

Effect of flexible walls on granular flows: Design of Flexible Intermediate Bulk Containers.

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1 Introduction

Solids are stored transported in Flexible Intermediate Bulk Containers (FIBCs), which are flexible containers made of plastic fabrics for storing granular materials up to 1 ton in weight. These are usually made of woven polypropylene, though other materials such as rubber and carbon fibers are also used. The bag has four handles which are used for lifting usually by cranes. The cross section of the container could be cylindrical (made of a single sheet), rectangular, or other shapes, either single fabric or with seams and with baffles for retaining shape. For filling, the FIBC has either an open top or a cylindrical inlet. Emptying is usually has a cylindrical discharge at the bottom which is usually tied and then covered in a second layer of fabric that can be closed. The discharge could also be through a plain bottom where the entire bottom opens, through a ‘diaper’ (circular cut-out in the bottom) or a spout. FIBCs are lifted by cranes using handles at the top, placed in cargo containers and then transported to the destination. They are then unloaded and placed on discharge stations, where the bottom is opened. Though granular flows in rigid containers have been widely studied, there is almost no study in open literature of granular flow through flexible containers. A modeling approach is proposed here for resolving some fundamental issues of the stress states in the granular assembly and the walls, how these are affected by geometry, wall properties and filling protocols, and how these affect the discharge rates.

The modeling approach, and its connections to representative design choices and performance metrics, is shown in figure 1. The static design choices include the fabric material and its mechanical properties, the geometry, the filling protocols and the transportation protocols for storage. These depends on the static states of the materials after filling and during transportation, the stress states of the granular material and the container wall. The design choices for discharge are the type of discharge (bulk or localised) and discharge unit design. If the discharge unit is made of flexible material, the discharge rates will depend on the stress state and the interaction between the flow and the flexible material. The performance metrics are the cost per unit load, and ability to enhance and control the filling and discharge rates. These depend on the ability to predict the stress states and the discharge rates.

