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Abstract

Calculation of the extraction force for a grain entrapment victim requires a coefficient of friction between the grain and the surface of the victim. Because denim is a common fabric for the work clothes that cover entrapment victims, the coefficient of friction between grain and denim becomes necessary. The purpose of this research was to calculate the apparent coefficient of friction of wheat on denim fabric using a proven procedure. The expectation is to improve the current understanding of conditions that influence extraction forces for victims buried in wheat. The apparent coefficient of friction of wheat on denim fabric was calculated to be 0.167 with a standard deviation of ±0.013. The wheat had a moisture content of 10.7% (w.b.) and bulk density of 778.5 kg m-3. The apparent coefficient of friction of wheat on denim was not significantly affected by pull speeds of 0.004, 0.008, and 0.021 mm s-1 nor normal grain pressures of 3.2, 4.8, 6.3, 7.9, and 11.1 kPa. This is a beginning of understanding the conditions that influence the extraction forces for grain entrapment victims.

Keywords

Farm safety, Grain entrapment, Grain rescue, Grain extraction

Disciplines

Bioresource and Agricultural Engineering | Ergonomics | Risk Analysis

Comments

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Apparent Coefficient of Friction of Wheat on Denim

C. V. Schwab

Abstract. *Calculation of the extraction force for a grain entrapment victim requires a coefficient of friction between the grain and the surface of the victim. Because denim is a common fabric for the work clothes that cover entrapment victims, the coefficient of friction between grain and denim becomes necessary. The purpose of this research was to calculate the apparent coefficient of friction of wheat on denim fabric using a proven procedure. The expectation is to improve the current understanding of conditions that influence extraction forces for victims buried in wheat. The apparent coefficient of friction of wheat on denim fabric was calculated to be 0.167 with a standard deviation of ±0.013. The wheat had a moisture content of 10.7% (w.b.) and bulk density of 778.5 kg m*$^{-3}$*. The apparent coefficient of friction of wheat on denim was not significantly affected by pull speeds of 0.004, 0.008, and 0.021 mm s*$^{-1}$* nor normal grain pressures of 3.2, 4.8, 6.3, 7.9, and 11.1 kPa. This is a beginning of understanding the conditions that influence the extraction forces for grain entrapment victims.*

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Designers of cylindrical metal grain bins calculate the loads exerted by grain on the bin walls and other bin components in contact with grain for the purpose of optimizing their designs between often opposing objectives of structural safety and manufacturing costs. An integral part of these calculations is a dimensionless term called the coefficient of friction of grain on the structural surface (ASABE, 2015). This dimensionless term influences the magnitudes of grain loads and the distribution of those loads. Several researchers (Bickert and Buelow, 1966; Brubaker and Pos, 1965; Clark and McFarland, 1973; Moore et al., 1984; Ross et al., 1987; Tsang-Mui-Chung et al., 1984) have developed and used devices to measure the coefficient of friction of grain on a structural surface.

A parallel application of the coefficient of friction is used by those calculating the forces required to extract buried objects. Reimbert and Reimbert (1976) calculated the tensile stress on a vertical rod buried in grain. Cowin and Trent (1980) developed an equation for predicting the forces required to extract a spherical shape from a static granular mass. The equation combines the gravitational weight of the object and the summation of boundary shear around the shape. Boundary shear is the pull exerted by individual granular kernels rubbing along the surface of the object. This pull increases as the lateral pressure increases.

Schwab et al. (1985) expanded on the principal of boundary shear identified by Cowin and Trent (1980). Schwab et al. (1985) combined boundary shear with Janssen's equation

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(Janssen, 1895) for predicting granular pressures and the approximate surface area of humans to develop a model for predicting the force required to extract a victim buried in grain. The frictional force of grain on the surface of the victim's body is the mechanism that transfers the lateral grain pressure into the force required for extraction. Most recently, Roberts et al. (2015) measured the differences in extraction forces with and without a grain rescue tube. They determined that the extraction force increased if no grain was removed from inside the tube. When grain was removed from inside the tube, the extraction force was less.

