VERTICAL LOADING OF TEMPERATURE CABLES

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ABSTRACT

The vertical loads imposed by wheat on five different temperature cables in a full-scale bin were measured. Tests were conducted to determine the influence of radial positioning of the cable, grain discharge rate, starting H/D ratio, and detention time on the vertical loads. Results illustrate where maximum vertical loads on temperature cables will occur under normal operating conditions.

KEYWORDS. Temperature, Wheat, Loads, Friction.

INTRODUCTION

One of the most popular methods of determining potential locations of spoilage in stored grains is through constant monitoring of the internal temperatures of the grain mass. Distinctive increases of the local temperatures in the grain are a good indication of potential spoilage problems. Daily inspection of the internal temperature of the stored grain can detect the presence of a "hot spot" before any grain is seriously deteriorated. The operator can then choose to aerate the grain to cool the "hot spot" or remove the grain from the bin. Daily monitoring of temperatures requires that sensing elements be placed within the grain mass.

A common method of monitoring temperatures in a mass of stored grain utilizes thermocouples attached at regular intervals to high-strength steel cables. The entire assembly including the thermocouples and the cables is coated with a protective jacket. Temperature-sensing cables are available in many types, differing in surface material, size and cross-sectional shape. These cables are typically suspended from a grain bin roof in a standard pattern so they form a three-dimensional matrix of temperature monitoring points.

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These cables are subject to vertical frictional loading during filling, storing, and emptying operations. Since these cables are supported by the roof of a grain bin, designers require design guidelines for estimating the magnitudes and characteristics of the vertical loading. The loads imposed on temperature sensing cables have caused localized failures in certain components of grain bins as reported by Wickstrom (1980).

The purpose of this study was to compare five different types of commercially available temperature sensing cables to determine the apparent coefficient of friction of wheat on the cables and the magnitude of vertical loading in a full-scale grain bin during both static and dynamic unloading conditions. The effects of emptying flow rate, starting grain height, detention time, and the radial position of the cables in the bin were determined.

EXPERIMENTAL METHODS

The experiments consisted of two parts: a laboratory study to determine the apparent dynamic coefficient of friction of grain on the cable surfaces; and a full-scale bin study to measure vertical frictional loading on the cables. Five types of temperature cables which represent several of the variations in commercially available cables were used in the experiments. The different dimensions and surfaces materials of the cables are given in Table 1 and the physical appearance is shown in figure 1. The cables used for the laboratory study were short sections identical to the cable specimens used in the bin study. The grain used was soft red winter wheat at 11.9% moisture content (wet basis) with an uncompacted bulk weight of 772.6 kg/m^3. The influences of different variables on parameters measured were determined using analysis of variance technique in SAS (1982).

The laboratory study was conducted to determine the apparent coefficient of friction of wheat on the temperature cables at different normal pressures. The magnitude of the

TABLE 1. Description of dimensions and surface materials for the temperature cables used in this experiment

Cable Number	Shape	Dimension (mm)	Surface Material	μ_{tc}
1	Oval	11.8 by 10.7	Nylon	0.242
2	Oval	7.8 by 4.7	Vinyl	0.335
3	Round	16.2	HDLE polyethylene	0.284
4	Oval	14.8 by 9.3	Nylon	0.293
5	Round	8.6	Vinyl	0.614

apparent coefficient of friction was determined by the friction device and procedure developed by Ross et al. (1987). The cable velocities used were 0.05 and 50 mm/min. The faster speed was used to determine if the temperatures cables exhibited a "wear-in" period reported by Richter (1954), Snyder et al. (1967), Bickert and Buelow (1966), and Thompson et al. (1983). The slow speed was used for the determinations of the apparent coefficient of friction. A combination of steel weights provided normal grain pressures of 3.5, 10.3, and 18.6 kPa.

Actual laboratory testing consisted of two parts which were wear-in and the determination of the apparent coefficient of friction. The wear-in test determined the change in the frictional force as a result of repetitively pulling the test cables through the grain. These tests consisted of 15 replications with a grain pressure of 18.6 kPa and a cable velocity of 50 mm/min. The apparent coefficient of friction was determined by three replications of the three grain pressures at a cable velocity of 0.05 mm/min. The magnitude of the force required to pull the cable was measured with an accuracy of 0.2 N.

