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Determination of Contents in Storage Bins and Silos

M. Ooms, Australia

Füllstands-Messung in Silos und Bunkern
Détermination des contenaces des réservoirs et silos de stockage
Determinación del contenido en tolvas y silos

貯蔵ビンおよびサイロ内の内容物の測定

贮料箱与地下仓的容量计定

تحديد المحتويات في العلب والصوامع

Summary

Modern process plant relies heavily on control systems for reliable and efficient operation. A control system generally consists of the storage bin, a sensor or transducer and electric signal conditioning circuitry. In most applications the transducer is the most vulnerable part of the control system. In many bulk materials handling installations the penalty for poor choice of transducer to measure bin contents may be material runout or equipment breakdown resulting in expensive plant downtime and loss of production.

The paper presents an overview of the various methods used to determine storage bin contents for auditing and process control purposes. Errors in the determination of both volumetric and mass contents are discussed. The problem of determining contents of individual bins in a common support structure where "difficult" materials are stored is also discussed and a solution given by way of a case study.

It is important that all of the factors discussed are considered and understood when designing an effective and reliable contents monitoring system to suit the requirements of bulk materials handling plant.

Nomenclature

- A Cross-sectional area of bin
- A_H Cross-sectional area as function of H
- b Exponent of equation (4)
- D Diameter of bin at parallel section
- E_L Errors from level measuring techniques
- E_W Errors from weighing techniques
- e Structural deformation
- g Gravitational acceleration
- H Total depth (height) of material in bin
- H_c Height from ground level to centre of projected area of bin
- H_e Equivalent height of rectangular projected area (neglecting slope of cone and bin top)
- H_o Vertical length of hopper section
- H_p Height of material in parallel section of bin
- K_j Janssen factor
- L Length for deflection measurement
- m Coefficient $m = 0$ for plane flow cylinders (end effects neglected) $m = 1$ for circular cylinders
- M Bin contents
- P Wind loading force
- r Radius of hopper section of bin
- W Weight of bulk solid material in bin
- z Depth variable
- θ Angle of repose at free surface
- α Hopper half angle
- ϵ Strain
- ϱ Bulk density when $\sigma = \sigma$
- ϱ_0 Bulk density when $\sigma = \sigma_{10}$
- σ_1 Major principal stress
- σ_{10} Empirical major principal stress
- σ_v Vertical stress in cylinder at depth $z = z$
- μ Frictional coefficient

Martin Ooms, Department of Mechanical Engineering, The University of Newcastle, 2308 N.S.W., Australia

1. Introduction

The development of sophisticated and powerful microprocessor based process controllers in recent years has placed an even greater demand on the transducers on which they depend for signal input. Increased understanding of bulk solid material behaviour under various storage and flow conditions has led to improved design of storage and handling facilities and in modern installations smooth controlled flow of materials is achievable when these available design techniques are utilised. The function of reliable bin level transducers then is extremely important.

Many large scale storage systems have been damaged and conveyor gantries backfilled with consequent expensive downtime when reliable bin level transducers have not been installed or when transducers have failed. Many failures occur under conditions where particular transducers have been unsuited. In many installations the use of a high accuracy, high cost transducer is not warranted for the functions which it is expected to perform. On the other hand, "initial cost" basis for choosing a transducer for level indication and control can lead to an unworkable solution.

To make the correct choice there is a need to understand the operating principles and limitations of various signal transducers used for measuring both the volumetric and mass contents of storage bins and surge hoppers which play a major role in process plants dependent on bulk materials handling operations. Parameters such as material stored, bin geometry, accuracy requirements, structural considerations and cost should all influence the choice of signal transducer, and are discussed in the presentation. Errors in the determination of both volumetric and mass contents resulting from such effects as material distribution, variation in bulk density, thermally induced loading, conveyor gantry live loads and wind loading are discussed in detail and ways to determine the magnitude of the various errors are presented.

The special problems associated with multiple storage bin systems supported within a common structure are discussed. Such systems give rise to interactionary loads on the structure which, when weighing devices are used to determine individual bin contents, can introduce errors. The ways of minimizing these errors, thereby maintaining accuracy, are presented. It is important that all of these factors be understood and considered when designing an effective bin weighing and process control system to suit the requirements of the materials handling industry.

2. Purpose of Bin Level Measurement

In modern automated bulk solids handling plants, transducers are required to provide reliable bin level measurement for various reasons.

a) Indication of Bin Contents

Reliable indication of storage bin contents will lead to more efficient manual operation of process plant. In its simplest form, a plant with a single storage bin, perhaps acting as a surge bin, will benefit from the installation of a level measuring transducer. It may only help to prevent material "run out" from the bin or overflow of the bin. However, in both cases the consequence of not having a reliable indication of bin contents would undoubtedly be process delays or plant breakdowns.

b) Process Control

Smooth operation in modern process plant is usually the result of reliable transducers and electronic control systems. The operations of conveyors, feeders, elevators and all other forms of ancillary equipment may all be controlled by signals from transducers. Complex control systems may run into considerable initial expense; however, the increase in productivity usually resulting from the use of reliable systems will offset this initial expense in a relatively short period of time compared with expected plant life.

