone flow comprising a slower moving outer annulus and a faster moving central core [Jenike 1987, Benink 1989].

While the forgoing discussion has included large scale industrial applications, the University and TUNRA research team has had a great deal of research and consulting experience dealing with projects on a wide range of scales including those comparable to the FIBC project. Having said this, it is clear that in the case of rigid bins and silos the modes of flow, notably the desirable mass-flow are quite predictable and achievable. This is not the case with FIBC's. The influence of the wall flexibilities and associated variations in geometrical loaded shape will no doubt have an influence on the mode of flow. Attention will need to be given to the "grey area" between mass flow and funnel flow and the possibilities for expanded flow. An important aspect of the FIBC design is the need to minimise segregation and prevent dust emissions

Furthermore, little is known with regards to the pressures experienced in FIBCs from either initial loading, transport (vibration) or the flexing of the flexible walls of the container. In addition, the rathole geometries that result from the material loading are also uncertain although TUNRA Bulk Solids has undertaken considerable research in rathole geometries of stockpiles. Whilst the loads and induced stresses in the bulk solids will be considerably higher in stockpiles, the theoretical approach would lend itself to adaption and application to the much smaller stresses that are likely to be experienced in FIBCs [Roberts et al 2005 and 2008].

There are a number of critical variables which will influence material discharge from such vessels. In particular the bulk properties (Flow properties) of the material such as bulk strength and frictional characteristics – both internal friction and boundary (or wall) friction. These characteristics depend critically on the consolidation loads that are applied to the material. These parameters will also determine to some degree the flow pattern of discharge.

The influence of transient variations in FIBC geometry during filling and emptying resulting from the container wall flexibilities, will need to be examined. For example, there will be dynamic variations in the wall loadings requiring examination. In particular, selection of the pressure ratios, the so-called K values, governing the normal wall stresses and the vertical pressures will need to be determined.

## 2.0 Approach

The approach adopted in this proposal is to start with a systematic experimental program to both assess the flow properties of the bulk materials to be tested and to analyse, empirically in the first instance, the flow patterns observed over a range of physical parameters that will impact the discharge characteristics of the FIBC. Of equal importance in this case will be the need to characterise the relevant physical parameters of the materials used to manufacture the FIBCs. Information such as, for example, their stress-strain orthotropic/isotropic and dynamic properties as linked to their robustness and long-term serviceability. In parallel, theoretical studies will be undertaken to better understand and ultimately aim to provide a systematic approach to the prediction of discharge characteristics based on the flow properties of the bulk solids to be handled.

Figure 1 outlines the envisaged test rig at full scale. Filling will be by overhead crane with the whole test rig mounted on load cells. An important aspect of the work will be the effect of the flexible walls, particularly 'wall bulging' due to load deformation. Both strain gauges and laser scanning and/or photo modelling software will be used to examine these phenomena. These techniques have been successfully used in other projects undertaken by TUNRA, including using Photo Modelling Software to measure the 3-dimensional profile of moving conveyor belt and exporting this profile as a boundary mesh into Discrete Element Method software, as shown in Figure 4. In order to illustrate the silo research facilities of TUNRA, Figure 3, showing a test silo during the filling phase, has been included.

The theories for mass and funnel-flow invariably consider the stress fields in bulk solids storage systems as 2-dimensional in either axi-symmetry or plane symmetry. However, the extrapolation of 2-dimensional stress theory to problems involving 3-dimensional stress states is often less than satisfactory. This applies to the determination of 'rathole' dimensions pertaining to funnel-flow where the current theories are found to be too conservative leading to an under-estimation of the draw-down and live capacity. Jenike's original funnel-flow theory was based on the concept of mass-flow in the axi-symmetric flow channel formed above the bin outlet, the surcharge loads on the bulk solids being completely ignored. This greatly underestimated the stable rathole dimension and is regarded as the lower bound solution which would only be approached if the bin were being filled and emptied simultaneously. As a consequence, in the mid 1960's Jenike's theory was modified, somewhat empirically, with the unconfined yield strength defining the diameter of the stable rathole being again based on 2-dimensional consolidation stress conditions. This modified solution is regarded as the upper bound solution, since it over-estimated the size of stable ratholes. While this was regarded as a quite conservative approach to funnel-flow design it will be too conservative for an FIBC or big bag application. As a result Roberts et al have proposed a more realistic solution based on hoop stress theory, which takes into consideration the 3-dimensional stress state occurring in the rathole. The simple model is illustrated in Figure 2. The theory is giving predictions that are much closer to those found in practice. However, it needs to be backed up by detailed, fundamental research to identify more precisely the geometry defining the stable annular ring of material at the upper lip of the rathole, as well as the geometry of the rathole. Furthermore, the consolidation stress variations governing the strength of the rathole needs to be studied in more depth as these will be particularly pertinent to the conditions experienced in FIBCs.

