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Prediction of Extraction Forces for Entrapment Victim in Common Grain Storage Conditions

Charles V. Schwab
Iowa State University, cvschwab@iastate.edu

Pamela J. Schwab
Civil Software Design LLC

Lauren E. Schwab
Iowa State University, lschwab@iastate.edu

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Abstract

One contributor to agriculture's high death rate is confined space fatalities caused by entrapment in granular materials. Over 1,000 grain-related fatalities have been documented by researchers in 43 states, and those states with the largest grain storage capacities have been shown to experience a proportionally large number of the suffocation fatalities. Several researchers have measured extraction forces in specific conditions, but a reference standard for estimating the extraction forces for a grain suffocation victim in common conditions is needed. A prediction model for estimating extraction forces was developed using the principle of boundary shear, an approximation of human surface area, and a commonly accepted equation for lateral granular pressure. This paper reintroduces the prediction model for extraction forces and explores several sensitivity analyses of input variables. It also updates anthropometric data used in the model calculations, and produces extraction force estimates for adult male victims submerged below the grain surface with different body shapes. Results from the prediction model are presented graphically for common input variables, various depths of entrapment, and adult male victim body sizes.

Keywords

Farm safety, Grain Suffocation, Prediction model, Rescue, Safety

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Ergonomics

Comments

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2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Prediction of Extraction Forces for Entrapment Victim in Common Grain Storage Conditions

Charles V. Schwab[1]
Pamela J. Schwab[2]
Lauren E. Schwab[3]
[1]***Iowa State University, 3335 Elings Hall, 605 Bissell Rd, Ames IA 50011-3270***

[2]***Civil Software Design LLC, P.O. Box 706, Ames IA 50010***

[3]***Iowa State University, 3335 Town Hall, 605 Bissell Rd, Ames IA 50011-3270***

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ABSTRACT. *One contributor to agriculture's high death rate is confined space fatalities caused by entrapment in granular materials. Over 1,000 grain-related fatalities have been documented by researchers in 43 states, and those states with the largest grain storage capacities have been shown to experience a proportionally large number of the suffocation fatalities. Several researchers have measured extraction forces in specific conditions, but a reference standard for estimating the extraction forces for a grain suffocation victim in common conditions is needed. A prediction model for estimating extraction forces was developed using the principle of boundary shear, an approximation of human surface area, and a commonly accepted equation for lateral granular pressure. This paper reintroduces the prediction model for extraction forces and explores several sensitivity analyses of input variables. It also updates anthropometric data used in the model calculations, and produces extraction force estimates for adult male victims submerged below the grain surface with different body shapes. Results from the prediction model are presented graphically for common input variables, various depths of entrapment, and adult male victim body sizes.*

Keywords. *Farm safety, Grain Suffocation, Prediction model, Rescue, Safety*

Introduction

The US agricultural workforce is not the largest workforce population for an industry in the United States but it receives the distinction as the deadliest industry with a worker fatality rate of 22.6 deaths per 100,000 workers (NSC 2017). This death rate is over seven times the all-industry average death rate of 3.0 deaths per 100,000 workers. Some of the other industries like mining, transportation/warehousing, construction, and manufacturing that the general public has typically viewed as dangerous have lower death rates than agriculture; 11.3, 12.8, 9.8, and 2.0 respectively.

One contributor to agriculture's high death rate is confined space fatalities caused by entrapment in grain. This confined space hazard has been acknowledged by many educators for decades (Loewer and Loewer, 1974, Smith et al., 1985, and Northeast Regional Agricultural Engineering Services, 1986). Over 1,000 grain-related fatalities were documented in 43 states from 1964 to 2016 (Issa et al., 2016). Issa et.al (2016) illustrated that states with a large number of farms with on-site grain storage (i.e. Iowa, Illinois, Indiana, Nebraska, and Wisconsin) experienced a proportionally larger number of these suffocation fatalities. The average financial loss associated with a grain suffocation victim would be the same as an occupational death, estimated at $1.0 million (NSC 2017).

Beyond reporting the numbers of grain suffocations occurring and the circumstances that were responsible for the tragic outcomes, it is important to understand the physical conditions during an entrapment episode. Schwab (1982) measured extraction forces for different test mannequins using two grains, three flow rates, and two flow conditions. He measured extraction forces for the 165-pound adult mannequin ranging from 951 to 2071 lb. This research is often the source for a common informational graphic that depicts the extraction force by depth submerged in grain for a 165-pound victim (see Figure 1).

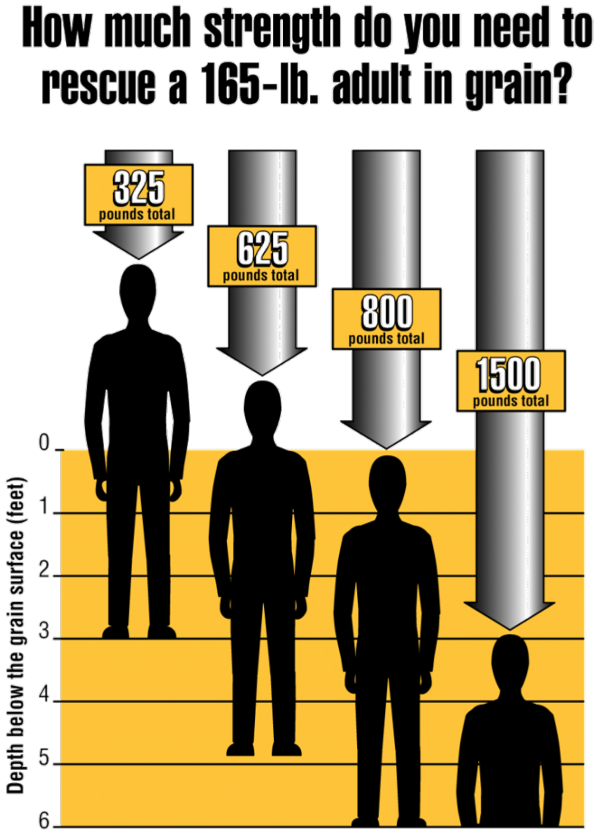

Figure 1. Graphic representation of the extraction force for a 165 lb adult male submerged at various depths below the grain surface (source: Schwab et al., 1997).

