# WALL PRESSURES IN GRAIN STORAGES

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## INTRODUCTION

The engineering profession has become increasingly sophisticated in many areas, but failure of structures for the storage of granular materials, are reported with discouraging frequency. Sadler (1983)describes a number of failures in silos used to store coal. For example, one newly constructed 18.3 m diameter by 55 m high raw coal silo in Kentucky, being emptied for the first time, developed horizontal cracks in the silo wall which grew rapidly in size and number. Within minutes the entire silo collapsed into a heap of concrete, steel and coal. He describes a number of other failures of coal silos after only a few years use; all developed large cracks before finally collapsing. A 9.1 m. diameter by 26.5 m high stave silo in Texas was constructed for the storage of high density polyethylene pellets. On the side above the discharge opening, the wall bulged out by 450 mm and had to be extensively repaired. In Iowa, an 11 m diameter by 36.6 m high grain silo sheared off along a roughly 45 degree diagonal across the entire diameter just above the side discharge opening in the wall, even though the walls were made of 150 mm thick reinforced concrete. In July of 1982, a steel bin at Whiting Iowa, 32 m in diameter by 18.3m high, full of corn, collapsed just as a camera crew from a nearby television station flew by. Viewers across Canada and the United States watching the evening news saw it tear apart like a zipper opening a giant can. Reports of cracks in Swedish grain silos prompted a survey in 1980 to determine the frequency and extent of damage in silos of this type. Thirty per cent of the 103 silos examined had developed vertical cracks, many of them of such width that rain water had been able to penetrate the walls and cause spoilage of the grain.

These are only a few examples of inadequate storages that became public knowledge. Neither engineers nor owners like to publicize their failures so there are undoubtedly many more. Lack of understanding of the behavior of granular materials in storage and the pressures they create is certainly indicated. Poor supervision during construction was probably a contributing factor in some cases.



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## HISTORICAL BACKGROUND

About 100 years ago, the rapidly expanding farming areas of the western world created a need for large terminal grain elevators to handle grain in bulk. A few structural failures at that time made it obvious that the Rankine and Coulomb theories would not accurately predict pressures in deep bins. Consequently there was considerable interest in measuring pressures in grain bins and developing prediction equations. A Canadian named Jamieson published an article in the 1903 issue of the Canadian Society of Civil Engineers Transactions detailing pressure measurements he made on model bins and in a terminal elevator at the port of Montreal. A few years prior to this a German mathematician named Janssen had derived an expression for static pressures in bins based on the equilibrium of a slice of the material. Ketchum (1919) in his book "Design of walls, bins and grain elevators" , summarized the work of a number of investigators, many of whom were comparing the theoetical equations of Janssen with their experimental work. Pleissner, for example measured pressures in four bins and reported that the ratio of lateral to vertical pressure was 0.3 to 0.35 for wheat in bins with smooth walls but 0.4 to 0.5 in rough-walled bins. Ketchum's review confirmed that Janssen's equation gave a good estimate of pressures during filling and under static conditions. His book may be the reason Janssen's equation is still so widely used to-day.

There are only a few papers in the technical literature between 1920 and 1960 on pressures in deep bins. There was considerable activity in the soil mechanics field, but this was directed more toward pressures in shallow structures such as retaining walls. A paper by Turitizin appeared in the 1963 issue of the ASCE proceedings which summarized work done by a number of Russian researchers and by the Reimbert brothers in France. He reported that Kovtun and Platonov had measured emptying pressures in a full size concrete bin that were 2.3 times the static pressure and that Kim had obseved that increased pressures during emptying were associated with mass flow, as opposed to funnel flow. Jenike(1963) conducted very extensive studies at the University of Utah on design of bins to promote flow. Subsequently he and his associates developed relations for pressures in bins, particularly those with steep hoppers. Walker (1963) in England, appears to have been one of the first to predict the sharp increase in pressure which occurs near the junction of a bin wall and a steep hopper. Several researches have since confirmed his theory, at least in general terms.

