Proceedings of The National Conference
On Undergraduate Research (NCUR) 2017
University of Memphis, TN
April 7-9, 2017

The Effect of Grain Shape on Side-Wall Pressure in Model Grain Silos

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Abstract

Granular materials are collections of macroscopic particles, such as corn, rice, and peas. Grain silos store granular particles and are subjected to irregular force build-up, which can have catastrophic results. It has long been observed that the pressure at the bottom of a silo is not proportional to the fill height of the silo. The force build-up on the side-walls of grain silos from materials of different aspect ratios, specifically corn, peas, and rice, was studied. The model silo used in the experiment was constructed out of sheet metal pipe 48 inches in length and 6 inches in diameter held in place by a frame constructed of 80/20 aluminum. A hopper with a diameter of 6.5 inches at its widest point and 1.5 inches at the bottom feeds the grain into the silo. Four identical 1.25 inch holes were sawed into the bottom of the wall of the silo to accommodate four force sensors. The four sensors were evenly spaced vertically and used disks of sheet metal approximately 1 inch in diameter screwed into the sensors internal load cell to evenly distribute the applied force. The fill height was approximately 40 inches from the bottom of the silo. Rice was found to exhibit more irregular force build-up, while corn and peas were more regular. Corn and peas followed Gaussian force distributions, but rice was more varied and randomly distributed around the mean force. Corn and peas tended to build up to a final force, while rice reached a maximum and then decreased. Finally, the time at which corn and peas reached a maximum force was more frequently at the end of a run than rice. Rice's irregularity is attributed to its large aspect ratio in comparison to peas and corn.

Keywords: Granular Materials, Granular Flow, Grain Silos

1. Introduction

Granular physics is commonly experienced because granular materials are abundant. Granular materials are one of the most manipulated materials in industry, second only to water[1]. Examples of granular materials include the sands on the beach, grains such as corn and rice, pharmaceutical pills, and even the rings of Saturn. Granular particles exhibit many unique properties. In particular, granular materials can encompass all three states of matter: for example, sand can be a solid when we walk on it at the beach, sand can also be a liquid as it pours through an hourglass, and sand can even be a gas in a sandstorm[2].

While granular materials are ubiquitous, there are still many open granular physics questions. The plethora of open questions makes it difficult to engineer systems that efficiently deal with granular materials. Many of the difficulties working with granular materials stem from the disorder present in both the position of the grains in a granular material as well as the distribution of internal forces in the granular material[3]. Jamming is another granular phenomenon that occurs when granular materials go from flowing (liquid) to jammed (the solid state)[4]. These unique properties lead to interesting granular phenomena. For instance, natural disasters, like avalanches and earthquakes, are dangerous granular phenomena. Excavation efforts are also affected by granular materials because of their transportation, which can be hindered by jamming[5]. Understanding the risks associated with certain granular materials and the impact grain shape has on these risks, can help recognize locations at risk for dangerous situations.

One especially important issue that has plagued those in the agriculture industry is granular storage, specifically storage in grain silos[6]. While force build-up in confined systems like grain silos has been researched for over a century, much is still not known about granular materials[4]. It has been observed that the properties of a granular material like moisture content influence loads in model silos, and these effects are not addressed by standard design codes[7]. Silos vary in design, and studies have examined a range of silo shapes including rectangular silos, circular silos, and hexagonal silos[8, 9, 10]. Grain silos often experience extreme deformation and even collapse due to the forces exerted by granular particles on silo walls (for an image of silo collapse, see reference 20). Pressure on silo walls from granular materials is known to be affected by the filling method of the silo, which can result in asymmetric mixed flow instead of mass flow[11, 12]. In addition, other studies have modeled grain flow and the resulting side-wall pressure in silos by using discrete element methods and finite element analysis[13, 14, 15, 16].