The bin study was conducted in a smooth-walled, galvanized steel bin 4.1 m in diameter. The bin floor was flat with both the unloading orifice and filling spout centrally located. Unloading flow rates of 36.3, 84.3, and 173.6 m^3/h were used. The flow rates correspond to grain velocities on the cables of 45.7, 106.7, and 1625.6 mm/min, respectively. Three identical temperature cables were located at three different radial positions as shown in figure 2. The radial positions were 0.1, 1.0, and 1.6 m from the center of the full-scale bin. These positions represent approximately 7, 50, and 80% of the bin radius, which translates to the center, midway and wall position, respectively.

The magnitude of the vertical frictional loading on the temperature cables in the full-scale bin was determined for three replications at a flow rate of 84.3 m^3/h and a H/D ratio of 3.5. Additional tests were performed on cable no. 3 to determine the influence of flow rate and starting grain height on the magnitudes of the vertical frictional loading. Two additional flow rates of 36.3 and 173.6 m^3/h at a H/D ratio of 3.5 were used. The influence of the starting grain height was examined by an additional test conducted with a H/D ratio of 1.0 and a flow rate of 84.3 m^3/h.

The temperature cables were suspended from load cells attached to the roof truss of the bin. The magnitude of the vertical frictional loading was measured with an accuracy of 5.6 N. The bottoms of the temperature cables were modified with the addition of an attaching lug. This lug was selected to have a cross-sectional area which was less than the temperature cable to minimize the additional loads resulting from the attaching mechanism. A piece of nylon twine was tied to the lug and passed through a hole in the floor. The twine was used to maintain the lateral placement of the temperature cables during filling by tying the twine to a fixed post under the bin floor. The twine was untied before the dynamic portion of the test began to allow the cables to move about freely during emptying.

The full-scale bin was filled continuously at a rate of 70.8 m^3/h to a depth of approximately 14.9 m at the apex of the surcharge. This depth was chosen to submerge the cables in a plug flow condition and to completely cover the surface of the cables. The cables were suspended 1.2 m above the floor of the bin to assure that the entire length was exposed to flowing grain. After emptying, the residual wheat in the bin reached approximately 1.1 m up the bin wall.

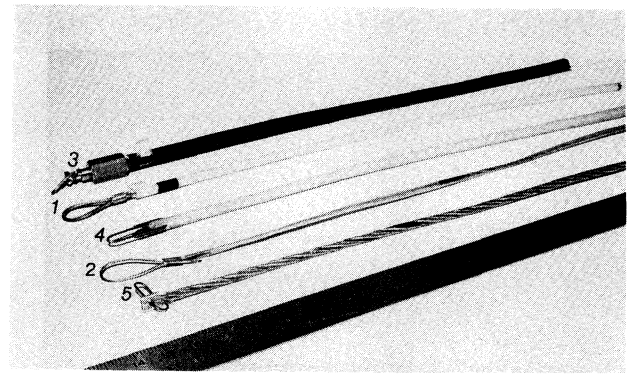

Figure 1–Temperature cables.

The vertical load on the cables and the grain height measurements were recorded immediately after filling was completed. The grain height was measured at two locations on the surface of the grain in the bin. The first location was near the bin wall and the second location was at half the distance of the bin radius. The grain height on each cable was calculated using an approximation of a conical grain surface estimated by the two depth readings. The dead weight of the temperature cables was removed from the