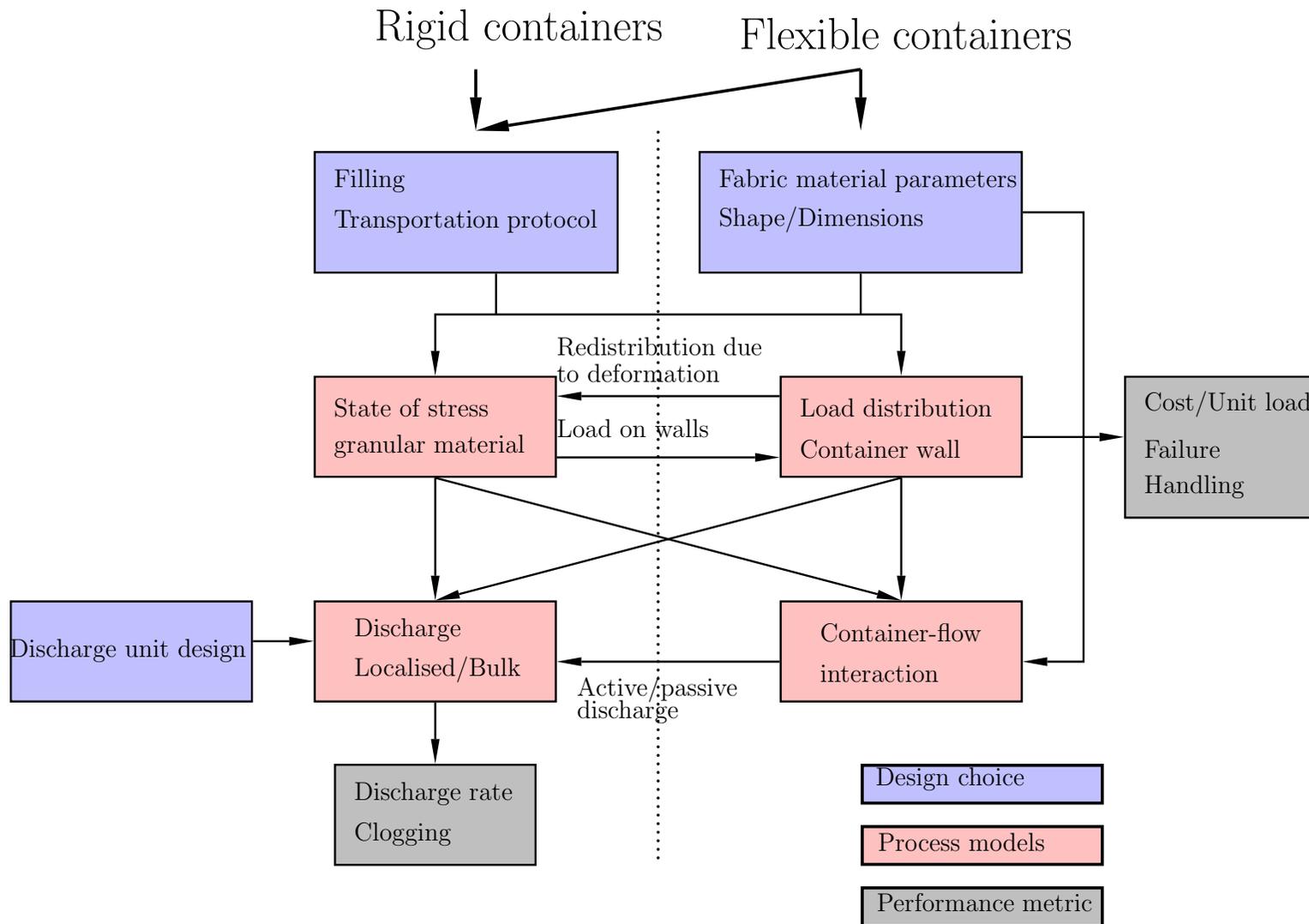


Figure 1: The static and dynamic processes that will be modeled (red boxes), the design choices that affect these processes (blue boxes) and the performance metrics determined by these processes (gray boxes).

Two models on the left, the stress state in a container and the discharge from the container, have been studied for rigid containers. New models are required for the two on the right, the stress state and deformation in the container wall and the flow-wall interaction. However, there is a two-way interaction between the models on the right and left. The container deformation causes particle rearrangements which alter the granular stress state, and particle rearrangement alters the load the wall and its displacement. The discharge rates depend on the stress state in a granular material. For the granular flow in a rigid container, the Beverloo correlation states that the discharge rate depends only on the diameter of the exit, but not on the overburden or the material density. In contrast, for a liquid, the Bernoulli equation states that the discharge rate depends on the exit diameter, height of column and density. It is necessary to examine this dependence for a material stored in a flexible container, and also examine the effect of dynamical interactions between the flow and the wall.

Feedback from IFPRI technical experts that would be useful for:

1. **A more comprehensive and granular list of design choices in design of FIBCs.**
2. **The performance metrics usually used for design of FIBCs.**

The proposed project will examine the stress state and discharge from flexible-walled containers from a fundamental perspective. The wall flexibility, which is hitherto missing in the description of granular flows, will be incorporated using models described in the main proposal. The research will focus on aspects in which there could be qualitative differences between the stress state and the flow dynamics in containers with flexible walls. In devising scale-up protocols for FIBCs, the wall material parameters will be included in the description, as will phenomena at both the particle scale and the macroscale. The analysis of stress state will include effect of wall deformation during the filling process on the stress, and examine the contrast between hydrostatic filling where the weight of the material is borne by the base, and Janssen filling where the load is on the walls. The study of discharge characteristics will examine the Beverloo law and the clogging possibility for hopper discharge, as well as effect of coupling between the granular and wall dynamics for discharge from a chute. These will enable us to construct a parameter map in the space consisting of dimensionless parameters for the granular and wall dynamics, where different discharge characteristics are observed. This can then be used to design FIBC dimensions and wall properties to attain specific stress states and discharge characteristics.