The initial cost of transducers, as part of a process control system, is fractional compared with the total cost of a typical system usually incorporating complex microprocessor based logic and display circuitry.

c) Inventory Auditing

With greater emphasis placed on economics, reliable bin level measurement is necessary so that at any instant a readout of bin level may be obtained by plant management. This information is necessary from a management viewpoint so that:

(i) Shift production can be recorded,
(ii) stock piles can be maintained, at known levels,
(iii) yield per unit of input can be recorded,
(iv) adequate forward planning becomes easier so that maintenance programs can be adhered to,
(v) simple inventory of incoming and outgoing bulk materials is essential for reliable cost accounting.

3. Transducers Commonly Used

A great deal of time and effort has been devoted to developing transducers for level detection. In the past much of the work has been concentrated on "liquid" level detection in tanks. With the increasing demands of modern process plant handling materials in granular and powdered forms many existing transducers are not suited and have been modified and other transducers designed for applications in bulk solids materials handling plant.

3.1 General Discussion of Methods

Bin level transducers generally fall into two broad groups according to function: Continuous and fixed point. Many of the transducers available rely on actual contact of the bulk solid material within the storage bin and are not suited to the hostile environment inside some bins. However, not all methods require a sensor to actually contact the material, therefore a further classification of the various techniques according to location may be desirable: Intrusive and non-intrusive.

a) Continuous Level Measurement

Continuous bin level transducers provide a continuity of measurement from the low end of the scale (bin empty) to the high end of the scale (bin full). All "weighing" systems fall into this classification of bin level measuring systems.

In a modern automated bulk solids handling plant with a control system that requires various signals for control of conveyors or feeders and where management requires an instantaneous readout of bin contents for inventory auditing, a Continuous Level Transducer is essential. In such applications involving inventory of the stored bulk solid material, either the volume, or more importantly the weight of the material is required.

The volume of the bulk solid within the storage bin is simply

$$V = \int_0^H A_H \, dH \tag{1}$$

The weight of the bulk solid then is given by

$$W = \varrho \int_0^H A_H \, dH \tag{2}$$

where

V = volume of bulk solid, m³
H = height above datum, m
A_H = cross-section area of bin as function of H, m²
ϱ = average bulk density of bulk soild, kg/m³
W = weight of bulk solid, kg.

b) Fixed Point Level Measurement

Fixed point bin level measuring transducers provide indication of bin contents at only one pre-determined and specific fixed level. This level needs to be chosen with reasonable discretion since once the transducer is located, relocation to another fixed point usually requires considerable cost, and with some devices, relocation or the addition of an extra fixed point indicator requires plant downtime. If the principal objective of the level system is to prevent overfill or runout, then simple fixed point transducers, which may be used to actuate alarms or control circuits, would be adequate.

c) Intrusive Transducers

Level measuring transducers that actually contact the bulk solid material or are located within the storage bin space are called intrusive transducers. Care is essential when choosing a suitable intrusive device; compatibility of the transducer and stored bulk solid usually becomes the prime consideration. Incompatibility will undoubtedly lead to a reduction in either or both performance and transducer life.

d) Non-Intrusive Transducers

Transducers used for bin "level" measurement located outside of the storage bin space are called non-intrusive transducers and have obvious advantages over intrusive devices in applications where the environment inside the storage bin is hostile to any protruberances of the bin space. In general, weighing techniques utilise non-intrusive transducers while true "level" measuring techniques usually utilise intrusive transducers. This is not always the case.

3.2 Specific Techniques

The various techniques of transducers are discussed and their typical applications given. Most of the devices are available through local distributors.

1. Capacitive Probes

Capacitive probes are intrusive transducers and may provide either fixed-point or continuous level detection by sensing the change in capacitance around the probe surface. This change is brought about by a variation in the amount of material around the probe surface resulting in an electrical output from the transducer electronics proportional to the quantity of material around the probe.

The change in capacitance is almost linear with material level, the degree of linearity depending on the shape of the storage bin and the nature of the material being stored. Accuracy and repeatability are limited by variations in bulk density, moisture content and particle size of the bulk solid material.

Capacitive probes may be used with both conductive or non-conductive bulk solid material, provided that the dielectric constant of the bulk material is greater than that of air.