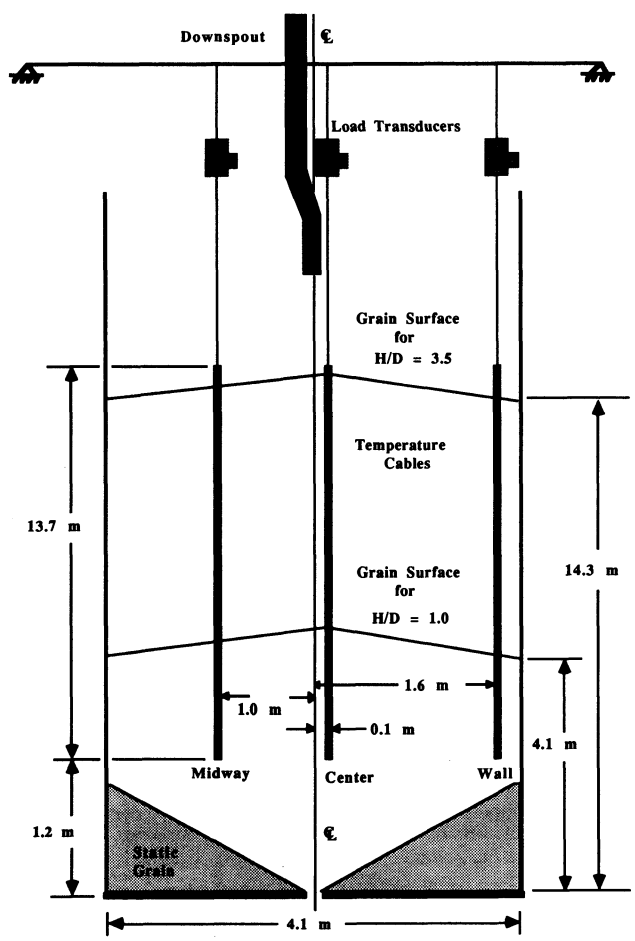

Figure 2–Full-scale bin facility.

results by zeroing the strain indicator prior to each test. The zero drift of the instrument was checked with an additional reading at the conclusion of each test. Any drift from zero was distributed throughout the results using a linear distribution. After filling, the grain was allowed to settle for 3 h. This settling period was used to allow the pressure conditions within the grain mass to stabilize. Loads measurements were taken every hour as the grain settled. After 3 h, the static portion of the bin test was completed.

The dynamic portion of the test began with the opening of the orifice. The strain indicator was set to display the load of the center cable and was watched closely until a maximum reading was observed. This generally occurred within the first minute of emptying. Once the maximum load for the center cable was observed, the display was switched to measure the midway cable. When the maximum occurred at the midway cable, the display was switched to the wall cable to observe the maximum load. Usually, all three cable readings were recorded within the first minute of the test. After the initial loads were recorded, an interval of 1 min between measurements was used for the first 5 min of the test. For the next 25 min, the readings were taken every 5 min, and the remainder of the test used an interval of 15 min. This was done because the load values changed very slowly after the first few minutes of emptying.

Results and Discussion

Coefficient of Friction

The phenomenon of "wear in" of the cable surfaces was examined by comparing the average force required to pull the cable through the pressurized grain mass for 15 repeated trials. The number of repetitions did not significantly influence the coefficient of friction at the 1.0% level. The surface of the cables, being comprised of long chain polymers, may not scrape the cutin from the grain as reported with the crystalline surface structure of galvanized steel used by Thompson et al. (1988). The soft, smooth surfaces of the plastics may tend to deform as the grain compresses. These physical differences in the surface materials of the cables could explain the variation between the observed results and the reported results from galvanized steel surfaces. The first peak on each graph was the result of the grain having reached the localized maximum static coefficient of friction. The maximum static coefficient of friction did not always occur at the first peak.

Slip-stick was examined by drawing the cables through the grain mass at a velocity low enough that the shape of the individual cycles of slipping and sticking became apparent on the force versus time chart. Different cable surfaces demonstrated notably different force versus time responses as shown in figure 3. The softer, tackier surface of the vinyl coverings produced a very defined sawtooth pattern similar to that of galvanized steel, while the harder, slicker surface of the nylon coverings produced a smoother, more continuous pattern resembling a damped sine wave. The nylon surfaces also showed a tendency to seek an asymptote faster than the vinyl surfaces. The HDLE polyethylene surface exhibited a sawtooth pattern but was quickly dampened similar to the pattern of the nylon surfaces. As the cables begin to move through the grain,