## PRESSURES IN DEEP BINS

The equations of Janssen have been shown to predict pressures during filling and under static conditions with reasonable accuracy, but many researchers have observed increased pressures during emptying. Codes for the guidance of designers have been developed in several countries which use Janssen's equations with multiplying factors to allow for larger pressures during emptying. Most of the recent research has focussed on describing the factors in Janssen's equation and the circumstances under which increased pressures occur.

The usual form for Janssen's equation is :

$$[1] \quad L = \frac{wR}{u'} \left(1 - \exp(-uKh/R)\right)$$

where:

L = lateral bin wall pressure at depth h

w = specific weight of stored material

R = hydraulic radius of storage structure, and is defined as the ratio of the cross-sectional area of the bin to the perimeter of the bin

K = the ratio of laterial to vertical pressure, L/V

u = coefficient of friction of stored material on the bin wall material, and

h = depth from the surface of material.

Values of u can be found in handbooks; for agricultural materials, papers by Brubaker and Pos(1965), Lawton(1980), and Munroe and Moysey(1970) can be consulted. All found a wide range of values, depending on the nature of the surface and the moisture content of the grain. Since lateral pressure is inversely proportional to u, an accurate value is essential to calculations.

The constant K has been the subject of much discussion. The term in brackets approaches one for very deep bins so the value of K is of little importance if the ratio of depth to diameter exceeds four. In soil mechanics it is usually taken as $1 - \sin\phi / 1 + \sin\phi$ for the active case and the inverse of this for the passive case. For the at rest condition a value of $1 - \sin\phi$ is often used. $\phi$ is the internal friction angle of the material. These expressions are for a semi-infinite mass but adjacent to a bin wall the value of k will be affected by the wall friction, and the following equations are recommended by Van Zanten and Mooij (1977) :

$$[2] \qquad K\ active = \frac{1 - \sin\phi \cos 2e}{1 + \sin\phi \cos 2e}$$

where

$$2e = \sin^{-1}\left(\frac{\sin\alpha}{\sin\phi}\right) - \alpha$$

and the following formula to determine K in passive yield case:

$$[3] \qquad K\ passive = \frac{1 + \sin\phi \cos 2B}{1 - \sin\phi \cos 2B}$$

where

$$2B = \sin^{-1}\left(\frac{\sin\alpha}{\sin\phi}\right) + \alpha$$

These equations are presented in nomograph form in a paper by Moysey (1979). The effective angle of internal friction is obviously required to determine K. This is sometimes taken as being the same as the angle of repose, but this is a crude approximation for some materials. $\phi$ is best determined by a triaxial test or a shear box test. Again, values for many materials can be obtained from handbooks and journal papers. Moysey and Hiltz (1985) have shown that for shear box tests, method of filling the box had a marked influence on the measured friction angle. Relating this to the work of Oda (1978), they suggest that use of a spreader which produces a sprinkling action as a bin is filled, will increase the value of $\phi$ and therefore reduce the lateral pressure on the walls.

Measurement of pressures in model and full-scale bins has shown that a number of factors can affect pressures during emptying. Nielsen and Kristiansen (1983) measured pressures in a reinforced concrete bin 7 m in diameter by 46 m high. When barley was spouted in at an angle so that it struck one wall halfway up the bin, static pressure on that wall at some levels was 50 % greater than on the opposite wall. Pieper (1969) has done a great many tests in a model bin 0.7 m square by 5 m high and found that wall pressures inrease during emptying , but the amount of the increase is dependent on the position of the discharge opening. For centric discharge, wall pressures were 30 % larger than filling but when the discharge opening was near the wall, pressures 70 % greater than during filling were observed.