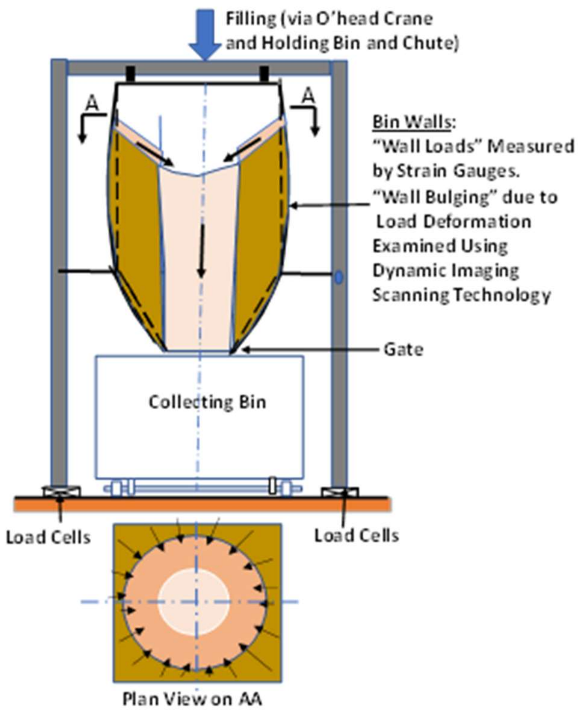



**Fig.1. Schematic of Test Rig**

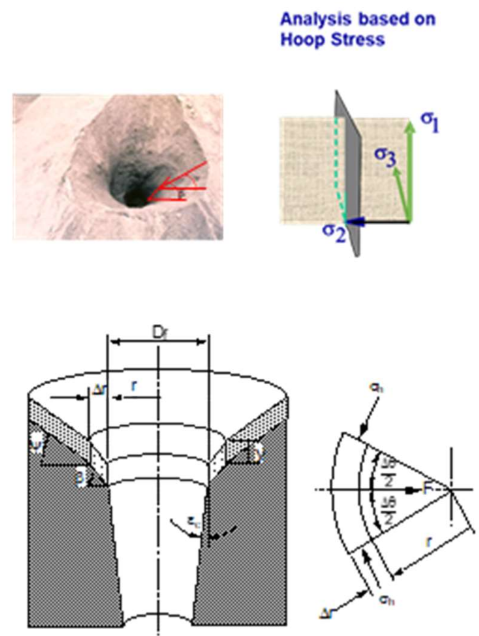



**Fig.2. Illustration of 3-D Funnel Flow**

**Fig.3. Silo Test Rig Showing Typical Test in Progress**

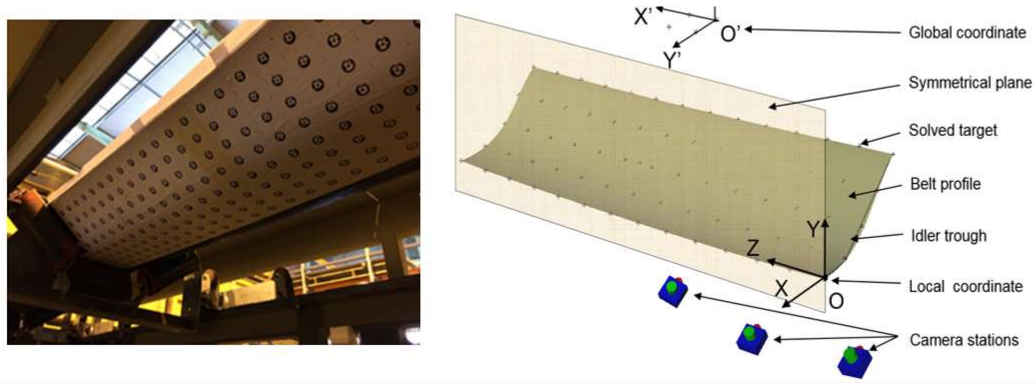



**Fig.4. Measuring the Dynamic Deflection of a Loaded Conveyor Belt using Photo Modelling Software**

We believe that this combined empirical and theoretical approach has the best chance of delivering a meaningful practical outcome whilst maintaining a focus on rigour to develop an improved understanding FIBC discharge behaviour. Furthermore, the facilities at TUNRA have the capability of testing at full scale (Figure 3).