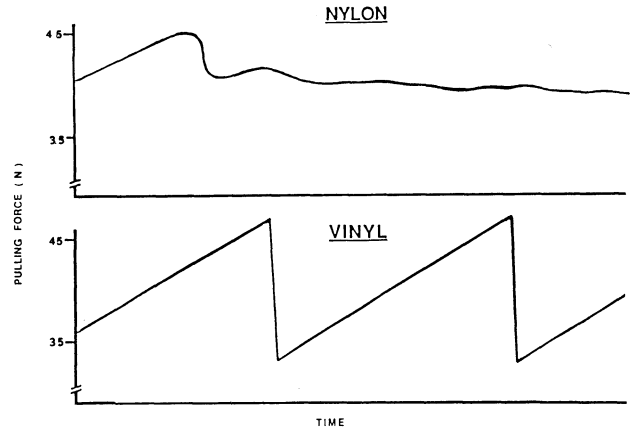

Figure 3–Comparison of the cyclic loading profiles caused by the slip-stick phenomenon observed for nylon and vinyl surfaces during dynamic testing.

the difference between the maximum and minimum values of the coefficient of friction becomes less. The asymptotic value was considered the average apparent dynamic coefficient of friction.

The influence of grain pressure on the coefficient of friction was examined by using the 0.05 mm/min velocity at normal grain pressures of 3.5, 10.3, and 18.6 kPa. Grain pressure significantly effected the coefficient of friction at the 1.0% level for all cable types, as illustrated in figure 4. Each cable type exhibited a different relationship between the grain pressure and the coefficient of friction. The points graphed represent the average of three replications for the coefficients of friction of each cable type. The vinyl surface of cable no. 5 clearly exhibits a coefficient which is 1.5 to 2.0 times greater than the magnitude measured for the other surfaces.

Bin Tests

The vertical frictional loads on the cables at the three radial positions are different. The influence of radial position on the loading of the cables was found to be significant at the 1.0% level. Thompson (1987) observed unequal loads on vinyl covered aircraft cables with respect to radial position. A difference between the rate of load change for cables at the wall position within the first few minutes of unloading and the same rate of change for the cables located at the center and midway positions was observed. The load on the cables at the wall position was

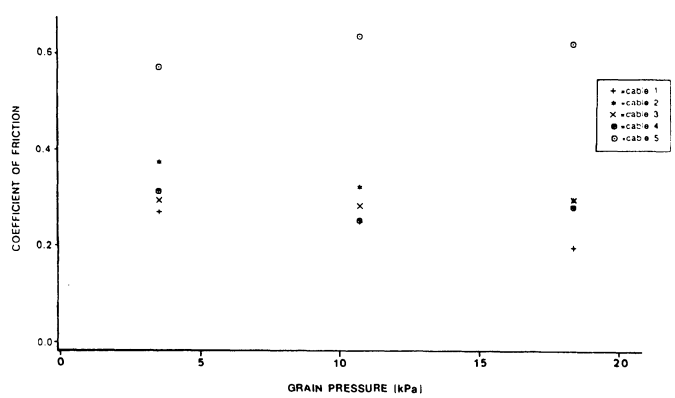

Figure 4–The average coefficients of friction for all five temperature cables as a function of grain pressure.

larger than the center and midway positions and the load for the wall position decreased slower than the other two positions.

The percent increase of the vertical load on each cable in the full-scale bin caused by the wheat mass changing from the static to dynamic state ranged from 10 to 100%. The increase was calculated by subtracting the last static load measurement from the first dynamic load measurement and dividing this difference by the last static load measurement. This sudden increase occurred immediately after initiation of emptying, and reached a maximum value within the first minute of emptying for essentially every test. This increase in vertical load was a result of the differences in the static to dynamic grain pressures.

The detention time between the end of filling and the start of unloading was determined to have a significant influence on the vertical loading of the temperature cables at the 1.0% level for all cables except cable 1. This effect is presumed to be a result of grain settling. Cable 1 showed no effect of detention time on the vertical loading at the 5.0% level of significance. The loads on the other cables generally increased 6.7% as the grain was allowed to settle.

The influence of the emptying flow rate on the vertical frictional loading was examined by using different flow rates. This effect was tested for only cable 3. Flow rate did not significantly influence the vertical loading at the 5.0% level. No clear difference existed between the loads on the cables at the different flow rates.