This study examines the effect of grain shape on force build-up over time on silo walls. Previous experiments by Janssen observed that vertical pressure at the bottom of a grain silo is not proportional to the fill height of the silo by measuring the pressure on the bottom of loaded silos[4]. Vertical force is distributed downward through the granular material through force chains, which places stress on the silo walls[3]. Another study on grain shape observed the behavior that resulted when external stresses were applied to anisotropic collections of grains[17]. This project examines local force build-up on silo walls using four quasi-particle scale strain gages located at the bottom of the silo. The failure of silos and other granular storage devices has the potential to cause physical and economic harm, so a successful solution and explanation for this occurrence would both improve the understanding of granular physics in the scientific community and provide a useful industrial solution to issues with granular storage that will improve efficiency and reduce risk.

2. Experimental Methods

A controlled grain silo system was needed to accurately examine the phenomena that occurs in grain silos. The model silo used in the experiment was constructed out of sheet metal pipe 48 inches in length and 6 inches in diameter held in place by a frame constructed of 80/20 aluminum. Though this a larger height to diameter ratio than typical industrial grain silos, this model is used to study basic questions of confined granular flow, which has applications to grain silos. A hopper with a diameter of 6.5 inches at its widest point and 1.5 inches at the bottom feeds the grain into the silo. Four identical 1.25 inch holes were sawed into the wall of the silo to accommodate four identical GLX force sensors (Figure 1). Held in place by a metal rod, the four sensors were evenly spaced vertically and used disks of sheet metal approximately 1 inch in diameter screwed into the sensors internal load cell to evenly distribute the applied force (Figure 2). The distance from the center of the top sensor and bottom sensor was 5.5 inches, and the distance from the bottom of the silo to the center of the top sensor was 8 inches. The fill height was approximately 40 inches from the bottom of the silo.

Because this project required a large number of data sets to produce accurate statistics, one hundred trials were performed for each grain type. A single trial involved lifting a bucket filled with one of the three grain types to the top

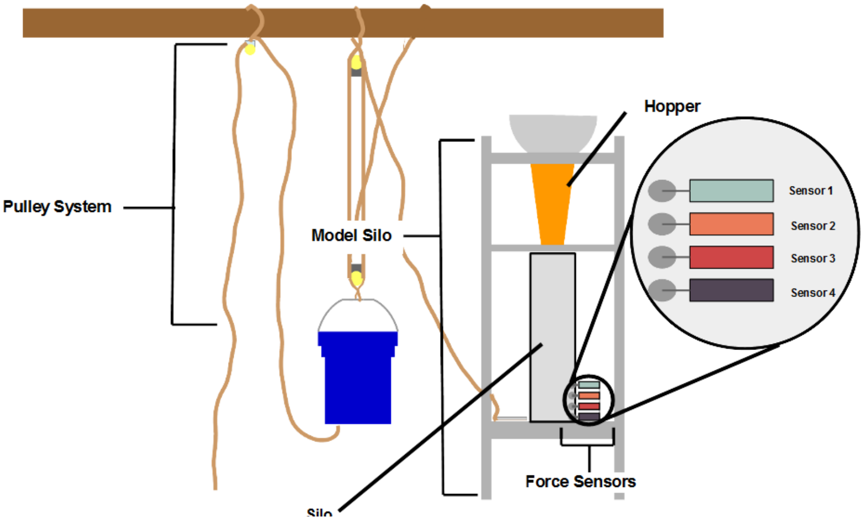

Figure 1: The experimental setup including the pulley system and model silo.

of the silo and pouring it into the hopper. The force sensors at the bottom of the silo collected data at a rate of 10 Hz, which was then exported for analysis in Python.

Figure 2: Sheet metal force disk, a single pea, kernel of corn, and grain of rice

To ensure that a large number of trials could be completed, a pulley system was created to lift the buckets, which on average weighed forty pounds each, to the top of the silo. After lifting the buckets up, which was significantly easier due to the pulley system's mechanical advantage that cut the force required to lift it to a third of the original value, the rope was tied to a cleat to prevent it from falling back down. An additional pulley was used to tilt the bucket, allowing the grain to be poured into the system. While the pulley system allowed the system to avoid doing more work against gravity, it was not possible to circumnavigate lifting the buckets to transfer the grain from the collection bucket back to the bucket in the pulley system.