Other researchers have measured extraction forces for different entrapment conditions. Roberts et al. (2015) measured the difference between extraction forces with and without a grain rescue tube around an entrapped victim. It was determined that the extraction force increased if no grain was removed from inside the tube compared to not using a grain rescue tube. When grain was removed from inside the tube, the extraction force was less. Issa and Field (2017) measured the extrication forces of a victim pulled from various angles. It was determined that sharper angles (15 to 30 degrees) of pull resulted in significant increases in the peak force by nearly 225 lb.

Schwab et al. (1985) expanded on the principle of boundary shear identified by Cowin and Trent (1980) and combined it with the Janssen (1895) equation for predicting granular pressures and approximated surface area of humans to develop a model for predicting the force required to extract a person trapped in grain. No other researcher has published a prediction model since, nor has much been done to refine the originally proposed model for determining extraction forces exerted on a victim entrapped in granular materials. The purpose of this paper is to reintroduce the prediction model, explore sensitivity analyses of input variables, update anthropometric data used in calculations, and produce extraction force estimates for adult male victims with different body shapes submerged below the grain surface.

Original Prediction Model

The original prediction model is divided into two conditions based on the victim's relative position to the grain surface. The first condition is when the victim is completely below the grain surface. The original prediction model for the first condition used the weight of the victim, vertical loading of grain above the victim, and the frictional loading on the victim. These three components for the first condition are expressed in Equation 1. The three distance measurements related to the victim and the top surface of the grain are illustrated by Figure 2.

$$F_{extraction} = \bar{W} + \frac{wRA_{tsa}}{\mu k}\left(1-\exp\left(\frac{-k\mu y_2}{R}\right)\right) + \frac{S\phi wR}{\mu y_1}\left[y_3 - y_2 + \frac{R}{k\mu}\left(\exp\left(\frac{-k\mu y_3}{R}\right) - \exp\left(\frac{-k\mu y_2}{R}\right)\right)\right] \qquad (1)$$

Where:

$\bar{W}$ is weight of the victim (lb)

w is the bulk weight of the granular material (lb/ft^3)

R is the hydraulic radius of the cylindrical bin (ft)

A_{tsa} is the top surface area of the victim (ft^2)

μ is the coefficient of friction of grain on grain (dl)

k is the ratio of vertical to lateral pressure (dl)

S is the surface area of the victim (ft^2)

ϕ is the coefficient of friction of grain on victim's surface (dl)

y_1 is the distance from the top of victim head to bottom of feet (ft)

y_2 is the distance from the top of victim head to top surface of grain (ft)

y_3 is the distance from the bottom of victim feet to top surface of grain (ft)

$F_{extraction}$ is the force required to extract the victim from the grain (lb)

The second condition is when the victim's shoulders are above the grain surface. The original model for the second condition used the weight of the victim and the frictional loading on the victim. These two components for the second condition are expressed in Equation 2. The prediction equations use information from the trapped victim, the granular material, and the diameter of the bin.

$$F_{extraction} = \bar{W} + \frac{S\phi wR}{\mu y_1}\left[y_3 + \frac{R}{k\mu}\left(\exp\left(\frac{-k\mu y_3}{R}\right) - \exp\left(\frac{-k\mu y_2}{R} - 1\right)\right)\right] \qquad (2)$$

The prediction model is only for enveloping flow conditions in a cylindrical bin with a grain height to bin diameter ratio of 1.5 or less. When grain height to bin diameter ratios are 2.0 or larger, the grain stored does not create an enveloping flow pattern on the top surface and greatly reduces the potential for submersion. The prediction model is not intended to estimate the extraction force for a victim submerged from a collapsed grain bridge. These conditions typically involve non free flowing granular material because the bridged-grain results from frozen or spoiled grain. For the purpose of this paper, only the first condition will be considered in the sensitivity analyses and used to construct the extraction forces for different male body shapes. The first condition covers the range where the largest extraction forces exist.

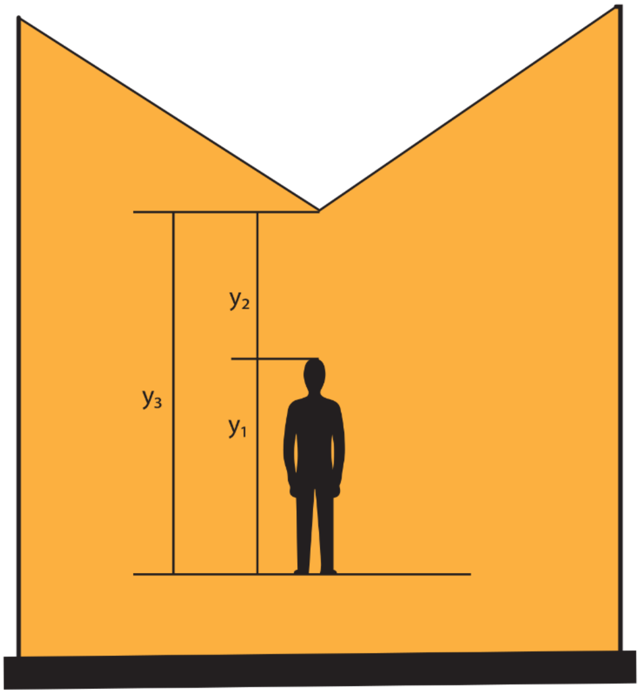

Figure 2. Three distance measurements of y_1, y_2, and y_3 connected to the victim used for estimating extraction force.

Prediction Model Sensitivity Analysis

Direct sensitivity analysis was conducted on the first condition of the extraction force prediction model. The partial differential of the force of extraction in Equation 1 was made for each variable in the equation except for y_2 because that variable is dependent on y_1 and y_3. The set of ten partial differential equations results are presented by variable and identified below.