The influence of the starting grain height on the vertical frictional loading of the temperature cables was examined by starting the tests at two grain heights in the full-scale bin. The height of grain in the bin was 14.3 and 4.1 m, providing H/D ratios of approximately 3.5 and 1.0, respectively. The statistical analysis compared only the loads recorded in the enveloping flow region for both starting heights. No significance difference between the loads was determined for cable 3 at the 5% level for the two different starting heights. The vertical load on the temperature cables at 3 m are similar whether the initial grain height was 14.3 or 4.1 m. The static to dynamic load shifts calculated for the two starting grain heights ranged from 25 to 100% increase in load. The lower starting height was observed to have smaller load shifts than the larger starting height at all three radial positions. The wall position cable exhibited a larger magnitude of load shift than the center and midway positions. This was attributed to the edge effect of the grain near the bin wall.

An analysis was performed to determine the effects of the cable surfaces characteristics on the vertical loading on the cables. The type cable surface was determined to have a significant influence on the loads imposed on the cables at the 1.0% level. The division of cables into categories by the magnitude of the vertical loading per unit area are presented in Table 2. The effect of the different cable sizes was removed by dividing the total load on each cable by the surface area submerged below the grain.

An estimate of the magnitude of the vertical frictional load on a temperature cable was determined by integrating the product of lateral grain pressure, surface area of the cable, and the apparent coefficient of friction of grain on the cable over the length of cable submerged below the grain surface. The lateral grain pressure was estimated by the equation derived in Janssen (1896) using μ and k values of 0.3 and 0.5, respectively. The values of μ and k were selected from the ASAE EP 433 (1989). The values of the remaining variables were obtained from the experimental conditions and results. The prediction equation for the vertical frictional load on the temperature cable is:

TABLE 2. The vertical load per unit surface area of the cable surfaces in descending order of magnitude

Full-Scale Bin		
Cable surface	Cable number*	Category†
Vinyl "A"	5	A highest
Vinyl "B"	2	B
Nylon "A"	1	C
Nylon "B"	4	C
HDLE polyethylene	3	D lowest

* This number corresponds to the number listed in figure 1.
† Categories with the same letters have magnitudes that are not significantly different at the 1 % level.

$$\text{LOAD} = F_{tc} \frac{\pi \mu_{tc} D_{tc} R_h \gamma}{\mu} \{ y + \frac{R_h}{\mu k} [\exp (-\frac{k \mu y}{R_h}) - 1] \} \quad (1)$$

where

y = the depth of grain covering the cable

k = the ratio of lateral to vertical grain pressure

R_h = hydraulic radius of bin(area divided by perimeter)

γ = uncompacted bulk weight of the grain

μ = coefficient of friction of grain on steel

μ_{tc} = apparent coefficient of friction of grain on cable

D_{tc} = equivalent diameter of the cable ($D_{tc} = \sqrt{4 \text{ area}/\pi}$)

F_{tc} = Multiplication Factor

The prediction equation was compared to the observed values of the vertical frictional loading on the five cables in the full-scale bin. The comparison between the predicted and observed loads is shown in figures 5 through 9. The prediction equation with a F_{tc} value of 1.40 provides an adequate estimate of the loads for an H/D ratio of the grain of less than 1.5. This multiplication factor is not to be interpreted as an overpressure factor as defined in engineering practices and design codes. This F_{tc} value provides a conservative estimate of the loads for an H/D ratio greater than 1.5. Different F_{tc} values were determined for the five cables at two radial positions and for H/D ratios greater than 1.5 by SAS (1982) nonlinear regression technique. The results of the center and midway radial positions were combined for this analysis because the differences between F_{tc} for these two positions were insignificant. The F_{tc} values determined by the nonlinear regression technique for each cable are given in Table 3. The average F_{tc} values for the wall and combined center and midway positions were used for predicting the loads for H/D ratios greater than 1.5. The average F_{tc} values estimates the observed loads better than the 1.40 value for

