

Predicting Powder Flow from Containers with Flexible Walls

Investigators

Professor Mark Jones

mark.jones@newcastle.edu.au

Professor Craig Wheeler

Dr Peter Robinson

Dr Michael Carr

Emeritus Professor Alan Roberts

Dr Bin Chen

Centre for Bulk Solids and Particulate Technologies (CBSPT)

In association with TUNRA Bulk Solids (TBS)

The University of Newcastle, Australia

www.centreforbulksolids.com.au

www.bulksolids.com.au

1.0 Background

This renewal proposal extends the work already undertaken on predicting powder flow from containers with flexible walls. To date, the focus of the project has been to investigate the flow behaviour during discharge of both free-flowing and cohesive bulk solids; investigating the load transfers between the material and the flexible walls and establishing the consolidation loads within the bulk material during various bag operations. The extremely flexible nature of the walls leads, not unexpectedly, to very different loading conditions when compared with the essentially rigid walls of conventional bins and hoppers. These consolidation loads are an essential component in determining outlet dimensions, particularly in funnel flow.

In the first two years of the initial project, we have focused on modelling the flexible bag wall using Discrete Element Modelling and comparing the results in DEM with a 2D physical model of the flexible bag to ensure that our modelling and simulations are grounded in reality. The results of this work have provided excellent insight into the nature of the flow from a flexible bag for a granular free-flowing material and for a powdered cohesive bulk solid. In addition, the interactions with the flexible wall and the impact of these interactions on the consolidation loads generated within the bulk solid have provided excellent results. A particular finding of the work is that the handling and transport of the bag have a significant effect on the consolidation loads generated within the material. This will provide a theoretical underpinning for a set of handling guidelines for handling bulk bags.

Two factors have become clear from this work so far. Firstly, the flow regime occurring during discharge from a bulk bag is almost always that of funnel flow. There is almost no sliding at the wall except perhaps for the final stage of discharge, where a bag completely empties. In all the critical stages of flow, only funnel flow is observed. Hence, it is the consolidation loads within the material that are the most critical determinant of discharge.

Significant effort has been applied to understanding the consolidation loads generated at various stages of bag handling. During initial filling, the consolidation loads generated approximate a hydrostatic head. There is no evidence of a Janssen effect since the flexible walls provide a very limited opportunity for the transfer of load to the walls, particularly in shear. However, once the bag is lifted, a significant lateral stress is developed in the material that is typically more than double the hydrostatic stress during the filling process. Further cycles of lifting the bag and setting it down lead to further increases in consolidation load being generated.

This behaviour has been investigated both by modelling and simulation in DEM and replicated in practice in the 2D rig using Tekscan pads to measure pressures exerted on the bag walls during filling, lifting of the bag and during discharge. These behaviours are similar to both free-flowing materials and cohesive powders. However, there are additional loads experienced when handling a cohesive bulk solid.

The 2-D rig has been extremely important in developing our understanding of flexible wall behaviour, and combined with the DEM modelling, has provided great insight into the consolidation loads developed within the material. These loads can then be applied using the Jenike Funnel Flow theory to determine outlet dimensions for funnel flow discharge using the Roberts modified approach. However, it is evident that, apart from the case of very free-flowing materials, it is unlikely that the outlet dimensions of typical big bags will ever be sufficient for unaided gravity flow except in cases where the consolidation loads are very low, which implies free-flowing material. Hence, the aims of the renewal project will be to extend the understanding derived from the initial three years to investigate the impact and efficacy of various flow promotion techniques such as vibration, aeration and mechanical manipulation.

In addition, members have also raised the issue of segregation, which will undoubtedly occur during the filling of bags, and while segregation is a very large subject, the renewal will attempt to address some of the major impacts of segregation on the discharge behaviour of bulk bags. The approach will be to monitor segregation occurring during filling and discharge and highlight any techniques that appear to minimise the effect of segregation. However, a fuller theoretical and experimental investigation may best be reserved for a follow-on project in the future.

The design of the full-scale rig has now been completed and will be built and commissioned during the third year of the initial project (first half of 2026). The purpose of the full-scale rig will be to confirm our findings from the 2-D rig and the DEM simulations. We intend to use the same materials (sand and Pellets) for this initial work and extend the testing to encompass two or three additional materials.

The full-scale rig has been designed to ensure that it can be relatively easily modified to incorporate flow promotion. This, together with the 2-D rig and the modelling and simulations developed so far, will provide the suite of tools required to move seamlessly into the renewal project.