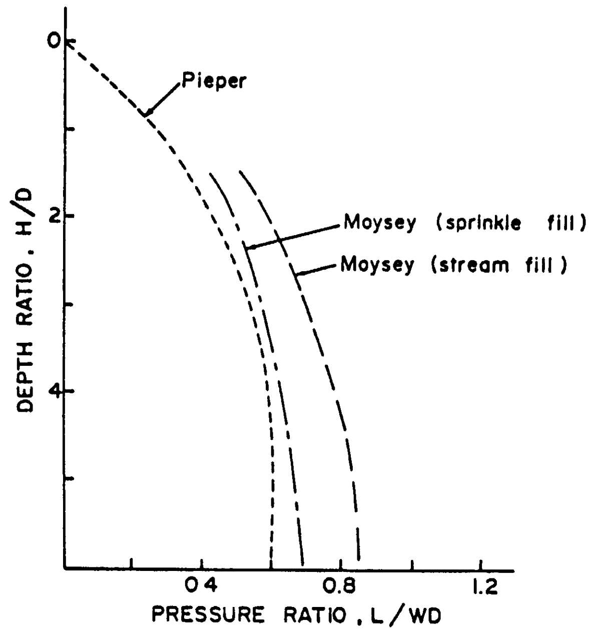


Fig.1. Wall pressure during filling with wheat in plywood (Pieper) and plexiglas (Moysey) model bins

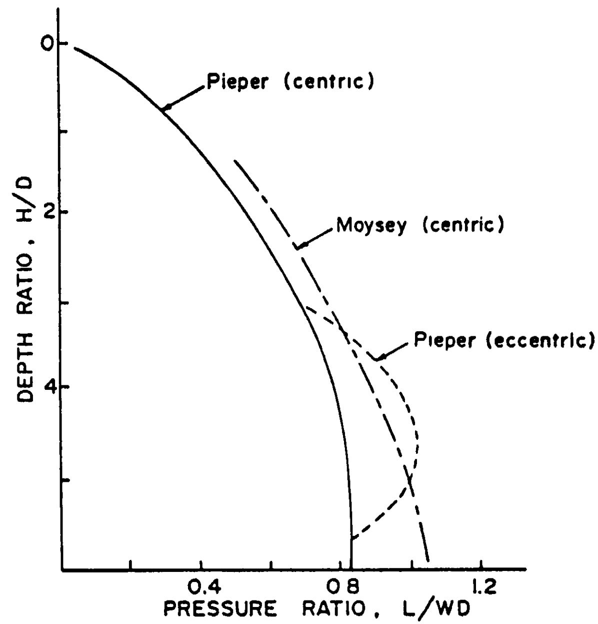


Fig.2. Wall pressures during emptying in plywood (Pieper) and plexiglas (Moysey) model bins

Figures 1 and 2 show this, along with some results obtained by Moysey(1984), in which he found that when a grain spreader was used during filling so as to produce a sprinkle fill, wall pressures during both filling and emptying were about 20 % less than if the grain entered in a stream. Pieper varied the emptying rate by a factor of ten with no effect on wall pressure. Van Zanten and Mooij (1977) and Van Zanten, Richards and Mooij (1977) used model bins 1.5 and 2.0 m diameter with sand and PVC powder as test materials. The bins were equipped with steep and shallow hoppers so as to produce mass and funnel flow, respectively. Wall pressures during emptying in the funnel flow bins were about double the filling pressures; in the mass flow bins pressures during emptying were triple the filling pressures in some parts of the bin.

Van Zanten, Richards and Mooij (1977) also measured pressures on the hopper walls and in the vicinity of the wall - hopper junction. These pressures were very large in the bins with steep hoppers, presumably because they produced mass flow. This phenomenon has been predicted and observed by a number of other researchers, eg. Clague and Wright (1973), Jenike, Johanson and Carson(1972). In some cases the local pressure just at the junction of the wall and hopper during emptying was five times what it was under static conditions. In funnel flow bins a funnel forms within the material itself, cushioning the effect on the hopper. When this occurs, maximum wall pressure during emptying will likely occur where this funnel intersects the bin wall.