The Northeast Regional Agricultural Engineering Service (NRAES, 1986) provides solutions for rescuing people entrapped in grain. NRAES instructs rescuers not to attempt to pull the victim free using ropes or harnesses. The reason given was that the tremendous drag created by the grain would likely cause further injury. Rescue procedures recommended by Worsing (1993) include the importance of a speedy removal of the victim, never using a rope to pull the victim, surrounding the victim with a cofferdam to prevent grain from covering the person, and cutting a V-shaped opening in the bin wall for grain removal. Roberts et al. (2011) summarized the evaluation of the findings from 686 grain entrapment cases. Their research acknowledged that the most effective extraction involved cutting or punching holes in the bin. They concluded that much remains unknown concerning the approaches to successfully rescue victims entrapped in grain.

The objectives of this study were to measure the magnitude of the coefficient of friction of wheat on denim fabric and explore the characteristics of the interactions between wheat and denim. The expectation is to improve the understanding of conditions that influence the forces for extraction of victims entrapped in grain.

Procedure

The magnitude of the apparent coefficient of friction was determined by the use of a friction device developed by Ross et al. (1987). The friction device is shown in figure 1. The test consisted of pulling a denim-covered blade (381 mm length, 76.2 mm width, and 2.7 mm thickness) through pressurized wheat at a controlled speed using a universal testing machine. This universal testing machine (MTS Criterion Series 60 with TW Elite 2.3) has a data recording force transducer with controlled velocity and an adjustable data acquisition rate of 1 to 5 Hz. The denim-covered blade was pulled through grain to simulate the condition of grain at the verge of impending motion to determine the coefficient of friction. The denim sample was cut from a bolt of generic denim purchased at a local fabric store. The three speeds tested were 0.004, 0.008, and 0.021 mm s^{-1}. The total travel distance of the blade never exceeded 4 mm.

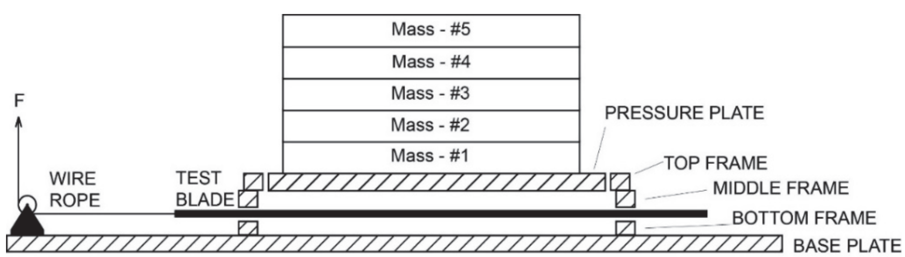

Figure 1. Schematic of the friction device used to measure the apparent coefficient of friction.

Table 1. Randomized order in which various combinations of speed and pressure were tested to eliminate systematic error.

Speed ($mm\ s^{-1}$)	Pressure (kPa)				
	3.2	4.8	6.3	7.9	11.1
0.004	41	27	3	7	37
	43	40	13	4	18
	26	29	25	35	23
0.008	38	10	14	1	15
	12	16	5	2	24
	22	8	21	45	19
0.021	6	39	28	34	33
	20	9	36	17	30
	44	11	32	31	42

The tension/compression force transducer used for measurements had a 223 N capacity. The non-linearity and hysteresis for the transducer were less than ±0.03% and ±0.02% of rated output, respectively. The expected accuracy of the transducer was ±0.1 N.

The grain mass was pressurized by confining the wheat within an open-top box with a free-floating lid on which different masses were stacked. Pressure was assumed to be constant throughout the wheat because of the small volume of grain. A combination of different masses provided normal grain pressures of 3.2, 4.8, 6.3, 7.9, and 11.1 kPa. These normal grain pressures were selected to represent an expected range of possible lateral grain pressures that could be applied to a 1.8 m tall person entrapped in grain but with the person's head still above the grain surface. A lateral grain pressure calculated by Janssen's equation, using a maximum design bulk density, a grain depth of 1.8 m, and other standard values would be less than the maximum normal grain pressure used in this experiment.

A test was begun by filling the lower section of the box with grain and striking-off the grain surface to make it even with the top edge of the bottom frame. The denim-covered blade was inserted through the end plates, which centered the blade along the line of pull. The middle frame of the box was then fastened to the bottom section and filled with wheat. The surface of the grain was struck-off level with the top surface of the middle frame. The top frame was fastened in place, and the pressure plate was carefully lowered into position. The appropriate masses were then stacked on the pressure plate. A cable connected the blade to the force transducer of the universal testing machine.