2. Resistive Probes

Resistive probes are suitable for fixed-point level indication of conductive material with a dielectric constant of 19 or higher. The resistive probe relies on the conductivity of the bulk solid to complete an electric circuit between the probe and the storage bin or, in the case where a non-conductive bin is used, between a pair of probes. In some applications special sensors with multiple sensitive "tips" are used and sense the level when a circuit is completed between these "tips". The accurarcy of this technique depends on the conductivity of the bulk solid. The conductivity varies with each material and depends on moisture content, bulk density and particle size of the material being stored.

With material such as raw coal, frequent failure of both cables and probes occurs during normal operation.

3. Vibrating Probes

Vibrating probes are fixed-point level detection devices fastened to the storage bin walls and protruding into the bulk solid material. The probes are forced to vibrate by an excitation device which is also able to measure the frequency or amplitude of the resultant vibration. When material contacts the probe the frequency of vibration changes, indicating that material is present at the sensor level.

Vibrating probes are reasonably delicate devices not suited to heavy and lumpy bulk solids.

4. Field Effect Probes

Field effect probes are fixed level sensors which operate with both conductive and non-conductive materials and are most suited for mounting in the sides of storage bins. The operating principle is that the proximity of material to the probe causes a change in the magnetic "field" which is sensed by the electronics inside the probe.

5. Deflection Probes

Deflection probes use a tapered steel rod which deflects when the material contacts the probe and actuates a switch. The probe is mounted vertically from the top of the bin and is suited for fixed-point level detection of top level only. The advantages of this type of probe are that it is unaffected by build-up and may be made robust to suit heavier bulk solid material.

6. Tilt Switches

Tilt switches are devices used for fixed-point level detection of top levels only and are usually fixed to the top of the storage bin and allowed to hang from a cable. The material level in the storage bin rises and causes the probe to tilt. The tilt switch inside the probe requires less than 20° rotation to operate. This usually involves a ball rolling off a small switch or mercury level when the required angle is reached.

Generally the advantages of using probes for fixed-point level detection in applications suited to their design are their low cost and generally low maintenance due to the fact that there are few or no moving parts. However, probes are intrusive devices and as such are exposed to the environment offered by the bulk material, and can cause serious obstruction to the flow of the stored material.

7. Electro-mechanical "Paddles"

Electro-mechanical paddles are fixed-point level sensing devices using the rotation of a "paddle" to sense the presence or absence of material. The moving paddle is driven by a low speed, low torque synchronous motor which rotates freely during the absence of material. When material comes into contact with the rotating paddle the resulting increase in torque actuates a switch, indicating that the required level is sensed. There are many types of paddles made from various materials to suit most applications. In some applications it has been found necessary to protect the moving parts from mechanical damage caused by the bulk solid material.

8. Retractable Electro-mechanical Devices

Rectractable level indicators are continuous level measuring instruments which are suited for most materials. Level measurement is made by means of lowering a weighted cable until it contacts the surface of the bulk solid. When the surface is reached the electronics sense that the cable slackens, causing the motor to reverse and rewind the cable. The length of the unwound cable indicates the level of the surface of the bulk solid. Although the period of contact with the bulk solid is only momentary, lasting for the time required by the electronics to sense the slack cable, these instruments are still considered to be intrusive as a result of damage experienced during use. Measuring may be performed manually or automatically but care should be taken to ensure that filling of the storage bin does not occur while level measurements are taken. Damage to this system may result when heavy coarse material is being charged, filling in over the cable while it is lowered. The retractable device is mounted on the top surface of the storage bin and does not offer any resistance to flow when measuring low levels, as is the case with fixed probes. Adequate stops are required to prevent complete runout and consequent damage to the cable in feeders and screw conveyor when the bin is allowed to empty. Difficulties have also been experienced in funnel flow and expanded flow storage bins when "piped" material has collapsed onto the cable, causing extensive damage to both the cable and mechanism.

9. Pressure Sensitive Diaphragms

Pressure sensitive diaphragms are fixed-point level sensors installed in the side walls of storage bins. The diaphragms are usually made of a flexible material which, when contacted by the bulk solid material, deflects sufficiently to activate a switch behind the diaphragm. A correctly installed pressure diaphragm (mounted flush with the internal surface of the storage bin) offers little resistance to material flow. These units are low initial cost items requiring little maintenance when installed in appropriate systems with suited bulk solid material.

10. Ultrasonic Detectors

Ultrasonic level measuring techniques use the principle of pulsed pressure waves, usually in the range of 30 kHz to 100 kHz. Two measuring methods are used, one as a continuous level indication system and one as a fixed-point level indication system.