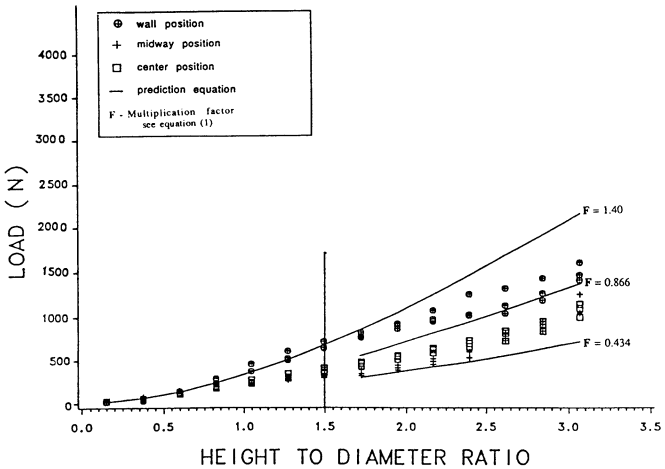

Figure 5–Comparison of the observed and predicted vertical frictional loads on temperature cable 1 for different radial positions in the full-scale bin.

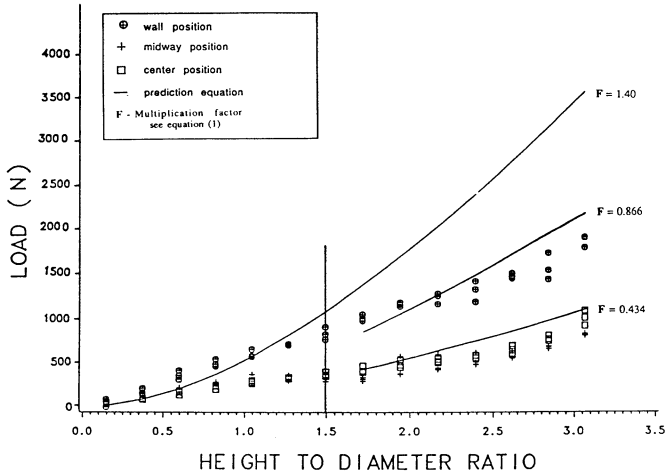

Figure 7–Comparison of the observed and predicted vertical frictional loads on temperature cable 3 for different radial positions in the full-scale bin.

H/D ratios greater than 1.5. These F_{tc} values are not to be interpreted as design parameters.

SUMMARY

This investigation determined the magnitudes and characteristics of the apparent coefficient of friction of wheat on five different commercially available temperature cables and the vertical frictional loading on the cables in a full-scale bin. The laboratory portion of the research showed that "wear-in" did not have a significant influence on the coefficient of friction for the temperature cables. The slip-stick phenomenon was observed for all temperature cables. The sawtooth pattern of the slip-stick phenomenon was observed for the vinyl surfaces and the smoother sine wave shape was recorded for the nylon surfaces. The coefficient of friction of wheat on all the different temperature cables was determined to be significantly influenced by normal grain pressure within the range of 3.5 to 18.6 kPa.

The full-scale bin study was conducted to investigate the vertical frictional loadings on the cables. The influence of the radial positioning, and surface material was determined to significantly influence the imposed loads. The vertical frictional loads were found to be the largest on the cables located at the radial position nearest the bin wall. The surface materials, vinyl and nylon, were observed to have significantly different magnitudes of vertical loads which correspond to the differences in the measured apparent coefficient of friction. The vertical loads in the full-scale bin were observed to increase as the detention time increased. The increase in the vertical loads resulting from detention time stopped after 3 h. The average change in the vertical loads with a 3-h detention time was approximately 6.7% of the initial load. The starting height of grain and the emptying flow rate were determined not to have a significant influence on the vertical frictional loads. The estimated vertical frictional loads by the prediction equation with different multiplication factors provides an adequate estimate of the observed values .