3. Results

The data from the trial runs was used to plot force as a function of time (Figure 3). Curves *A*, *B*, *C*, and *D* show the variety of force profiles that appeared throughout the project. Each graph reveals different details about the force build-up of the particular granular material. Peas, corn, and rice exhibit all four shapes with differing frequencies. It is possible for a multitude of profiles to appear simultaneously in a single run (Figure 5).

Interpretation of the data required statistical analysis, primarily done in Python. Plots *A*, *B*, and C are histograms of maximum force for each grain type (Figure 4). Using Python, a Gaussian curve fit was fitted to each histogram[18, 19]. This indicates if there is a meaningful statistical distribution present. The histograms show that corn and peas have less variation than rice. Rice has a much larger standard deviation than peas and corn, as well as a larger mean force.

Plot *D*, Figure 4 is a graph of the maximum force for the individual sensors, with error bars representing the standard deviation of the data set. Because the error bars intersect one another, the data collected from each sensor is not statistically distinct. If the system behaved like a classical fluid, it would be expected that the bottom force sensor would experience more force; however, this only occurs with the bottom sensor in trials with rice, and not with any other sensor for the other grain types.

An analytical metric was applied to the data sets to characterize the curves represented in Figure 3. This metric indicates how closely the final force was to the maximum force. A value closer to one represents a dominance of curves *A* and *C*. Histograms of the characterization method using force are shown in Figure 6. Because there are many occurrences for which the ratio is close to one for corn and peas, shapes *A* and *C* dominate. However, there is a wider range of values shown for rice, which indicates that shapes *B* and *D* are more frequent than in peas and corn.

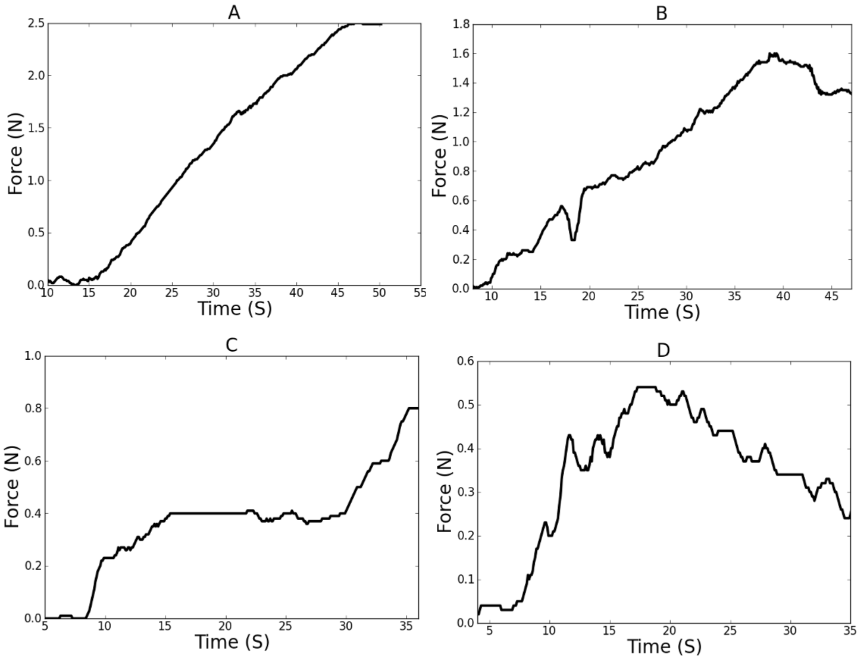

Figure 3: Examples of the force profiles that were exhibited in the experiment throughout various trials with different grains. These representative curves appear in all grain types, but with varying frequency.