Continuous level measurement uses the echo method, where ultrasonic pulses are transmitted onto the free surface of the bulk solid material and reflected back to a receiver. The time taken for the reflected signal to reach the receiver is usually proportional to the level of bulk solids in the bin. Such devices are usually mounted on the top of the storage bin so that the ultrasonic pulses are beamed downward onto the free surface. The spread of the beam may be adjusted to suit particular applications with the widest spread usually giving the highest sensitivity.

Absorption of ultrasonic pressure waves is the principle used for fixed-point level detection. In applications of this nature the source and receiver of ultrasound are mounted diametrically opposed on the storage bin walls. When the bulk solid material reaches the level of the sensor, the ultrasound is absorbed, with a resulting change in amplitude of the sound pressure wave seen by the receiver.

The various techniques discussed to this point have all used intrusive transducers. The following techniques use non-intrusive transducers where sensors are completely external to the storage bin and require no contact with the bulk solid material to determine level.

11. Nuclear Level Detectors

Nuclear level detection may be used for either fixed point or continuous level sensing. A radio-active source radiates through the storage bin walls and into the storage bin and through the material to a detector. When bulk solid material is present, some of the gamma radiation is absorbed while the remainder is sensed by the detector and converted to an electrical signal. This method of level detection is extremely effective since the source and detector are located wholly outside the storage bin. Although relatively safe radio-active materials are used, the very existence of this type of material in production plants may meet with some resistance.

The remaining techniques utilise transducers which determine the weight of material within a storage bin and where necessary this may be used for level control. In many operations of process plant such as batching, packaging, transport or simple storage, the usual unit of measure is weight, and directly determining weight is in many cases the simplest and most accurate solution.

12. Load Cells and Load Beams

Load cells are special load-bearing structures designed to produce an electrical signal proportional to the load applied to the cell. They are usually fitted under some load-bearing part of the storage bin supporting structure so that the weight of the storage bin and contents applies a force to the cell, causing a change in strain in the internal structure of the load cell. The internal parts are usually fitted with foil strain gauges arranged in a number of orientations to produce varying degrees of sensitivity and linearity. For small storage bins, a tension load cell may be used to support the storage bin and contents from overhead structures. Load cells are designed to accept vertical forces representing the weight of the storage bin and contents. In some applications restraining flexures are necessary to counter any side loads which may be applied by conveyor gantries, discharge chutes or any other structures. These restraining flexures must be kept elastic and repeatable in the load plane and the magnitude of the exerted forces by the flexures must be kept as low as possible. For new storage systems, where the support structure has been designed for load cells, installation costs may be low. For existing storage bins, particularly larger bins, considerable modifications may be necessary, resulting in system downtime and loss of production, usually at relatively high cost.

Load beams carry loads so that the sensor is subjected to transverse or shear forces. The advantages of load beams over conventional load cells are their increased immunity to side loads and their lower cost. In many applications load beams or shear beams, as they are sometimes called, will operate quite within required accuracy tolerances without needing the restraining flexures required for load cells. Both load cells and load beams provide continuous level output of bulk solid storage bin contents and are in no way limited by the type of material stored. The only obvious problems of using weighing techniques for "level" control are associated with variations in average bulk density of the material.

13. Strain Measuring Devices

Strain links are simple, bolt-on devices designed for attachment to loaded structural members supporting the storage bin to give continuous indication of strain in that support member. This strain should be proportional to load in the bin if the link has been correctly installed on a structural member influenced only by the bin and contents. Again the strain is converted to an electrical signal using strain gauge techniques and since there are no moving parts in the sensor, the system is very reliable. The accuracy for correctly applied strain links may be in the order of 0.5% to 2%, depending on the storage bin structure and the number of sensors used. Strain links are low initial cost items and are quick and easy to install, requiring no downtime or loss of production because no structural modifications are necessary. Temperature differences between the sensor and the structural member to which it is attached may cause apparent strain which may be a source of error. This can be reduced by adequate thermal shielding to reduce the temperature differential. In some applications the level of strain present in the supporting structure may not be adequate to produce the required electrical output. These situations require special treatment such as amplification of strain levels, to produce an electrical signal which will be unaffected by an electrically noisy environment.

14. Linear Displacement Transducers

Linear displacement transducers are also able to sense weight by measuring the actual deformation of support columns in the structure supporting storage bins. These devices again are continuous measuring devices which are low to medium initial cost and are quick and easy to install. Adequate thermal protection is required to minimise errors resulting from thermally induced apparent strain. In the case of some displacement transducers adequate environmental protection is necessary to protect the moving parts from contamination by foreign matter in hostile environments. System accuracies of 0.5% are claimed for correctly installed systems. Installation techniques similar to strain links are required.