This research determined the vertical frictional loadings on temperature cables and the influences of different factors. Additional research should be conducted to evaluate the effect of different methods of cable installation. The magnitudes of the vertical frictional

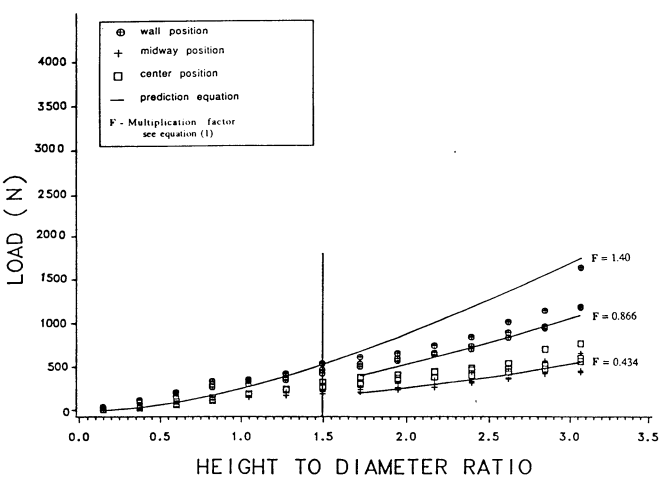

Figure 6–Comparison of the observed and predicted vertical frictional loads on temperature cable 2 for different radial positions in the full-scale bin.

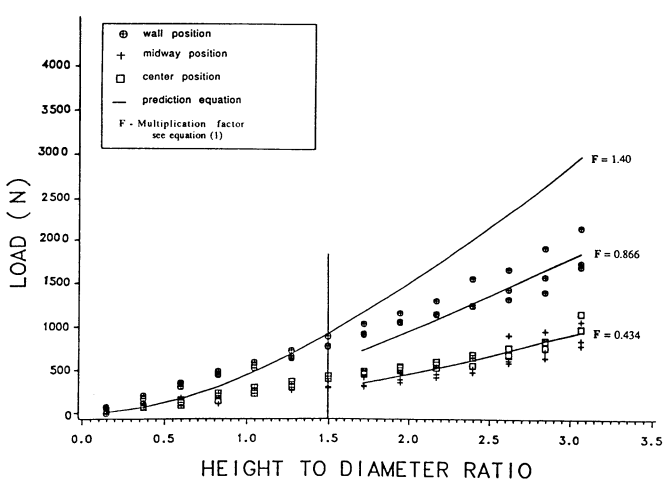

Figure 8–Comparison of the observed and predicted vertical frictional loads on temperature cable 4 for different radial positions in the full-scale bin.

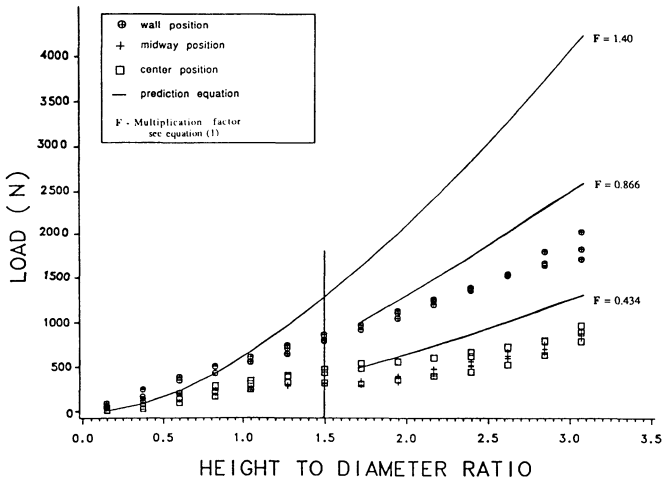

Figure 9–Comparison of the observed and predicted vertical frictional loads on temperature cable 5 for different radial positions in the full-scale bin.

loadings observed in the full-scale study were relatively small compared to the breaking strength of the cables. By combining future research with this established database, an accurate prediction method can be developed.

TABLE 3. The multiplication factor* used in the vertical frictional loading calculations†

	Multiplication factor (F_{tc})	
Cable number	Wall position	Center & midway position
1	1.008	0.643
2	0.979	0.484
3	0.770	0.330
4	0.911	0.429
5	0.663	0.283
Average ± SDev.‡	0.866 ± 0.146	0.434 ± 0.141

* These values are not considered for design evaluation.
† On the five temperature cables of wheat estimated by a nonlinear regression of the full-scale results.
‡ The average value was used to calculate the predicted loads on the temperature cables for an H/D ratios > 1.5.

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