Weight of the victim partial differential equation:

$$\frac{\partial F}{\partial \bar{W}} = 1 \tag{3}$$

Bulk weight of the granular material partial differential equation:

$$\frac{\partial F}{\partial w} = \frac{RA_{tsa}}{\mu k}\left[1 - \exp\left(\frac{-k\mu y_2}{R}\right)\right] + \frac{S\phi R}{\mu y_1}\left[y_3 - y_2 + \frac{R}{\mu k}\exp\left(\frac{-k\mu y_3}{R}\right) - \exp\left(\frac{-k\mu y_2}{R}\right)\right] \tag{4}$$

Hydraulic radius of the cylindrical bin partial differential equation:

$$\frac{\partial F}{\partial R} = \frac{wA_{tsa}}{\mu k}\left[1 - \exp\left(\frac{-k\mu y_2}{R}\right)\right] - \frac{wA_{tsa}y_2}{R}\exp\left(\frac{-k\mu y_2}{R}\right) + \frac{S\phi w}{\mu y_1}\left[\begin{array}{l} y_3 - y_2 + \dfrac{2R}{\mu k}\exp\left(\dfrac{-k\mu y_3}{R}\right) + y_3\exp\left(\dfrac{-k\mu y_3}{R}\right) - \\ \exp\left(\dfrac{-k\mu y_2}{R}\right) + \dfrac{\mu k y_2}{R}\exp\left(\dfrac{-k\mu y_2}{R}\right) \end{array}\right] \tag{5}$$

Top surface area of the victim partial differential equation:

$$\frac{\partial F}{\partial A_{tsa}} = \frac{wR}{\mu k}\left[1 - \exp\left(\frac{-k\mu y_2}{R}\right)\right] \tag{6}$$

The coefficient of friction of grain on grain partial differential equation:

$$\begin{aligned}\frac{\partial F}{\partial \mu} = {} & \frac{wRA_{tsa}}{\mu^2 k}\left[\exp\left(\frac{-k\mu y_2}{R}\right)-1\right]+\frac{wA_{tsa}y_2}{\mu}\exp\left(\frac{-k\mu y_2}{R}\right)+ \\ & \frac{S\phi wR}{\mu^2 y_1}\left[\begin{array}{l} y_2-y_3-\dfrac{2R}{\mu k}\exp\left(\dfrac{-k\mu y_3}{R}\right)-Ry_3\exp\left(\dfrac{-k\mu y_3}{R}\right)+ \\ \exp\left(\dfrac{-k\mu y_2}{R}\right)+\dfrac{\mu k y_2}{R}\exp\left(\dfrac{-k\mu y_2}{R}\right) \end{array}\right]\end{aligned} \tag{7}$$

The ratio of vertical to lateral pressure partial differential equation:

$$\begin{aligned}\frac{\partial F}{\partial k} = {} & \frac{wRA_{tsa}}{\mu k^2}\left[\exp\left(\frac{-k\mu y_2}{R}\right)-1\right]+ \\ & \frac{wA_{tsa}y_2}{k}\exp\left(\frac{-k\mu y_2}{R}\right)+ \\ & \frac{S\phi w}{y_1}\left[y_2\exp\left(\frac{-k\mu y_2}{R}\right)-\frac{Ry_3}{k\mu}\exp\left(\frac{-k\mu y_3}{R}\right)-\frac{R^2}{k^2\mu^2}\exp\left(\frac{-k\mu y_3}{R}\right)\right]\Bigg]\end{aligned} \tag{8}$$

The surface area of the victim partial differential equation:

$$\frac{\partial F}{\partial S}=\frac{\phi wR}{\mu y_1}\left[y_3-y_2+\frac{R}{k\mu}\exp\left(\frac{-k\mu y_3}{R}\right)-\exp\left(\frac{-k\mu y_2}{R}\right)\right]\Bigg] \tag{9}$$

The coefficient of friction of grain on victim’s surface partial differential equation:

$$\frac{\partial F}{\partial \phi}=\frac{SwR}{\mu y_1}\left[y_3-y_2+\frac{R}{k\mu}\exp\left(\frac{-k\mu y_3}{R}\right)-\exp\left(\frac{-k\mu y_2}{R}\right)\right]\Bigg] \tag{10}$$

The distance from the bottom of the victim’s feet to the top surface of grain partial differential equation:

$$\frac{\partial F}{\partial y_3}=\frac{S\phi wR}{\mu y_1}\left[1-\exp\left(\frac{-k\mu y_3}{R}\right)\right]\Bigg] \tag{11}$$

The distance from the top of the victim’s head to bottom of the feet partial differential equation:

$$\frac{\partial F}{\partial y_1}=\frac{S\phi wR}{\mu y_1^2}\left[y_2-y_3-\frac{R}{\mu k}\exp\left(\frac{-k\mu y_3}{R}\right)+\exp\left(\frac{-k\mu y_2}{R}\right)\right]\Bigg] \tag{12}$$

As described by Hamby (1994), a sensitivity coefficient for these nine variables were calculated using the partial differential equations and the quotient of the variable and resulting force of extraction to normalize the product (Equation 13). This dimensionless sensitivity coefficient can be used to determine the importance of the prediction model parameter. The sensitivity coefficient for each independent variable was calculated for different fractions of the base variable and plotted. The base values of the independent variables are given in Table 1. The resulting graph of sensitivity coefficients for each independent variable is shown in Figure 3. The coefficient of friction of grain on grain and the stature of the victim, surface area of the victim, and bulk weight of grain are group together near a sensitivity coefficient of 31. The top surface area of the victim, weight of victim, and coefficient of friction of grain on victim are cluster near a sensitivity coefficient of zero. The sensitivity coefficients for hydraulic radius, ratio of vertical to lateral, and the coefficient of grain on grain appear to have an observable increase over the range of base values used. The sensitivity coefficients of the other independent variables appear to have very insignificant slope over the range of base values used.

$$\theta_i=\frac{\partial F}{\partial X_i}\left(\frac{X_i}{F_i}\right) \tag{13}$$

Table 1. Extraction force prediction model independent variables and the associated base value used in the sensitivity analysis and the base extraction force predictions for the base values

Variable	Base value	Units
μ	0.38	dl
R	7.5	ft
w	45.6	lb/ft^3
S	19.0	ft^2
y_1	6.0	ft
ϕ	0.6	dl
k	0.5	dl
y_3	10.0	ft
$\bar{W}$	165.0	lb
A_{tsa}	0.62	ft^2
$F_{extraction}$	1932.0	lb