The physical phenomena being modeled are described in words without any mathematical formulation, so that the focus is on the physics involved. The author would be happy to provide the mathematical formalism if required. In the description below, coloured in blue are the fundamental questions which we plan to pursue and would appreciate feedback from IFPRI members, and coloured in red are the kinds of information that can be provided by IFPRI members. Apart from the questions raised below, we will also come up with additional questions as the analysis is carried out, and address these.

2 Stress state

The state of stress in a container with flexible walls made of a granular material could be very different from a rigid container, because the walls of the container can deform in response to applied stresses. It is known that very small particle rearrangements can cause a large change in the stress state in the bulk granular material. In addition, it is also necessary to specify the state of stress of the wall of the material in the filled state as well. In this context, there are several fundamental open questions with regard to the state of stress when the material is filled into a flexible container.

2.1 Container material parameters

The walls of the container is made of thin sheets of polymers, which stretches and bends under applied loads. The motion of an elastic sheet under an applied load is described by a displacement fields u_1 and u_2 in two directions along the surface and a displacement field w perpendicular to the surface, as shown in figure 2. These fields are governed by the Foppl-von Karman equations which contain force balances perpendicular and

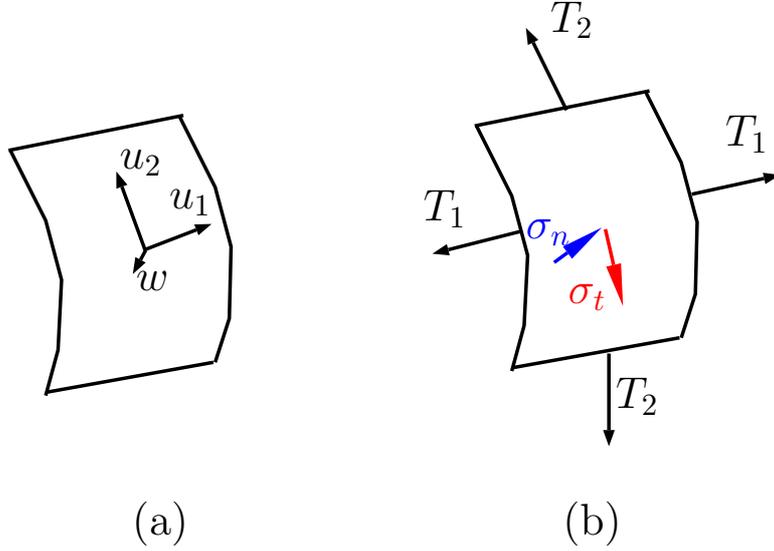


Figure 2: The co-ordinate system used for analysing deformation of an elastic sheet (a) and the force balance on the elastic sheet (b).

parallel to the surface. The detailed form of the equations is not provided here, since these are not easy to solve and excessive detail is not necessary at this stage. We just provide the physical meaning of the terms in the equations, to describe the differences between the present system and the classical theories for elastic sheets, and explain why current continuum models and software can not be easily used.

The force balance normal to the surface contains the following terms.

1. The applied stress (force/area) perpendicular to the surface (σ_n in figure 2 (b)).
2. The bending term which depends on displacement perpendicular to the surface; this contains the flexural rigidity $D = (Eh^3/12(1 - \nu^2))$, where E is the Young's modulus, h is the plate thickness and ν is the Poisson ratio.
3. The Cauchy stress tensor along the surface which, when substituted into the equations contains the parameter Eh , and the Poisson ratio ν .
4. There is a tension term in the two orthogonal directions, T_1 and T_2 in figure 2 (b), which is *not* included in the classical theories for elastic sheets. The tension T is the force per unit length, which is the total weight of the granular material divided by the perimeter of the horizontal cross section if all the load is on the base.