**3.0 Experimental Program**

The experimental program will be split into three phases:

**a) Design and construction of the experimental rig**

Initially, a test rig will be developed based on the most common form of FIBC, the so called 'Big Bag'. The rig will be designed to be able to reasonably represent the following set of conditions:

- Facilitate filling of the FIBC
- Be able to apply vibration to the FIBC to represent consolidation during transport
- Be able to lift the FIBC into the position required for the FIBC to fully extend the outlet so that discharge can occur
- Be able to adequately determine the FIBC/bag geometry during discharge
- Be able to test a range of bulk materials from free-flowing granules through to cohesive powers representative of the materials of interest to IFPRI members
- Be able to video the discharge, determine the geometry of the flow channel and the mode of flow (mass flow/funnel/flow/intermediate flow)

Allow the potential use of an Inertial Measurement Unit (IMU) to assist in tracking flow within the vessel

**b) Comprehensive Flow Property Testing of the materials to be used for testing**

The characteristics of the materials to be handled in conjunction with the physical geometry of the FIBC will be fundamental to the way in which the materials behave and discharge. For the range of materials to be tested, which will be decided in consultation with the participating members of IFPRI, a comprehensive set of flow property tests will be carried out. These will be determined using the Jenike method and will include:

- Instantaneous and Timed flow functions undertaken for both low and high consolidation suitable for this application
- Flow Function determined under vibration [Roberts 1987]
- Flow Function determined using the hoop stress theory
- Static angle of internal friction

- Effective angle of internal friction
- Bulk Density over a suitable range of consolidation loads
- Wall yield Locus and wall friction angle against a sample of the FIBC wall material across a suitable range of normal stress.

The flow property testing and research facilities of TUNRA are quite comprehensive. Pictures of these facilities are provided in the Appendix by way of illustration.

These tests will be undertaken at suitable values of material moisture content.

**c) Experimental testing to determine the discharge characteristics of the FIBC under a comprehensive range of test conditions.**

The third section of the Experimental program will involve Flow and discharge testing of the FIBC using several materials and over a range of conditions such as:

- Discharge following time consolidation
- Discharge following consolidation under vibration to simulate consolidation during transport
- Intermittent discharge – stop / start over a range of filling levels and degrees of consolidation
- Determination of rupture lines in the flow and the potential boundaries between mass flow/funnel flow/intermediate flow
- Determine material flow channel geometry over a range of fill levels and consolidation states
- The influence of variations in FIBC geometry resulting from the analysis and selection of the pressure ratios, the so-called K values, governing the normal wall stresses and the vertical pressures

**4.0 Theoretical Program**

In parallel with the Experimental Program, the Theoretical Program of work will follow several themes. In practice, the theoretical and experimental programs will inform each other and will inevitably lead to modifications to the research plan. The theoretical areas of enquiry will be as follows:

- Review current mass flow and funnel flow theory particularly the more recent approaches to the radial stress theory using 3-D average stress or hoop stress models developed by Roberts et al.
- Look at the potential application of the revised theoretical approach to rat-hole geometry developed for gravity flow stockpiles for application to the FIBC scale at suitable consolidation stresses
- Develop existing attempts to codify intermediate flow – boundaries and flow regimes in the context of small-scale volumes applicable to FIBCs
- Use DEM approaches to simulate the discharge behaviour particularly related to velocity profiles/distributions within the flow and attempt to match these to actual observed behaviour
- Use the outputs of both the experimental/empirical data and observations together with the outputs of the theoretical studies to develop and codify a systematic design approach to predicting discharge performance.

**5.0 Deliverables**

Whilst it is impossible to predict with certainty the output of the project, the following outlines the anticipated outcomes over the three years.