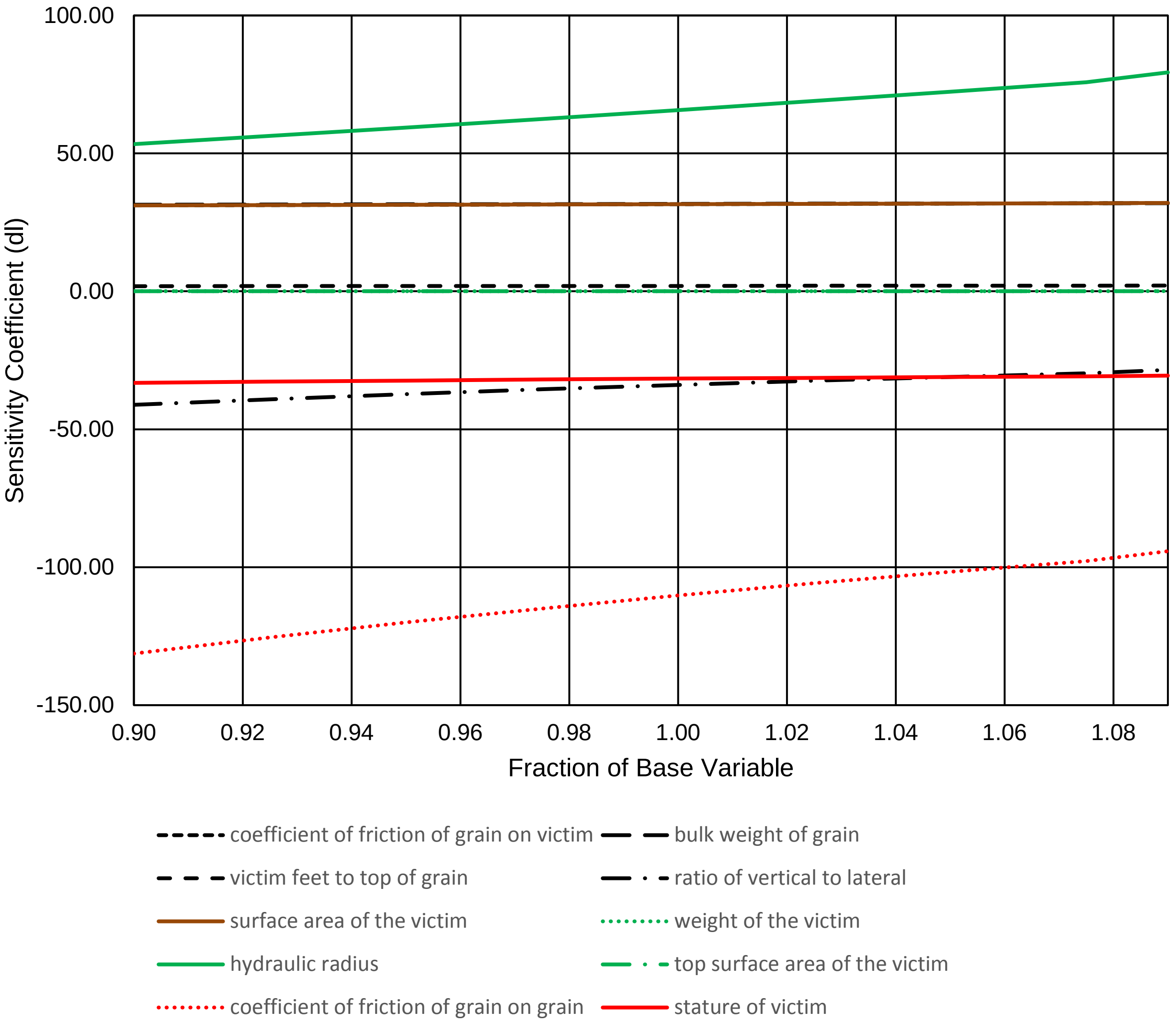

Figure 3. Graph of sensitivity coefficients vs the fractional change in the base variable for the ten independent variables used in the extraction force prediction model

Comparing these sensitivity coefficient findings with the one-at-a-time sensitivity measures offers additional insight for the prediction model variables. Each independent variable was varied by -10, -7.5, -5, -2.5, 0, 2.5, 5, 7.5, and 10 percent of a set base value (see Table 1). The percent of the extraction force (dependent variable) was calculated and plotted by the fractional change in the base variable (independent variable). Figure 4 shows the resulting graph of this one-at-a-time sensitivity analysis.