## DESIGN EQUATIONS and CODES

Guidance in the design of structures for the storage of granular materials has been available in the form of building codes and codes of practice for a few years. The American Conrete Institute published a proposed standard in the ACI journal in 1975, and updated it in 1983. The section on loads shows Janssen's equation and Reimbert's equation and recommends that k be taken as 1-sin $\phi$ / 1+sin $\phi$. Overpressure factors, which are to be multiplied by the Janssen pressure, range from 1.35 to 2.0 at various depths in the bin; see figure 3. Some suggestions for overpressure factors due to eccentric openings is also given, along with comments on the effect of aeration in powders and of temperature change. A table listing values of bulk density, internal friction angles and wall friction co-efficients is provided, but it is done with a wide brush, so a designer would have to consult other sources when doing a specific design.

The German standard, DIN 1055 Blatt 6, predates the ACI standard by 10 years or more, and the two have many

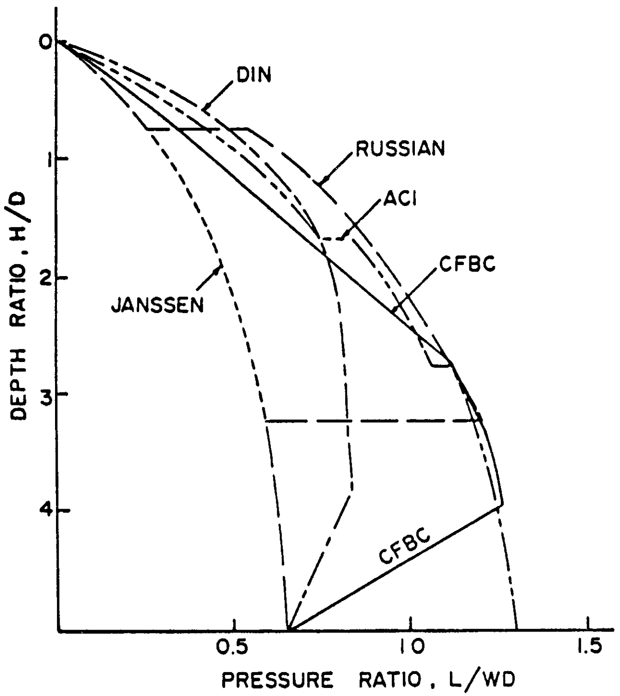


Fig. 3. Comparison of Janssen pressure with emptying pressures recommended by building codes for u = .364 and K = .43

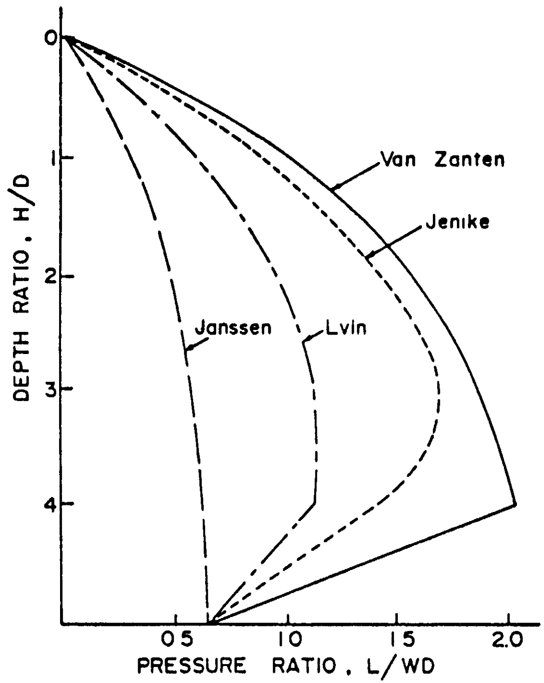


Fig. 4. Emptying pressures recommended by three authors compared to Janssen for u = .364, K = .43

similarities. The DIN differs by making the wall friction a function of the internal friction angle, u = tan (0.75 $\phi$) during filling and tan (0.6 $\phi$) during emptying. Eccentric emptying is handled by assuming an imaginary bin of larger size. Figure 3 compares the DIN and ACI standard. Also shown is the requirement of the Russian code; it recommends much larger pressures in the lower part of the bin. The Canadian Farm Building Code included requirements for storage bins for the first time in 1983. Like the others, it relies on Janssen's equation and multiplying factors. It provides a more comprehensive listing of internal friction angles and K values for agricultural materials than the others.