In the direction parallel to the surface, it is usually assumed that the divergence of the stress is equal to zero. When a granular material is filled in a container, there could be a non-zero shear stress at the wall depending on the force transmission mechanisms, shown by σ_t in figure 2 (b). Therefore, the tangential stress balance is fundamentally different from that in classical theories of elasticity. In summary, there are two effects not included in classical theories for elastic sheets, which are the tangential stress at the surface and the tension. The other parameter of interest for the integrity of the container is the tension at which the material fails, T_f .

2.2 Scale-up

In the scale-up of filling and discharge processes, scale models of smaller dimensions are made and tested for the dimension, stress state and discharge characteristics. In this scale-up process, dimensionless parameters have to

be kept a constant between the model and actual system, in order to predict the deformation during filling and discharge characteristics of the actual system. In addition to the weight of the material W and the dimensions (height and cross-section), there are dimensional parameters characterising the tension and elasticity of the material that are important. Based on the discussion of constitutive relations in the previous sub-section, the dimensional parameters are the flexural rigidity $D = (Eh^3/12(1 - \nu)^2)$, elasticity modulus Eh , and the tension T_f at which material fails. The tension in the material is determined by the loads and the dimensions of the container. The characteristic tension is the total weight W divided by the perimeter l_p of the horizontal cross section,

$$T = \frac{W}{l_p}.$$

Based on this, we can formulate the dimensionless ratio of the tension and the elasticity modulus, (T/Eh) , and the ‘Foppl parameter’ (D/EL^2) , where L is the characteristic length scale. The Foppl parameter is usually small, but the scaled tension (T/Eh) is a parameter which will affect the stress state when filled and the discharge characteristics. There are also particle-particle and particle-wall friction coefficients.

There are also some dimensional parameters at the particle scale that affect the state of stress. When material is filled in to a flexible container, wall displacement of the order of one particle diameter could result in rearrangement of particles and reconfiguration of the stress fabric. It is necessary to relate the wall tension and properties and the minimum displacement for particle rearrangements, in order to infer the state of stress in the final filled state. Additionally, friction between particles and between the particles and wall can be used to modify the nature of stress fabric.

The protocol for scale-up is one of the aspects to be considered in this project:

1. Identify and estimate all the dimensional parameters that determine the stress state in the granular material and the container, and formulate dimensionless groups that characteristise the system.
2. For scale-up, determine the dimensionless groups to be maintained constant in FIBC filling and discharge.

Information from IFPRI technical experts that would be useful for this are:

1. Are the elasticity parameters known for the wall material of FIBCs, have tensile tests been carried out to determine the elasticity modulus, and is the elasticity used as an input for design?
2. Are there current scale-up protocols for FIBCs?

2.3 Janssen vs. hydrostatic regime

The hydrostatic pressure at the bottom of a container filled with liquid is proportional to the height of the liquid, and it increases linearly with height, as shown by the blue pressure profiles in figure 3. Here, there is a pressure exerted on the walls of the container, but there is no shear stress on the walls. In contrast, when a bulk granular material is filled in a rigid silo, the pressure at the bottom does not increase with height, but it saturates at a constant value when the height exceeds a critical value, as shown by the red pressure profile in figure 3. The weight of the granular material is transferred to the wall of the silo, and there is a shear stress exerted on the wall due to frictional wall-particle forces. In a flexible container, there will be wall motion as the material is filled, and in subsequent compaction at a location as the overburden increases. This will result in rearrangement of particles and contacts, and this could transfer the load from the base to the walls or vice versa. A fundamental unresolved issue is whether there are distinct Janssen and hydrostatic regimes in a flexible container, or some other intermediate state. The state of stress will also determine the storage and discharge characteristics of the material. If the filling is hydrostatic, the weight of the material is transmitted to the base, and a higher yield strength of the base material is required in contrast to the Janssen filling. If the weight of the material is transmitted to the sides requiring less strength at the base, but there is the possibility of clogging of the material. Therefore, identification of parameter regimes for different stress states is likely to provide guidance for material selection and shape design.