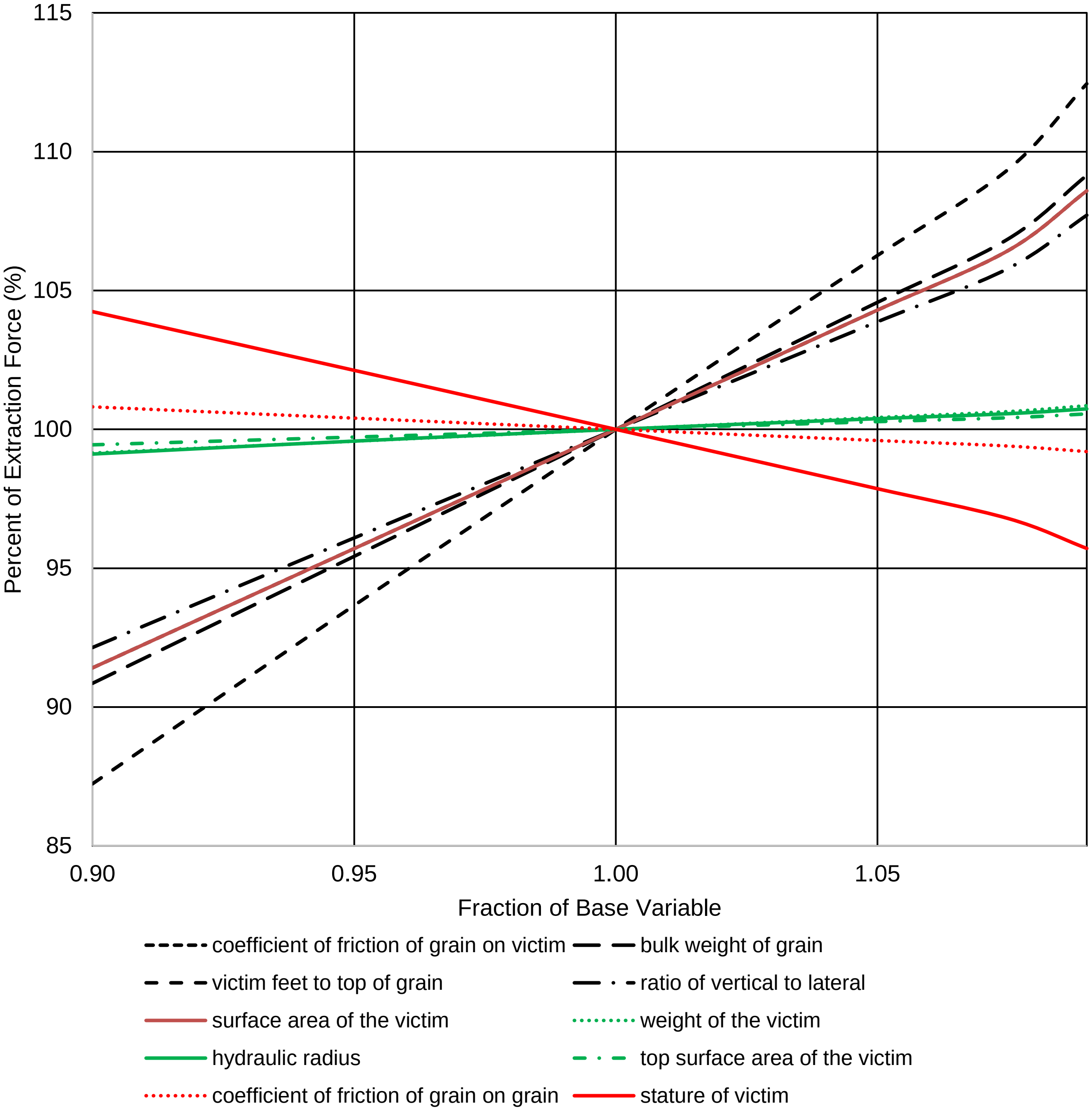

Figure 4. Graph of the percent of the prediction model extraction force (dependent variable) vs the fraction change in the base variable (independent variables)

The most influential independent variable appears to be the coefficient of friction of grain on victim. When this independent variable changes by 10 percent, so does the dependent variable of extraction force. The independent variables of weight of the victim, hydraulic radius, and top surface area of the victim have the very little change in the dependent variable, shown by having less than 1 percent change observed for the dependent variable for the maximum change of 10 percent in the independent variable. The independent variables of bulk weight of grain, surface area of victim, victim feet to top of grain, and ratio of vertical to lateral, have more impact in the dependent variable but are less than the most influential independent variable of the coefficient of friction of grain on victim. The independent variables of the coefficient of friction of grain on grain and stature of victim are only two independent variables that yield an inverse influence. When these independent variables are increased by 10 percent the dependent variable is decreased. As the stature of victim increases the component of extraction force decreases. The reverse is true as the stature of victim decreases, the component of extraction force increases. An unexpected outcome with this analysis is the small magnitude of impact the top surface area of the victim has on the force of extraction prediction. Initially this was expected to have more influence. The focus of interest for the independent variables of surface area of victim, bulk weight of grain, coefficient of friction of grain on victim, and ratio of vertical to lateral are warranted. These have significant influence on the predicted force for extraction and are changeable, unlike the influential independent variable of the victim feet to top of grain.

Anthropometric Data

The physical measurements for a victim used in the original prediction model were from anthropometric measurements reported by Dreyfuss (1959). The anthropometric data for a 50 percentile male adult was used to estimate the surface area of a submerged victim using simple geometric solids. The simple geometric solids used were right ellipsoidal cylinder, frustum of a right cone, and obelisk. The surface area of a submerged victim was estimated by summing different body part calculations as shown in Table 2.

At the time when the prediction model was developed, these were acceptable body dimensions and surface area values. However, today the standard shapes of human beings are considerably different than a standard body shape defined over 4 decades ago. Today there is acceptance that there are more varieties of human shapes than the standard idealized shape used in the past anthropometric models. The technology used to collect physical shape data, changes in population that impacts standard human dimensions, and the ability to estimate surface area has changed.

Table 2. Surface area values for the 50 percentile male with corresponding geometric solids used [a]

Body part	Geometric Solid	Surface area (in^2)	Surface area (ft^2)
Head	right ellipsoidal cylinder	182	1.3
Shoulder	obelisk	147	1.0
Torso	right ellipsoidal cylinder	1162	8.1
Thigh	frustum of a right cone	588	4.1
Calf	right ellipsoidal cylinder	442	3.1
Feet	partial obelisk	217	1.5
Total surface area		2738	19.0

[a] Source of data in table: Schwab (1982)

The anthropometric data for stature and body mass index (BMI) for a 50 percentile male from the government report DHHS (2016) and the University of Michigan Transportation Research Institute (UMTRI) human model was used to construct a computer generated 50 percentile male model that could be used in a comparison of total surface area calculations of the initial estimate of 19.0 ft^2 (see Table 2). Two major differences were the physical body shapes between these two 50 percentile males are because of how the population has changed from 4 decades ago and the methodology of calculating the total surface area of the victim using crude geometric solids. The computer calculated surface area of a 50 percentile male UMTRI human model was determined to be 20.25 ft^2. The 6 percent difference between these two surface area calculations is reasonable given the different ways to estimate surface area of a human male and the variation caused by physical changes to the average human body measurements over the span of decades.

Extraction Force Predictions for Males

A question that is repeatedly asked, concentrates around the extraction force predictions for males that are not 165-pound, 6 foot in stature, and considered in perfect physical shape. This section of the paper will examine three human statures (tall, medium, and short) and four human body mass indexes (underweight, normal, overweight, and extreme obesity). Several calculations will be performed to determine the extraction force predictions for these conditions varying the depth the victim's feet are buried below the grain.