**Year 1**

- Design and build test facility
- Provide Flow properties data for the test materials

- Provide preliminary findings on discharge tests and flow regimes
- Report on Theoretical review and developments to date
- Review of progress and refine program for Year 2

**Year 2**

- Report on full-scale material discharge testing for a range of materials under a range of conditions (fill level, consolidation, flow regimes observed)
- Report on theoretical developments and their application to FIBCs including the matching of theoretical developments to observed behaviour
- Report on the development of initial systematic design approach to predict discharge performance
- Validate as far as possible the theoretical outcomes with experimental data
- Review of progress and refine program for Year 3

**Year 3**

- Provide a validated systematic design approach to predict discharge performance
- Provide report on the theoretical approach supported by experimental data
- Report on the user experience from initial use of the process in the field
- Provide Final Report to IFPRI members
- Provide scope of potential future work to build on the outputs of the Project

## 6.0 How this project could leverage into existing programs

The Centre for Bulk Solids and Particulate Technologies (CBSPT) and TUNRA Bulk Solids (TBS) have nearly 50 years' experience of developing technological solutions to materials handling problems in industry varying in scale from the smaller scale process problems through to large scale mining problems.

Over the last decade, TBS has developed methods to model large scale gravity flow stockpiles which involves predicting the geometry of the funnel flow ratholes in order to estimate the live capacity of stockpiles. These techniques have been shown to provide much more accurate predictions of flow performance and live capacity when compared with existing funnel flow theory and they have now been used very successfully in industry. These techniques could be applied to the FIBC case under much lower consolidation loads. This has the potential to contribute considerably to this project.

In addition, TBS has vast experience in physically modelling industrial situations and has the experience and capability to design and build an appropriate test facility. The Researchers in the Centre and TBS have the intellectual capacity appropriate experience to tackle this problem.

## 7.0 How IFPRI members could be involved

Members of IFPRI involved in the project will be an invaluable asset in the selection of materials to be tested that are safe to do so in our laboratory and that reasonably represent the practicalities of FIBC or 'Big-bag' operations in their facilities. The opportunity will also be available for members to have input to and be consulted on the proposed test program to ensure that we not only fully understand the problems they experience but also provide a test program that realistically mimics the real-world experience in industry. Members may also able to supply big-bags for test.

We would also be pleased to form a reference group of members to provide updates on progress and to engage in suitable discussion to ensure the project remains on-track and relevant.

## 8.0 Budget and Timing

IFPRI has a standardised approach to the budget being **USD 40,000** per annum for a period of 3 years subject to satisfactory progress. If successful, the project would commence in September 2023. It would be our intention to recruit a Research Higher Degree candidate to work with the project team with the HDR Stipend being drawn from the project budget. The research is pre-competitive, and no ownership of intellectual property is claimed by IFPRI for the research undertaken.

## 9.0 References


**Benink E.J. 1989**, Flow and stress analysis of cohesionless bulk materials in silos related to codes. Doctoral Thesis (The university of Twente, Enschede, The Netherlands)

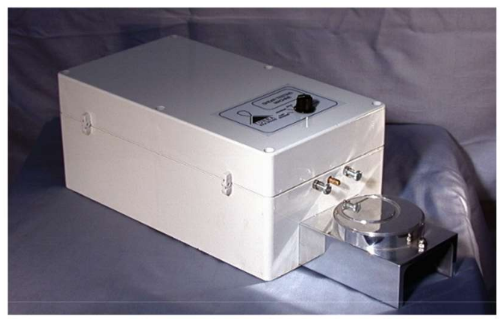
**Jenike A.W. 1987**. A theory of flow of particulate solids in converging and diverging channels based on a conical yield function. Powder Technology, 229-236

**Roberts, A.W. 1997**. Vibrations of fine powders and its applications. Chapter 5, Handbook of Powder Science and Technology, Second Edition, Edited by Fayed M.E. and Otten L, Chapman & Hall

**Roberts, A.W. 2005**.Characterisation for hoppers and stockpile design. Chapter 3, Characterisation of Bulk Solids. Edited McGlinchey, Blackwell Publishing

**Roberts, A.W., Wiche, S.J. and Krull, T. (2008).** Review of Funnel-Flow Theory in Relation to Draw-Down and Live Capacity of Gravity Reclaim Stockpiles Bulk Solids and Powder Science and Technology. Vol.3, No.2, pp.97-107.

**Flow Property Laboratory and Test Cell Controlled Load Consolidation Benches**



## Flow Property Measurement

**Left to Right from Top -300mm dia Inverted Wall Shear Tester; Direct Shear Tester; 300mm dia DirectShear Cell Tester with Hydraulic Loading; Flowability Uniaxial Tester**