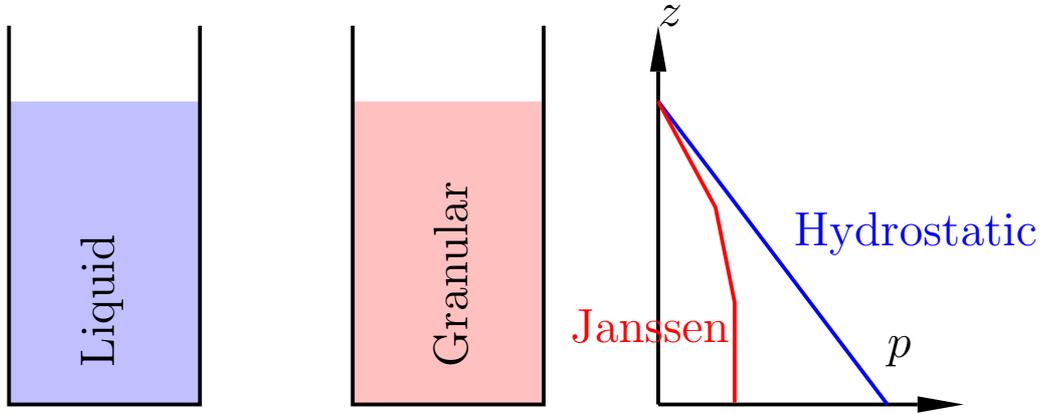


Figure 3: Pressure variation with height in the hydrostatic and Janssen regimes.

The distinction between the Janssen and hydrostatic regimes is proposed to be explored in both experiments and simulations. The fundamental question is:

1. What are the material parameters and dimensions for which the load in an FIBC transmitted to the walls, and what are the material parameters and dimension ratios for which it is transmitted to the base.
2. How does flow filling protocol affect state of stress.
3. What is the minimum wall displacement, and the normal stress, for rearrangement of particles and the stress state.

The simulation methodologies for modeling flexible bases were described in the original proposal. In experiments, it is proposed to fill flexible containers with different dimensions, wall elasticity, tension and loading with materials of different densities, and use stress transducers to determine the load on the bottom and on the walls.

Information from IFPRI technical experts that would be useful for this are:

1. Have these two different filling regimes been examined in FIBCs, or is only either one observed in practice?
2. Have wall stress measurements been carried out to determine the stress state, and its evolution during filling?

3 Discharge

The discharge from FIBCs can be divided into two broad categories, bulk discharge and hopper discharge.

3.1 Bulk discharge

In the discharge of materials through vertical chutes, it is desirable to design the properties so that the discharge rates are controlled and repeatable. When the wall is made of a flexible material, there are at least three methods by which the wall dynamics could affect discharge.

1. The shape of the container could change, and this could affect the discharge rate,
2. The state of stress in the filled state could be influenced by the flexibility of the material, and this could affect the discharge.

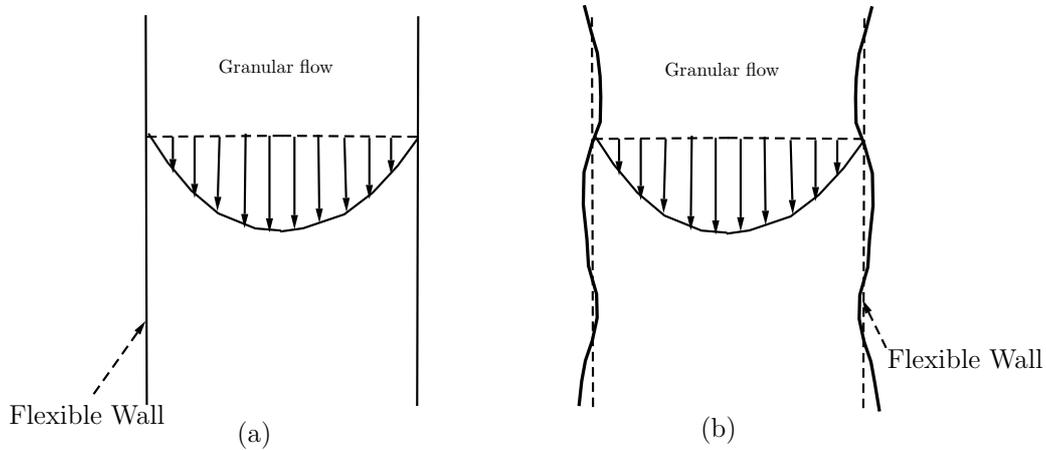


Figure 4: A passive wall with no dynamical coupling to the flow (a) and spontaneous wall motion with dynamical coupling to the flow (b).