3.3 Considerations Affecting Choice of Transducer

When an engineer is confronted with the problem of obtaining reliable bin "level" or bin contents indication, there are many considerations affecting the choice for the most cost effective system from the many different devices available to him. The most important considerations are:

Function

Quite often the most obvious question of function is overlooked. If simple level of contents to prevent overfill or runout is required, then for many materials, low cost, limited accuracy fixed point transducers are adequate and provide for reliable bin level indication. Control circuitry or alarms may be energised from these fixed-point devices. As with all fixed-point devices once installed their location is fixed and relocation of the device is necessary to alter the level sensed. In some instances a low cost continuous device has advantages of cost and performance over fixed-point devices when more than two levels are required to be sensed. The advantage comes from being able to choose an infinite number of "level" sensing points between bin empty and bin full.

Material Stored

When intrusive transducers are used for bin level measurement the possible effects of the material on the transducer needs to be considered. Some materials may be abrasive or corrosive in nature and could therefore significantly reduce the performance and life of intrusive devices. Other materials may be stored at elevated temperatures and pressures in which case the transducer able to tolerate the conditions is required. Powders or granules which are cohesive will affect the accuracy of some intrusive devices and could require regular cleaning to maintain reliable performance. Larger and relatively heavy particulate bulk solids, such as run of mines coal, will cause serious mechanical damage to intrusive wall mounted devices. Extremely dusty or excessively moist conditions generated by material inside storage bins have provided significant problems to ultrasonic transducers. The dusty or misty environment causes excessive errors when using this method of bin level measurement.

Flow Characteristics of Bin and Material

For many bulk solid storage installations smooth and reliable flow of material from storage bins is essential. In some instances an intrusive bin level device installed as a low level sensor in the hopper section of a mass flow bin could seriously impede the flowability of material from the bin and have a serious effect on overall plant process. For all materials not exhibiting free flowing characteristics the type of intrusive device and the location for the device should be chosen with caution. In a mass flow situation the material discharges from the bin *en masse*, sliding down the bin wall toward the hopper opening. The forces on a protuberance such as an intrusive transducer are quite large, particularly if the transducer is located within the hopper section of the bin. On the other hand, in funnel flow bins the forces on protuberances are relatively low and damage to intrusive devices is usually less likely to occur from material discharge forces. Forces exerted on bin level probes during material consolidation over extended storage periods could significantly reduce probe in-service life.

Accuracy Required

In some applications there has been a general tendency to over emphasize the requirements of accuracy, quite often leading to decisions to use unnecessarily expensive devices. Placing accuracy before practicability too could lead to an unwise decision when choosing a bin level method. In the case where simple level measurement is required, system accuracies of 2%—5% would be quite adequate to prevent material overfill or runout. However in many of the cases recently investigated, the stated requirements are generally 0.5% or better. To achieve system accuracies of this order, considerable unnecessary expense is generally involved, when an alternative less expensive system could adequately provide the desired accuracy.

Storage Bin Design

The storage bin physical dimensions can sometimes significantly influence the choice of bin level transducer. Ultrasonic transducers have limited range so therefore are not suited to providing continuous level measurement in tall narrow storage bins. On the other hand squat flat bottom bins used to store bulk solids which are not free flowing will provide problems of accuracy to side mounted intrusive probes when these are used. Larger structures supporting storage bins may not be suitable for the common weighing devices discussed earlier. For example, very large capacity bins generally require costly modifications to structural members when load cells are used as weighing devices after the bin has been commissioned. A common structure supporting multiple bins may not be suited to bolt-on strain transducers or load cells and in many practical applications for weighing, the supporting structure requires careful scrutiny so that the most cost effective solution to the problem can be provided.

Cost

The purchase of new items of equipment for industrial applications is generally made in accordance with reasonably strict budgeting guidelines. With bin level equipment, a tight budget usually manages to achieve minimum capital expenditure, however in some applications this leads to an unwise choice of transducer and subsequently results in high maintenance expenditure. In some installations replacement with more suitable equipment is found necessary after an in-service period, effectively increasing the cost by a factor of 2 to 4 times and also resulting in many unnecessary interruptions to normal plant operation.

As a general guide Table 1 shows the various transducer types, their operating principle, typical application and relative costs.

4. System Errors in Contents Measurement

The nature and behaviour of some bulk solid materials in storage bins can contribute large errors to bin level measuring systems if the transducer or overall system is unsuited to the conditions. Unlike liquid "level" in storage tanks or ponds, bulk solids "level" is a misnomer. The shape of the free surface of the stored bulk solid depends entirely on the material and on the condition of the material at a particular time. Many cohesive bulk solids which exhibit seemingly repeatable behaviour during filling operations, will behave in an erratic and unpredictable manner during discharge operations. This leads to large errors in true "level" measuring techniques for the determination of volume or weight. It also leads to apparent unreliable results when using weighing techniques to determine bin "level".

4.1 Errors in "Level" Measurement

In equations (1) and (2) of Section 3.1, it was shown that the volume or weight of stored bulk solid material could simply be determined from "level" measurements.