The sequence of the 45 test combinations of normal grain pressures, pull speeds, and replications were randomized. This randomization was done to reduce potential testing errors. The order in which various combination of speed and pressure were used in the measurements is shown in table 1.

The soft red spring wheat used in this test had a moisture content of 10.7% (w.b.) and an uncompressed bulk density of 778.5 kg m^{-3}. The variety was titled Siouxland Wheat. The wheat moisture content and bulk density were monitored before and after the testing. No changes in the properties were observed.

Results

A series of 500 to 800 force measurements were recorded for each replication. The number of force measurements depended on the speed of the blade being pulled and the data acquisition rate. More force measurements were recorded for the faster pull speed because it was sampled at a higher rate. A typical force versus time trace for five different normal grain pressures applied to the top surface of the grain is shown in figure 2. The average force measured during each test was converted to the apparent coefficient of friction using equation 1 (Thompson et al., 1988):

$$\mu = \frac{F}{2P(LW + kLt)} \tag{1}$$

where

μ = apparent coefficient of friction of wheat on denim (dimensionless)
F = force required to pull the test blade through the wheat (N)
P = pressure exerted by the wheat (N m^{-2})
L = length of the test blade (m)
W = width of test blade (m)
t = thickness of test blade (m)
k = horizontal to vertical pressure ratio (0.5) defined by ASABE Standard EP433 (ASABE, 2015).

An analysis of variance was performed for the apparent coefficient of friction. At the 0.05 significance level, the coefficient of friction was not significantly affected by the normal grain pressure or the pull speed. Figure 3 is a plot of the apparent coefficient of friction for the five normal grain pressures. The resulting average value of the apparent coefficient of friction of wheat on denim was determined to be 0.167 with a standard deviation of ±0.013.

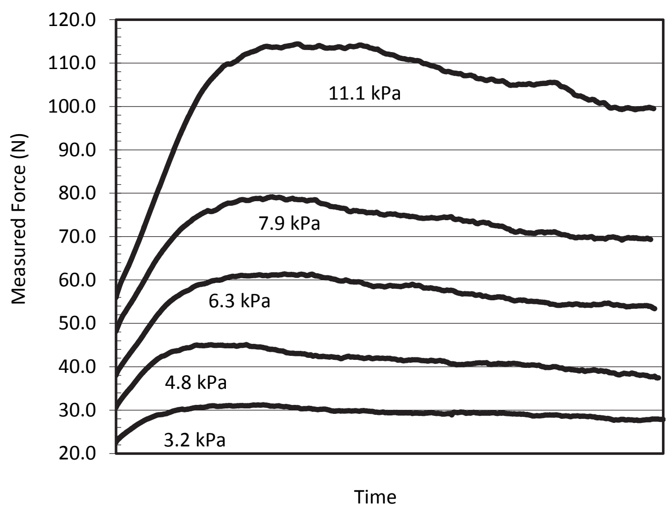

Figure 2. Typical example of measured force traces over time for the five normal grain pressures.