A total of 68 human models were constructed using DHHS (2016) anthropometric data, and UMTRI (2018) male human models. The purpose of these human samples was to determine the influence that the human variables of stature, body mass index, and age have on the calculated surface area of a victim. It was determined that there is a good relationship with surface area values between stature and body mass index. These relationships for stature and body mass index are shown in Figures 4 and 5. The age of the subject has no significant relationship with the value of victim surface area and will not be used in developing data for the extraction force prediction model.

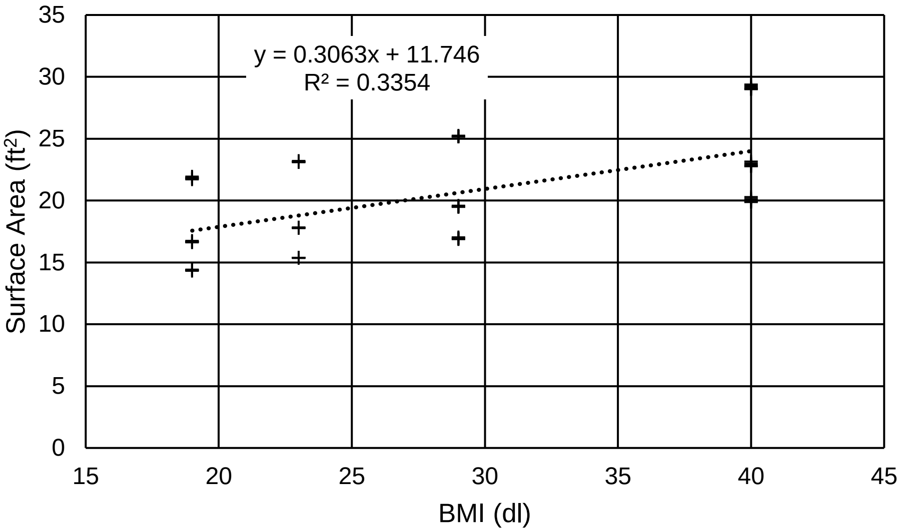

Figure 4. Estimated surface area of victim’s relationship with body mass index (BMI)

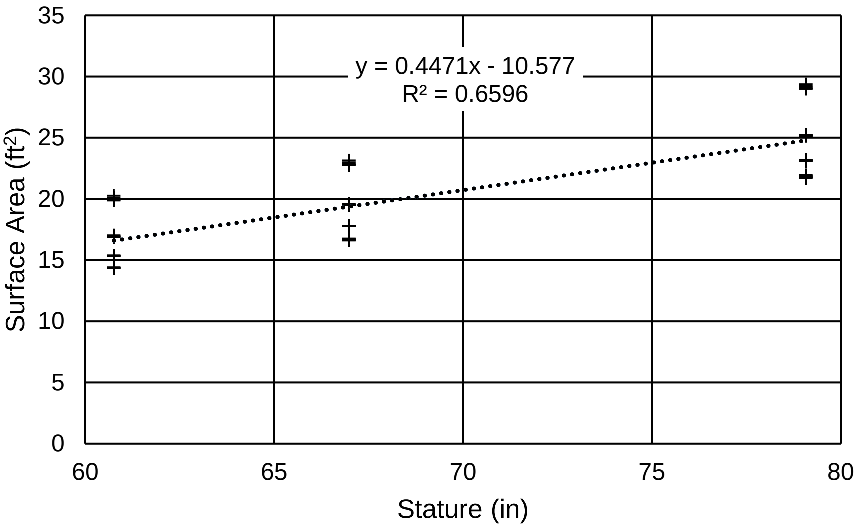

Figure 5. Estimated surface area of victim’s relationship with stature

For the purpose of this paper the extraction force prediction model was slightly modified. The weight of the victim was removed from the equation. Since the weight of the victim is a constant variable in the extraction force prediction, it does not influence other components of the prediction model calculations directly. Indirectly, the variations of victim’s weight influences are handled through the stature and body mass index influences on the surface area. In other words, the surface area changes are not tied to the variation between 10, 20, or 30 pounds of the victim’s weight as much as it is between the victim being underweight and overweight.

Modified extraction forces for a total of twelve male human body conditions combining stature and body mass indexes were calculated for submersion depths (y_3) from 10 to 25 ft. The body conditions were tall underweight (TU), tall normal (TN), tall overweight (TO), tall extreme obesity (TEO), medium underweight (MU), medium normal (MN), medium overweight (MO), and medium extreme obesity (MEO), short underweight (SU), short normal (SN), short overweight (SO), and short extreme obesity (SEO). The modified extraction forces for the twelve conditions are presented in Figures 6, 7, and 8. Estimating the extraction force requires adding the weight of the victim to the modified extraction force (equation 14).