The volume

$$V = \int_0^H A_H \, dH \tag{3}$$

and the weight

$$W = \varrho \int_0^H A_H \, dH$$

are simply a function of the variables as shown. However, variations within these variables may contribute errors of significant magnitude.

Consider each of the variables separately.

a) Variations in Cross-Section of the Bin

Variations in A, the cross-sectional area, may be due to one or all of the following conditions:

(i) Large initial manufacturing tolerance of the fabricated shell,
(ii) deflection of the shell under load from the bulk solid material,
(iii) deflections due to thermal strain either as a result of ambient conditions or operating temperatures.

Deflection of the shell under load or as a result of thermal strain, is not generally considered a source of significant error. Manufacturing tolerances of fabricated shells have been the cause of errors, however they are repeatable errors and as such are easily isolated.

b) Variations in Average Bulk Density

Variations in ϱ, the average bulk density, can have a significant effect on the accuracy when using level measuring techniques to determine the weight of material held within a storage space. The average bulk density will vary considerably when influenced by one or more of these conditions:

(i) Variation in particle size of the bulk solid. One storage bin may be used to store a material of basically the same composition, differing only in particle size and therefore bulk density. Weight determination using level techniques can then become a problem.
(ii) Variation in moisture content will cause significant errors usually proportional to the variation of moisture content.
(iii) Variations in operating temperature will have a direct effect on changing average bulk density.
(iv) Consolidation periods in many bulk solids will provide significant changes in average bulk density.

The variation in bulk density with consolidation stress is given by [1]:

$$\varrho = \varrho_0 \left(\frac{\sigma_1}{\sigma_{10}}\right)^b \tag{4}$$

McLean and Arnold [2] derived the expression

$$\frac{d\sigma_v}{dz} = \varrho g - \frac{2(m+1)\mu K_j \sigma_v}{D} \tag{5}$$

for variations in vertical stress. Using numerical solutions obtained from equation (5) incorporating the effects of equation (4) the contents of a bin may be evaluated using the expression

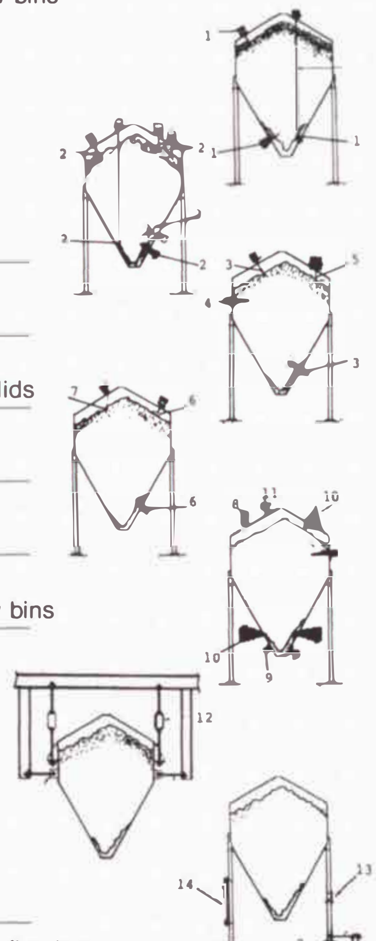
$$M = \int_0^H \varrho A \, dz \tag{6}$$

where H is the total depth of bulk solid material in the bin.

McLean and Arnold found that for cylindrical bins with a H/D ratio of 2, an approximate analysis assuming a constant value for bulk density overestimated bin contents by approximately 4 % compared to numerical solutions obtained from equations (4), (5) and (6). As suggested by McLean and Arnold the errors increase when aspect ratio H/D is decreased.