2.0 Approach

A major output of the initial project has been to develop a model for the consolidation loads developed in the bulk solid in a bulk bag with highly flexible walls. The consolidation loads generated will vary depending on how the bag is handled and transported. This work has led to a series of models and simulations being developed for a variety of bag conditions, and these will be verified through full-scale validation using the full-scale test rig shown in Figure 1.

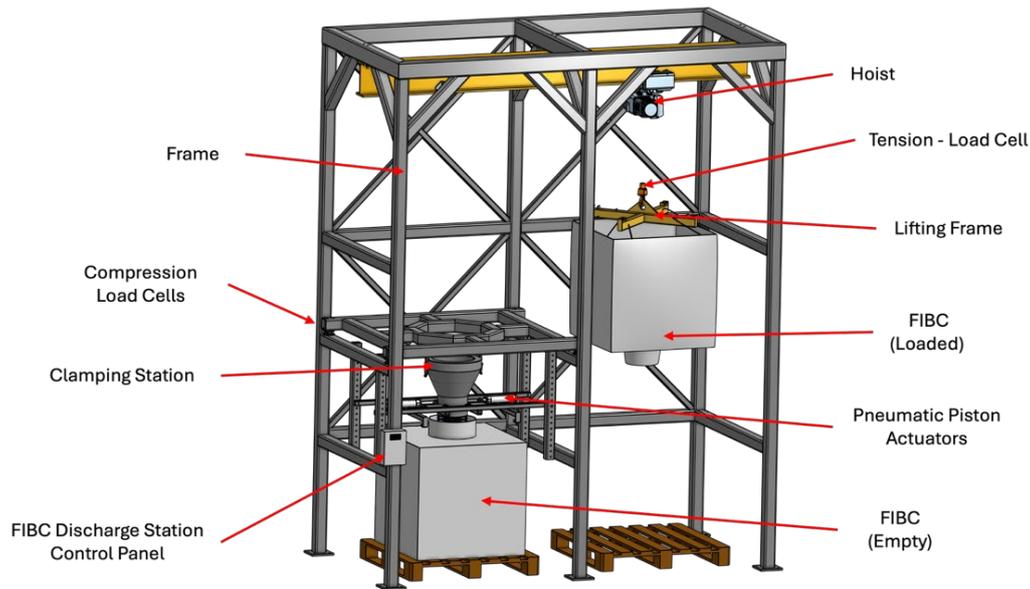


Figure 1 - Full-Scale FIBC Discharge Station

An additional finding from the initial project is that, in almost all circumstances, the discharge from the bulk bag will be funnel flow. The theoretical approach to funnel flow derived by Jenike requires a determination of the consolidation loads in order to determine the critical outlet dimension to ensure complete discharge under gravity flow.

The theory for funnel flow invariably considers 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. In the mid-1960s, 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 overestimates the size of stable ratholes. While this was regarded as quite a conservative approach to funnel flow design, it will be too conservative for an FIBC or big bag application. As a result, Roberts proposed a more realistic solution based on hoop stress theory, which takes into consideration the 3-dimensional stress state occurring within the rathole. The relevance of hoop stress was shown to extend across scales, from stockpiles to small-scale laboratory models. This same approach is being applied to the bulk bag situation, but incorporating new consolidation models derived from the initial project.

However, it is clear that in many cases, the cohesive nature of the bulk solid will generate consolidation loads that lead to very large outlet dimensions being required. In such cases, there will be a need for additional measures to aid discharge, and this will be the focus of the renewal project.

The approach will be similar to that of the initial project, with an emphasis on practical empirical testing underpinned by theoretical modelling and DEM simulation. 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 of FIBC discharge behaviour. Furthermore, the tools developed in the initial project will be readily applied to this continuation project.

3.0 Experimental Program

The experimental program will be split into three phases:

a) **Modification of the experimental rig**

The existing test rig developed and constructed for the initial project has been designed to ensure that, with fairly minimal changes can accommodate a variety of discharge aids. The 2-D rig will also be available to undertake initial testing using discharge aids. The approach here will not be to replicate commercial proprietary discharge aids but rather to understand the generic application of vibration, aeration and mechanical manipulation to provide understanding of these processes, which will lead to better application as well as the formulation of guidelines regarding how these discharge aids should be used. Initially, a test rig will be developed based on the most common form of FIBC, the so-called 'Big Bag'. The rig will be modified 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
- Apply vibration to aid discharge
- Apply aeration to aid discharge
- Mechanically manipulate the bag in order to facilitate discharge
- Investigate the effect of discharge aids on different bag types
- Investigate discharge rates that can be achieved.

b) **Comprehensive Flow Property Testing of the materials under the influence of vibration and aeration.**

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 both under instantaneous conditions and under the influence of vibration. These will be determined using the Jenike method.