3. There could be a dynamical coupling between the wall dynamics and the flowing granular material, which could affect the discharge rates. The distinction between discharge without and with dynamical coupling is shown in figure 4, where the wall is passive in the absence of coupling in figure 4 (a), but there are wall oscillations and waves coupled with granular flow in figure 4 (b). There are at least two different types of instabilities known in literature, that for fluid flow past flexible surfaces, and that for shearing of frictional materials like rubber resulting in stick-slip motion (Schallmach waves).

The first of the above will be studied as part of the formalism for scale-up in section 2.2, and then we will use the formalism of Jenicke to predict the flow rate for the deformed container shape. The second and third topics above will be examined as part of this project. The specific issues are the following.

1. How is the rate of discharge from a chute affected by the state of stress, specifically the Janssen vs. hydrostatic stress regimes.
2. The dynamical coupling between the flow of a granular material through a flexible walled chute, and the instability that could result from this coupling.

Information from IFPRI technical experts that would be useful for this are:

1. Is it known how the filling protocol, for example, filling through the center or raining particles uniformly, affects the discharge?
2. Have surface waves or stick-slip motion been observed during discharge of granular materials from chutes with flexible walls?

3.2 Hopper discharge

Hoppers are used when localisation of the discharge is necessary, and hopper discharge rates depend on the characteristics of the granular flow in the vicinity of the hopper. While discharge from rigid hoppers is a well-studied problem, there have been virtually no studies on discharge from flexible or compliant hoppers. The Beverloo law is used for predicting the dependence of the outlet flow rate on the diameter. This is based on simple dimensional analysis, assuming that the only relevant parameters are the size of the outlet and the gravitational acceleration. The flow rate is *not* dependent on the overburden. The Beverloo law is applicable for granular materials because of the Janssen criterion, where the pressure on the base is independent of the



Figure 5: Clogging in an outlet with a rigid base (a) and unclogging due to wall displacement on the order of a particle diameter in an outlet with a flexible base (b).

height of the granular material. In contrast, for liquids in a container, the discharge rate does depend on the height through the Bernoulli equation. An issue of interest is how the discharge rates depend on the state of stress in the container.

Ideally, narrow hoppers can be used to localise the discharge, but the flow rate depends on the dimension of the hopper, and clogging of granular materials is a significant problem in hopper discharge. Clogs are due to arches which are difficult to break up in rigid hoppers, as shown in the left in figure 5 for an outlet in a rigid base. When the base is flexible, it is expected that deformation on the scale of one particle diameter will be able to break up arches, as shown on the right in figure 5. The flexibility of the wall material can be designed so that the the wall displacement exceeds a minimum value in the presence of the load exerted by the arch, so clogs can be broken up.

The fundamental issues that will be considered in the first phase are the following.

1. How is the Beverloo law for hopper discharge modified if the discharge is through a flexible hopper? Can the elastic properties be designed to control the flow rate?
2. How do the elastic properties of the hopper affect the clogging rates in the discharge of dry granular materials?

Active devices such as ‘massage paddles’ are used to enhance hopper discharge in FIBCs. The use of active devices will be considered in the next phase after these fundamental issues are resolved.

Information from IFPRI technical experts that would be useful for this are:

1. Has a comparison been made of discharge from hoppers with rigid walls and those with flexible walls of the same shape, and has the Beverloo correlation been verified?
2. Has the clogging behaviour through flexible hoppers been compared with those through rigid hoppers of the same shape?