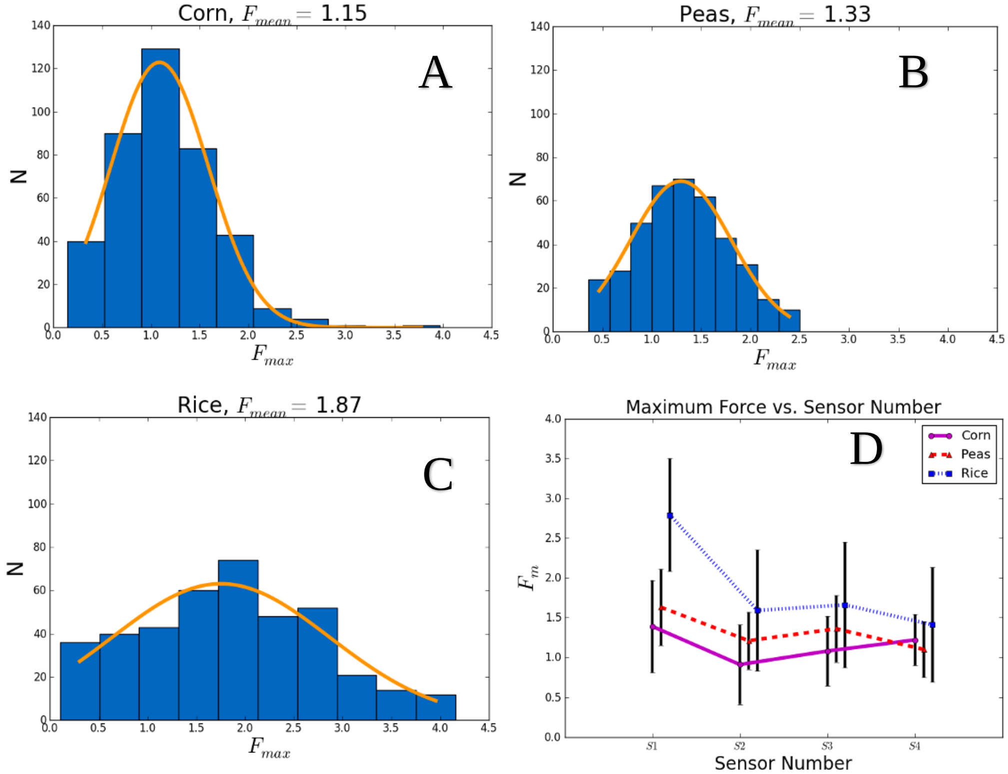

Figure 4: Figures A, B, and C are maximum force histograms for each grain type. Figure D is a graph of the maximum force for the individual sensors with error bars representing standard deviation