By their very nature building codes cannot provide a designer with all the information he needs. Other sources of information must frequently be sought, and the following are suggested as helpful.

The series of papers by Van Zanten, Everts et al provide equations for estimating pressures on bin walls and hoppers that are helpful to better understanding the problem. The series by Jenike, Johanson and Carson provide a number of graphs for estimating wall pressures for a variety of combinations of u and K, which illustrate the great range of pressures which might occur with different products. Equations for deriving these graphs are not easily followed. A theoretical approach by Lvin(1970) is intriguing. He derived equations for bin pressures using a series of concentric rings, rather than a slice as Janssen did. Pressures calculated from his equations are larger than Janssen's in the upper part of the bin, but identical at depths of a few diameters. Lvin also derived an expression for the pressure during emptying which is refreshingly simple, compared to most. It is :

$$L_{\text{emptying}} = L_{\text{filling}} [0.71 + 0.29m]$$

where m is the ratio of K passive to K active.

Figure 4 shows a comparison of the recommendations for emptying pressure given by the equations of Lvin, Van Zanten and Jenike, compared to the Janssen curve for static pressure. Note that the calculations were made for values of u and K typical of wheat in a bin with smooth walls; pressure ratios for other values of these variables may be considerably different. The recommendations of both Jenike and Van Zanten are for funnel flow bins. For this case, Van Zanten et al multiply the Janssen pressure by the ratio of K passive to K active, which produces very large values. For mass flow bins both Van Zanten and Jenike recommend even greater pressures. The curves of figure 4 show pressure ratios in excess of 1.5, appreciably larger than is suggested by the curves of fig. 3, based on building codes. The curve calculated from Lvin's work seems to correspond better to the observations of Pieper and Moysey.

## FACTORS OF UNDETERMINED MAGNITUDE

Why should there be such a wide range of design pressures? Perhaps some of it goes back to methods used in experiments. For example, Van Zanten and Mooij measured very high pressures at " induced irregularities" - ledges or ribs of some sort which caused a distortion in the flow pattern. In bins where the height to diameter ratio exceeds three, the whole mass of material tends to move down as a solid slug. If the bin tapers in the direction of flow so that this mass is forced into a smaller cross-section, greatly increased pressures can result. Both of these features should obviously be eliminated by the designer. There are also unknowns that must be guarded against. Henny et al (1983) observed that the top surface of the maize in a silo moved up and down with changes in temperature. This would lead one to speculate that passive case pressures might be reached, making Van Zanten's recommendations logical. In a few cases, observers have noted that large bins have vibrated severely during emptying. This seems to have occurred where the product in storage contained a range of particle sizes ; coal and corn containing fines, for example. These mixtures may have more tendency to bridge and form domes; if these domes form and collapse every few seconds, severe vibrations might result. Another concern is increase in moisture content of materials during storage, which can cause them to swell and greatly increase wall pressures. Fortunately this happens very infrequently.

## SUMMARY

Many factors can affect the pressures that granular materials exert on bin walls. Some, like wall friction co-efficient, are measurable and are included in design equations, but others are not well understood. Extreme pressures are most likely to occur when:

a) the ratio of bin height to bin diameter exceeds two,

b) a steep hopper is used to produce mass flow,

c) the stored material does not flow freely,

d) ledges and ribs on bin wall surfaces force the flowing material through a smaller cross-section,

e) the stored material increases in moisture content.

In cases such as these it may not be necessary to design for pressures greater than are suggested by codes.

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