$$F_{extraction} = \bar{W} + F_{modified} \tag{14}$$

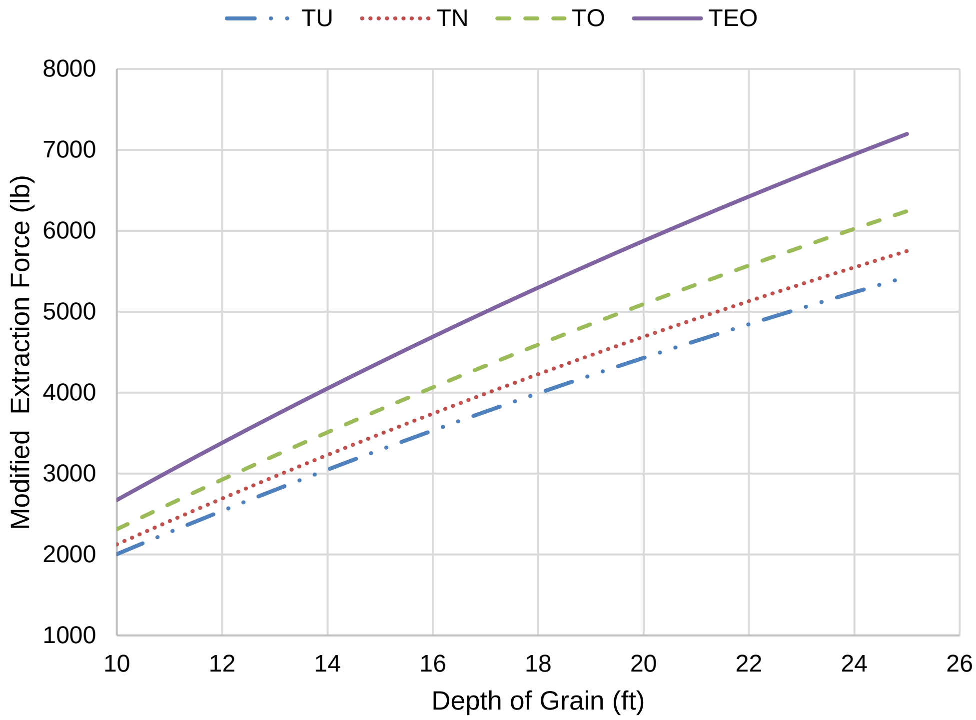

Figure 6. Estimated modified extraction force for tall height victims (stature – 79 inches) with different body types

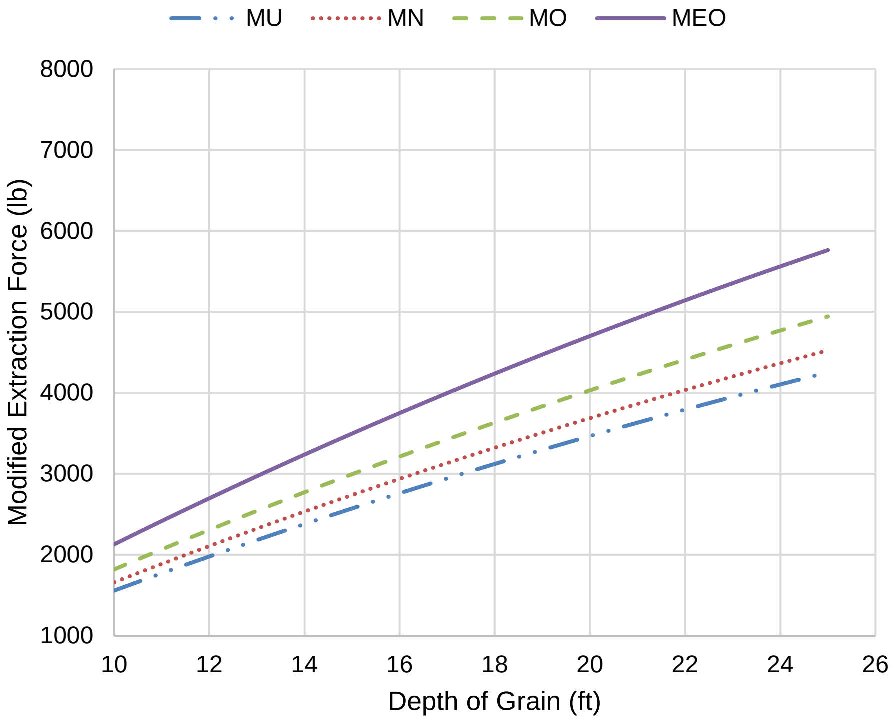

Figure 7. Estimated modified extraction force for medium height victims (stature – 67 inches) with different body types

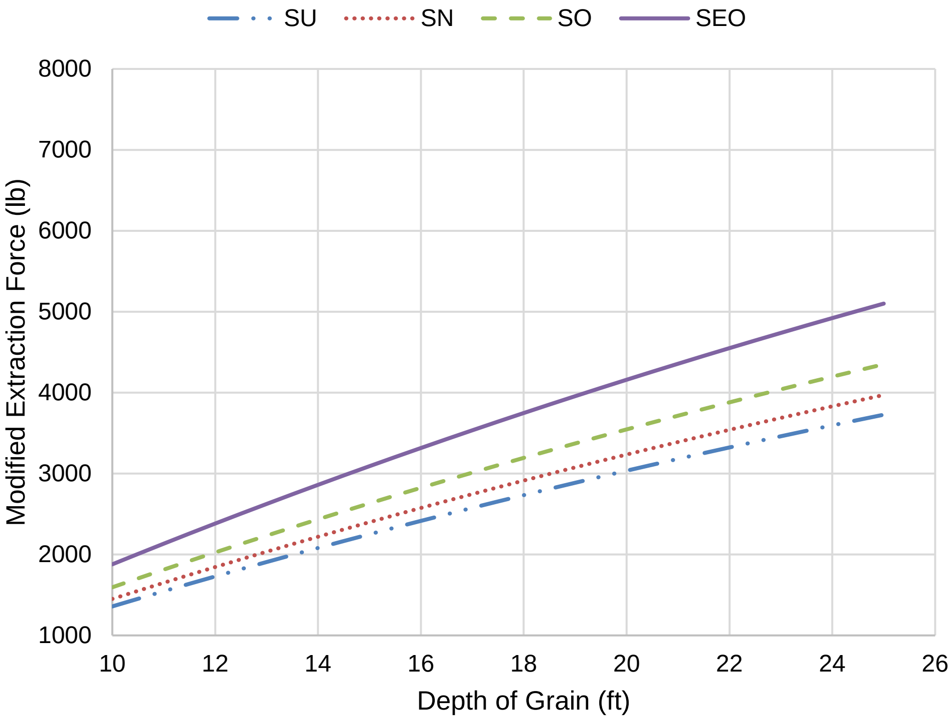

Figure 8. Estimated modified extraction force for short height victims (stature – 61 inches) with different body types

Comparing the modified extraction force between the extreme conditions is shown in Figure 9. The upper loading condition of being tall extreme obesity adult male is plotted with the lower loading condition of short underweight adult male. For another reference point, the medium height normal weight adult male is shown. There is considerable variation between these extreme conditions that can be nearly 1,000 pounds at low depths up to 3,000 pounds at larger depths.