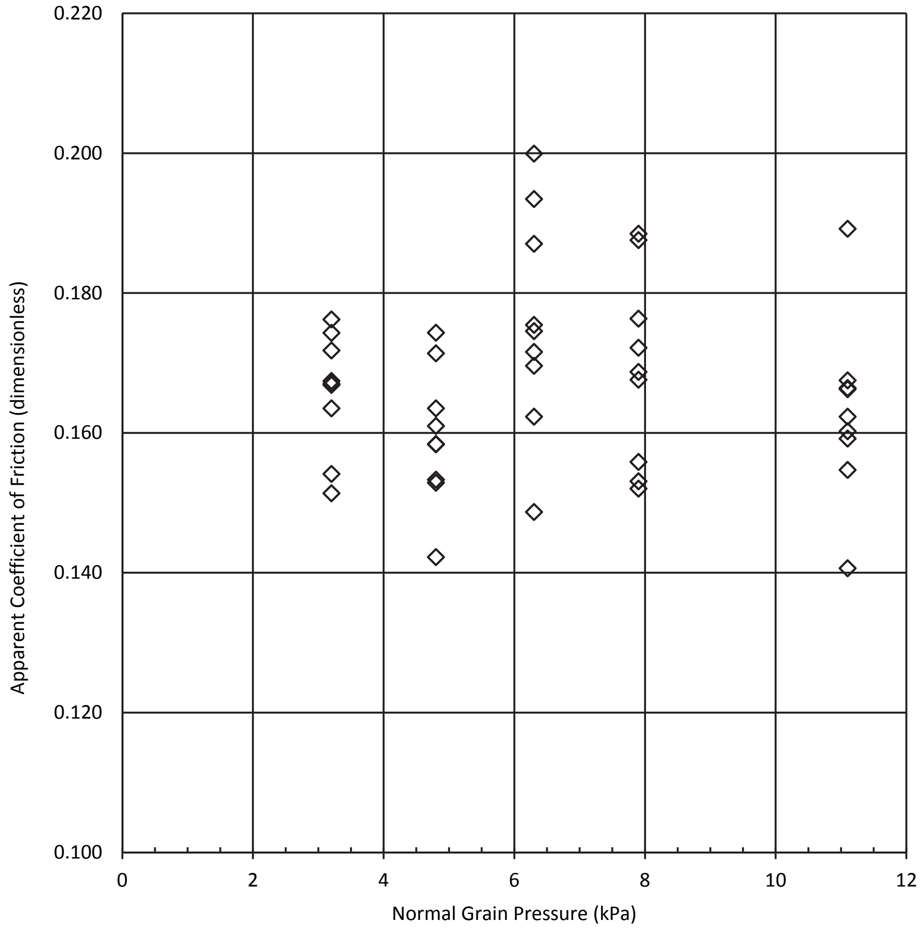

Figure 3. Apparent coefficient of friction of wheat on denim for normal grain pressures.

Discussion

The force trace shapes (fig. 2) do not exhibit the cyclic loading profiles caused by the slip-stick phenomenon of wheat on metal or cardboard (Thompson et al., 1988; Ross et al., 1987). In other words, the jagged sawtooth profile is not present for wheat on denim. The loading profile observed for wheat on denim was a smooth continuous line. The force trace shape is similar to the loading profile of red winter wheat on a nylon temperature cable (Schwab et al., 1991). A damped sine wave would be an accurate description of the loading profile.

The denim fabric sample was observed to have a pattern of weave. It was cut producing a specific pattern at a 45° angle to the direction of pull. Examination of a pair of pants made with denim fabric revealed that the "ribs" of the fabric ran at a 45° angle to the vertical direction. The direction of pull on the denim sample would then best represent a person in denim clothing being pulled out of the grain.

The denim fabric was observed to be stretched before the end of each replication. There was a noticeable (enough to be visually identifiable) amount of loose fabric bunched toward the end of the test blade, and that loose fabric was not there prior to testing. The force measuring process stretched the denim fabric from its initial length of 535 mm. The elongation of the original denim sample could be as much as 3.8 mm, the distance traveled by the blade, but it was not measured. Higher normal grain pressures exhibited more bunching than lower normal grain pressures. It is expected that the elongation of the sample occurred during the initial buildup of the peak force but did not impact the force values used to calculate the apparent coefficient of friction. The stretchy nature of the denim fabric also contributed to the smooth force trace.

The apparent coefficient of friction of wheat on denim of 0.167 is considerably less than the estimated value of 0.5 used by Schwab et al. (1985). When considering the substantial difference between the measurement in this article and the 0.5 value, it should be noted that the 0.5 value was obtained using nonlinear regression to relate the vertical loading on mannequins to the normal force exerted on the mannequins by the grain as calculated from Janssen's equation. Part of the model fitting included the vertical loading condition in which the subject was buried below the surface. This submerged condition experienced the largest vertical loading and had the greatest influence on the estimation of the apparent coefficient of friction. The difference between these coefficient of friction values could also be the result of different surface configurations, different denim fabrics, and different properties of the wheat samples, such as variety and moisture content.

Summary

This research helps explain one aspect of the relevant physical characteristics that will lead to a better understanding of what occurs when a victim is entrapped in a free-flowing granular material like wheat. The calculated value of 0.167 for the apparent coefficient of friction of wheat on denim fabric is a starting point.

There are additional values of apparent coefficient of friction to be determined for grains other than wheat. In addition, the relationships between grain moisture content and the apparent coefficient of friction of grain on fabric should be investigated. A closer examination of the influence of fabric pattern orientation and stretching on the apparent coefficient of friction will also lead to a better understanding of how clothing impacts the vertical loading of victims entrapped in grain.

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