This will require the development of a bench-scale test rig to determine the flow functions and wall friction conditions whilst under the influence of vibration. This will elaborate on work previously undertaken by Roberts, who conducted a series of experiments to investigate the influence of vibration on bulk solid behaviour under various conditions. In these studies, a vibrating shear cell was used to generate material flow functions utilising both pseudo-random and sinusoidal function generators. His investigation demonstrated that vibration can significantly improve flow in conventional bins, forming a strong foundation for the present investigation. Tests will also evaluate the influence of aeration in reducing wall friction and improving the flowability of the bulk solid.

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

The third section of the Experimental program will involve Flow and discharge testing of the FIBC using vibration, aeration and mechanical manipulation 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

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. An outcome of the initial project was to develop a theoretical model for consolidation loads generated within a flexible Bulk Bag under several different scenarios. This work will be extended to examine the influence of vibration, aeration and mechanical manipulation on the consolidation loads generated and their influence on discharge behaviour.

The theoretical areas of enquiry will be as follows:

- Investigate existing funnel flow theories, particularly the 3-D hoop stress and radial stress approaches developed by Roberts, to determine how major consolidation stresses derived from vibrated and conditioned flow functions may influence rathole stability, outlet sizing, and overall flow channel formation in flexible-walled containers.
- Continue to develop and extend the DEM and flexible-wall modelling framework to incorporate vibrated, and pre-consolidated conditions, using simulation outputs such as velocity fields, stress evolution, and flow regime transitions to inform and validate the broader theoretical understanding of discharge mechanisms.
- Explore methods and extend prior work to quantify discharge rates from flexible containers under varying consolidation and flow-aid conditions, vibration, and aeration effects, and compare these with observed discharge behaviour across a range of materials.
- Examine the influence of surcharge and transient loads acting on the hopper or outlet region, including those arising from vibration, handling irregularities, or eccentric lifting, to understand how these effects may alter internal stress distributions, deformation patterns, and flow uniformity during discharge.
- Investigate the mechanisms of segregation during both filling and discharge of flexible-walled containers, exploring how particle size distribution, density variation, and consolidation history influence internal layering and flow channel development, and explore how vibration, aeration, or mechanical manipulation may mitigate or exacerbate segregation effects on discharge consistency and mass flow uniformity.

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

- Modify the test facility to accommodate the application of vibration and aeration
- Provide Flow properties data for the test materials, including under the influence of vibration and aeration
- Provide findings on discharge tests and flow regimes under the influence of vibration
- Report on Theoretical review and developments to date
- Provide initial guidelines for the application of vibration to aid in discharge
- Review of progress and refine the program for Year 2

Year 2

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

Year 3

- Provide a validated systematic design approach to predict discharge performance under the influence of a variety of discharge aids
- Provide a 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 the 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 just celebrated 50 years of experience in developing technological solutions to materials handling problems in industry, varying in scale from the smaller-scale process problems through to large-scale mining operations.

Over the last decade, TBS has developed methods to model large-scale gravity flow stockpiles, which involve 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 have been applied to the FIBC case under much lower consolidation loads and have been shown to provide a useful approach to predicting discharge behaviour. This has the potential to contribute considerably to the next phase of the project.

The initial project and this proposed renewal fall within the core competencies of TUNRA Bulk Solids and the Centre for Bulk Solids.

7.0 How IFPRI members could be involved

The initial project has garnered significant interest from the IFPRI members, evidenced by the number of members who have volunteered to be involved in the Liaison Group for this project.

Over the first two years of the project, regular update and consultation meetings have been held where progress has been discussed and guidance regarding the future of the project has been provided. We believe the input and collegiality in the conduct of this project are leading to good outcomes, and members have had the opportunity to shape and advise on the project direction. We envisage this very successful approach being continued into the renewal project.

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 February 2027. 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. 1961**. Gravity Flow of Bulk Solids, Bulletin No. 108. Salt Lake City, UT: University of Utah, 1961
- 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, 146-201.
- Roberts, A.W. 2005**. Characterisation for hoppers and stockpile design. Chapter 3, Characterisation of Bulk Solids. Edited McGlinchey, Blackwell Publishing, 85-131.
- 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.
- Goodey, R.J., Brown, C.J. and Rotter, M.J. 2006**. Predicted patterns of filling pressures in thin-walled square silos. Engineering Structures.