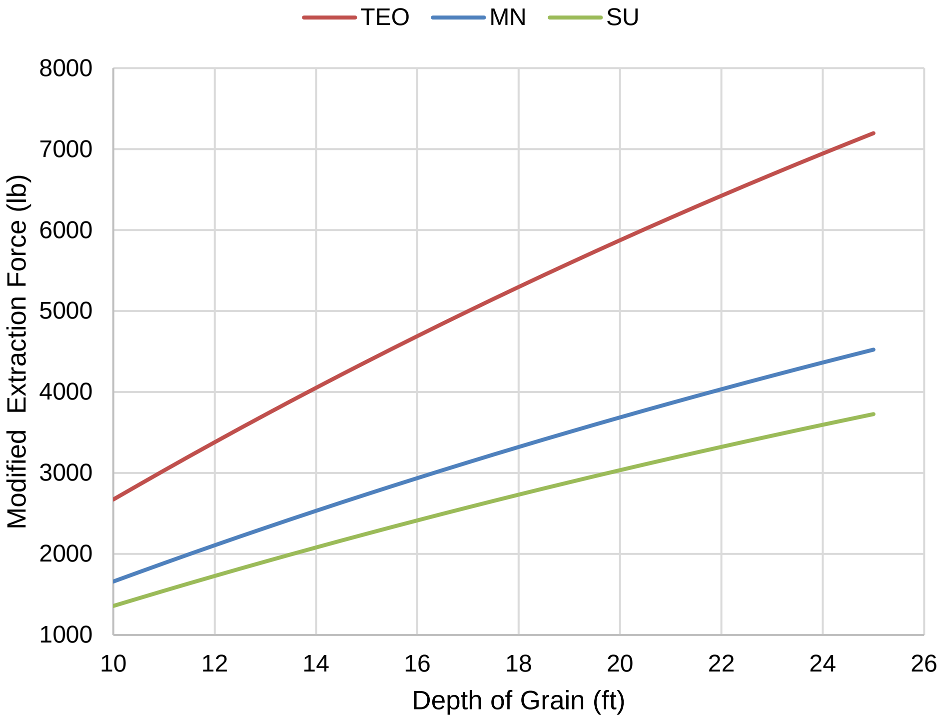

Figure 9. Estimated modified extraction force for three conditions representing two extreme conditions of short underweight to tall extreme obesity and the middle condition of medium normal

Summary

This paper presented the existing extraction force prediction model, explored sensitivity analyses of input variables, updated anthropometric data used in calculations, and produced extraction force estimates for adult male victims with different body types for various depths where the victim is below the grain surface. The model presentation and sensitivity analyses provides a better understanding of the variables that are used in the model. It also helps focus additional research efforts of those variables that have the greatest influence on the extraction force predictions.

The ability to generate different human shape models permits the exploration of how some of the human variables can influence the estimates for extraction forces. Now a victim that can be classified as a tall extreme obesity person can have an estimate for extraction force that can vary from a victim that can be classified as a short underweight person. The estimated extraction forces can change from 7,197 lb to 3,727 lb respectively. These results increase the understanding of the original extraction force prediction model and help deliver focus for new research on topics that can better improve this extraction force prediction model. This also addresses the question of what would be the extraction force if the male victim is not a 165-pound, 6 foot in stature, in perfect physical shape.

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References

Cowin, S. C., & Trent, L. E. (1980). Force of extraction for a cylinder buried in sand. *J. Appl. Mech.*, 47(4), 969-971. doi:https://doi.org/10.1115/1.3153829

Dreyfuss, H. 1959. *The measure of man*. New York, N.Y.:Whitney Library of Design.

Hamby, D.M. (1994). A review of techniques for parameter sensitivity analysis of environmental models, *Environmental Monitoring and Assessment* 32: 135-154.

Hamby, D.M. (1995). A comparison of sensitivity analysis techniques, *Health Physics* 68: 195-204.

Issa, S. F., Cheng, Y.-H., & Field, W. (2016). Summary of Agricultural Confined-Space Related Cases: 1964-2013. *J. Agric. Saf. Health*, 22(1), 33. doi:https://doi.org/10.13031/jash.22.10955

Issa, S. F. & Field, W. E. 2017. Determining the Pull-Forces Required to Extricate a Victim Entrapped at Various Angles in a Grain Mass. *Safety*, 2017;3(1):11 doi:https://doi.org/10.3390/safety3010011

Janssen, H. A. (1895). Versuche über getreidedruck in silozellen. Verein Deutschen Ingenieure Zeitschrift, 39, 1045-1049.

Loewer, O. J., and D. H. Loewer. 1974. Suffocation hazards in grain bins. Cooperative Extension Service AEN-39, University of Kentucky, Lexington, KY.

Northeast Regional Agricultural Engineering Service. 1986. *Farm accident rescue*. NREAS-10. Ithaca, NY.

National Safety Council. 2017. *Injury Facts*, 2017 Edition. Itasca, IL 60143.

Roberts, M. J., Field, W. E., Maier, D. E., & Stroshine, R. L. (2015). Determination of entrapment victim extrication forces with and without use of a grain rescue tube. *J. Agric. Saf. Health*, 21(2), 71-83. doi:https://doi.org/10.13031/jash.21.10150

Schwab, C. V., L. Miller, and D. Goering. 1997. Tug-of-War with GRAIN: A Grain Safety Curriculum. Iowa State University Extension publication EDC-116. ISU University Extension, Ames, IA 50011-3080.

Schwab, C. V. 1982. Inflow velocity and forces acting on a person trapped in enveloping flow of granular material. Unpublished MS thesis, Lexington, KY: University of Kentucky, Department of Agricultural Engineering.

Schwab, C. V., Ross, I. J., Piercy, L. R., & McKenzie, B. A. (1985). Vertical pull and immersion velocity of mannequins trapped in enveloping grain flow. *Trans. ASAE*, 28(6), 1997-2002. doi:https://doi.org/10.13031/2013.32555

Smith, M., R. Andrews, and P. Hillers. 1985. Grain bin rescue. *National Institute for Farm Safety* Columbia MO.

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES. Anthropometric Reference Data for Children and Adults: United States, 2011–2014. DHHS Publication No. 2016–1604 Hyattsville, Maryland

University of Michigan Transportation Research Institute. (2018). Online Statistical Body Shape Models. Retrieved from www. http://humanshape.org/