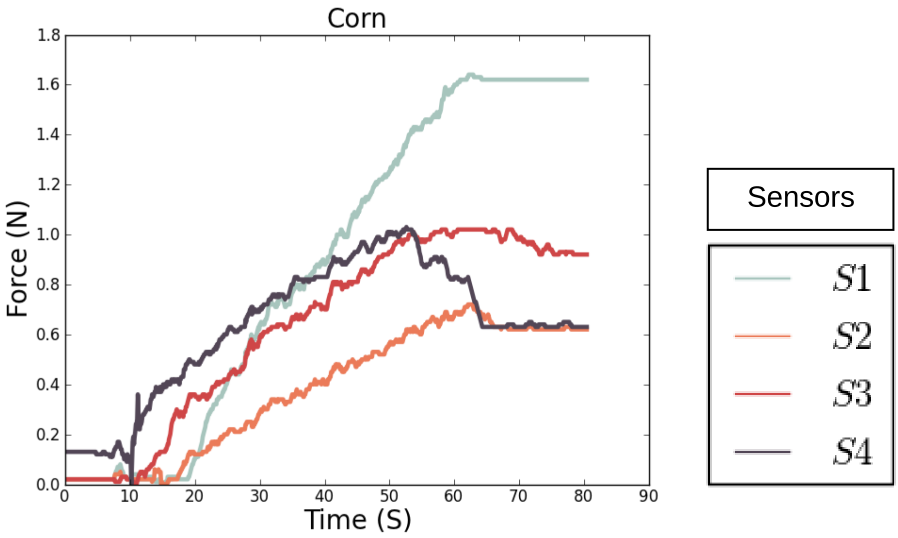

Figure 5: Multiple different force profiles present in a single run

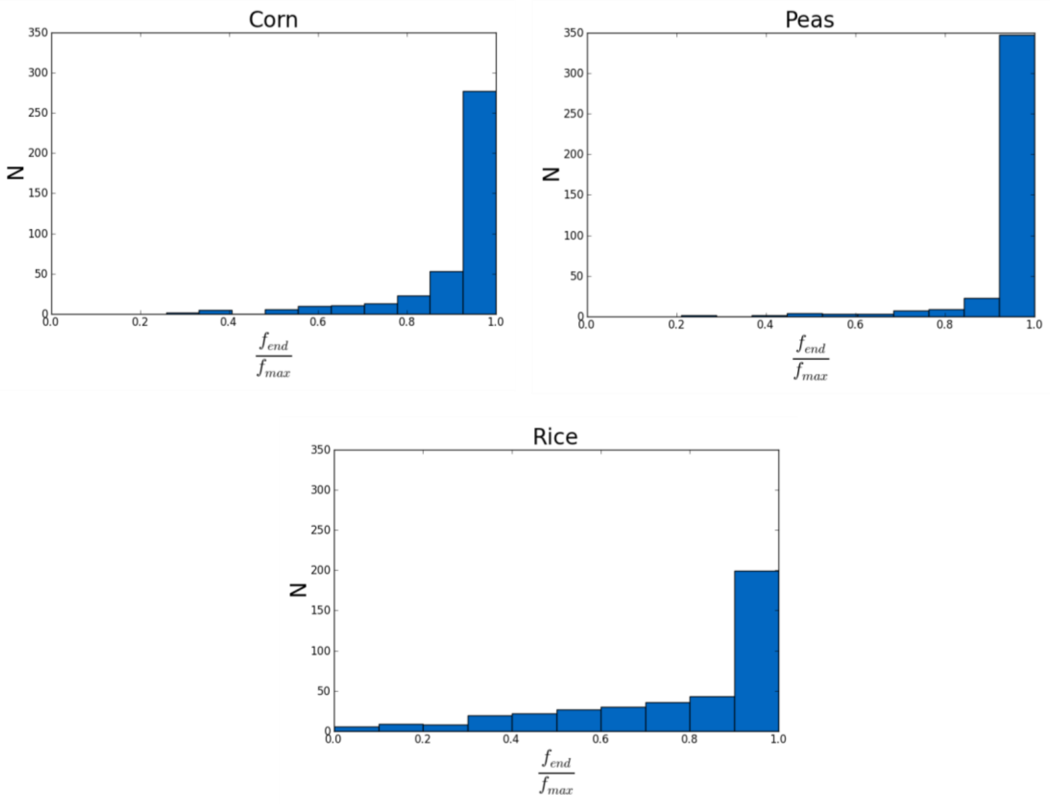

Figure 6: Histograms of the ratio of the final force and maximum force for each grain type

4. Conclusions

The results of this experiment reflect the differences in each grain type used: corn, peas, and rice. The spherical shape and more regular nature of peas produced much more regular data. The dominance of curves *A* and *C* indicates that the force build-up is more regular as well, building up to the maximum value instead of building and then decreasing like in curves *B* and *D.* Corn was close in nature to peas, possessing some of the same characteristic curves and data based on the metrics used. Rice's large aspect ratio produced irregular curves and data (Figure 2). Rice's irregular shape causes it to experience jamming more often. Small fluctuations in force along a curve are due to jamming, and subsequently unjamming, then building force again (Figure 3, graph *D*).

The maximum force histograms of corn, peas, and rice show strong differences between the three. While corn and peas are similar, rice does not appear to follow a Gaussian force distribution. Corn and peas have maximum force histograms that are more evenly distributed around the mean.

In conclusion, the force profiles shown by rice were much more irregular than the force profiles shown by corn and peas. Peas and corn more closely follow Gaussian force distributions than rice, which was more randomly distributed around the mean. Peas and corn more frequently show force profiles in which the final force is equal to the maximum force than rice. Finally, the maximum force for peas and corn more frequently occurs at the final time than rice. This irregular behavior is attributed to rice's large aspect ratio. This research expanded the understanding of how granular materials of different shapes behave. This knowledge will help improve the safety and efficiency of new granular storage systems.

5. Acknowledgements

I would like to thank Dr. Eli Owens for help on this work, James Satterfield for preliminary work, and Taylor Davidson for building the silo.

6. References

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