Table 1: Chart of transducer performance

Transducer type	Mode of operation	Generally unsuited applications and limitations	Typical applications	Relative costs
1. Capacitive Probe	Capacitance of material around probe surface	• Low level sensing in mass flow bins (i) Impedes flowability (ii) Subject to damage • Large particulate dense bulk solids cause demage • Abrasive bulk solids • Adhesive bulk solids	Fixed point and continuous	Low-medium
2. Resistive Probe	Conductivity of material completes circuit		Fixed point	Low-medium
3. Vibrating Probe	Mass of material inhibits vibration		Fixed point	Medium
4. Field Effect Probe	Magnetic effect of material around probe		Fixed point	Medium
5. Deflection Probe	Mass of material forcing deflection of probe	• Low level sensing	Top level fixed point	Low
6. Electro-mechanical Paddles	Mass of material inhibits rotation of paddle	• Large particulate bulk solids • Adhesive and abrasive bulk solids	Fixed point	Medium
7. Tilt Switches	Mass of material causes device to partially rotate	• Large particulate bulk solids • Top level sensing	Top level fixed point	Low
8. Retractable Electro-mechanical Device	Probe is lowered onto material surface and retracted	• Large particulate bulk solids • Funnel flow bins	Readings may be determined at will for all levels	Medium
9. Pressure Sensitive Diaphragms	Mass of material exerting forces on sides of bins	• Pressurised bins • Abrasive material in mass flow bins	Fixed point	Low
10. Ultrasonic Detectors	Sound pressure waves emitted and absorbed	• Dusty environment • High bins	Fixed point or continuous	Medium
11. Nuclear Detectors	Gamma radiation emitted and absorbed	• Radiation hazard	Fixed point or continuous	High
12. Load Cells Load Beams	Mass of bulk solid applies force to load cell	• Very large bins • Silos on ground	Continuous weight sensing	Medium-High
13. Strain Measuring Devices	Mass of bulk solid causing structural strain	• Underground R.O.M. bins • Silos on ground	Continuous weight sensing	Low
14. Displacement Transducers	Mass of bulk solid causing structural deflection	• Structures with low levels of deflection • Dusty environments • Silos on ground	Continuous weight sensing	Low-Medium



A combination of time consolidation, variations in particle size and moisture content has accounted for errors in excess of 10% in practical applications. Changes in moisture content alone of 10% are not uncommon for some bulk solids.

c) The Determination of Height H

The largest source of error in many applications of weight determination through level measurement is generally caused by the variation in H, the level of bulk solid stored.

Errors may originate from the measurement technique adopted but in most instances the nature and behaviour of the bulk solid material will contribute the largest errors. Many cohesive bulk solids which exhibit repeatable behaviour during filling operations, will behave in an erratic and unpredictable way during discharge operations. The shape of the free surface, where level measurements are taken, will depend on whether material is being charged into the bin or discharged from the bin and will depend on:

(i) Nature of material handled,
(ii) moisture content of the material,
(iii) particle size,
(iv) consolidation or storage time,
(v) uneven distribution of material in the bin,
(vi) a combination of any or all of these conditions.

During discharge of cohesive bulk solids it is not uncommon in funnel flow bins to see the material form quasi-stable pipes or ratholes. In situations like this, level indicators would produce quite large errors as shown in Fig. 1.

Consider the change in free surface shape from when a cohesive material is charged into a bin to when material is discharged from the same bin as shown in Fig. 2.

The errors in level measurement may be expressed as a percentage of the calculated weight of bulk solid material in the bin.

$$W = \varrho \int_0^{H} A_H \, dH \pm E_L \quad (7)$$

where E_L is the error due to inaccuracies caused by the shape change of the material free surface and level measurement.

Consider a simple storage bin of circular cross-section, as shown in Fig. 2. Neglecting the effects of the apex of the hopper below the opening, we have, for low levels, i.e., levels within the hopper section of the bin [3]:

$$W = \varrho \int_0^{H} \pi r_H^2 \, dH \pm \frac{\varrho \pi r_H^3 \tan\theta}{3} \quad (8)$$

and for high levels, i.e., levels within the parallel section of the bin [3]:

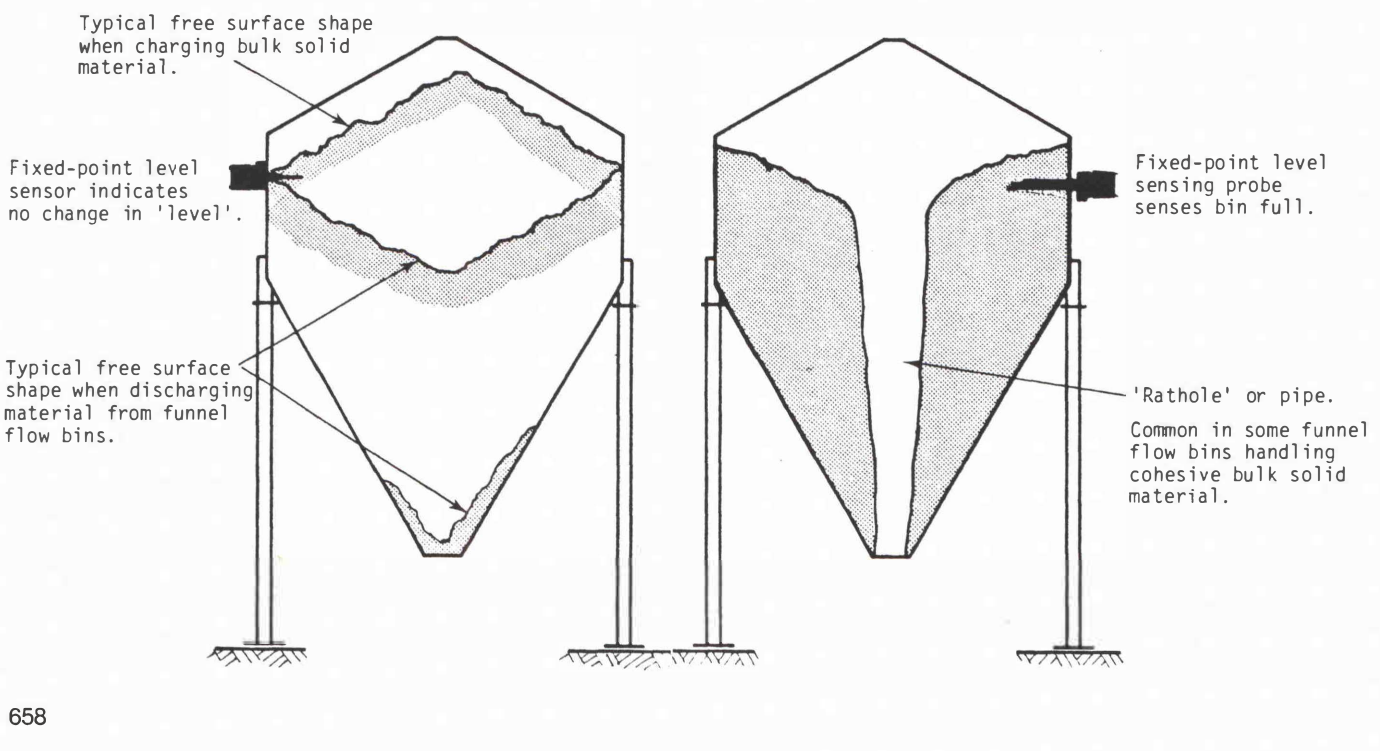
$$W = \varrho \left[\int_0^{H_0} \pi r_H^2 \, dH + \frac{\pi D^2 H_p}{4} \right] \pm \frac{\varrho \pi D^3 \tan\theta}{24} \quad (9)$$

Assumed in this model is that the material is charged centrally and discharged from a central outlet so that the material is uniformly distributed over the cross-sectional area.

Looking at equation (8) we have

$$E_L = \pm \frac{\varrho \pi r_H^3 \tan\theta}{3}$$

Fig. 1: Variation in free surface shape during charging and discharging material from a funnel flow bin or silo



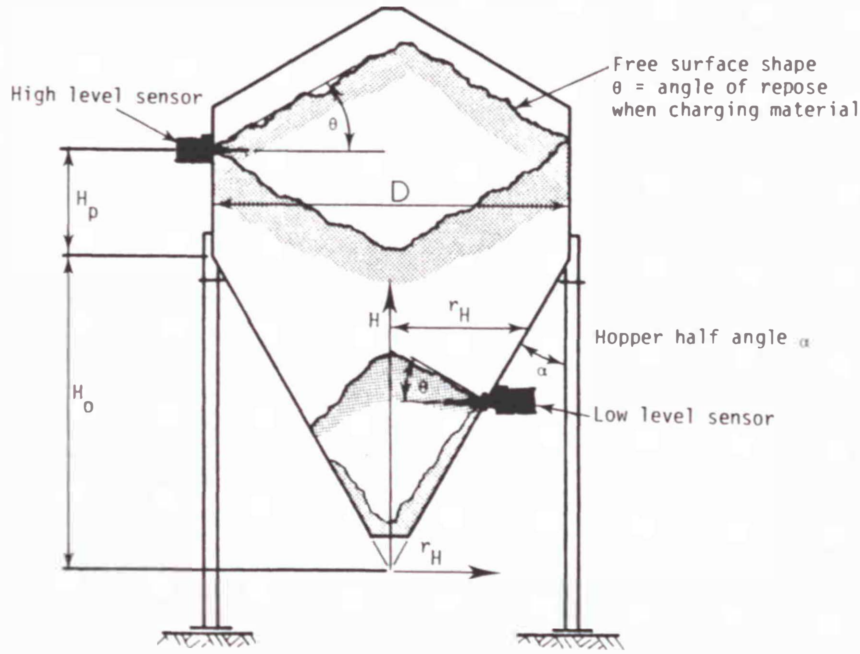


Fig. 2: A typical storage bin of circular cross-section exhibiting funnel flow characteristics

Plotting E_L as a percentage of bin contents against angle of repose θ as shown in Fig. 3, we find the errors are quite significant with respect to the true quantity of material in the bin at the level being measured.

As shown in Fig. 3, and as expected, the errors become larger as the hopper half angle is increased. Variations of hopper half angle from $r_H = 2H$ ($\alpha = 63°$) to $r_H = H/2$ ($\alpha = 26°$) are shown. Another point that should be noted is

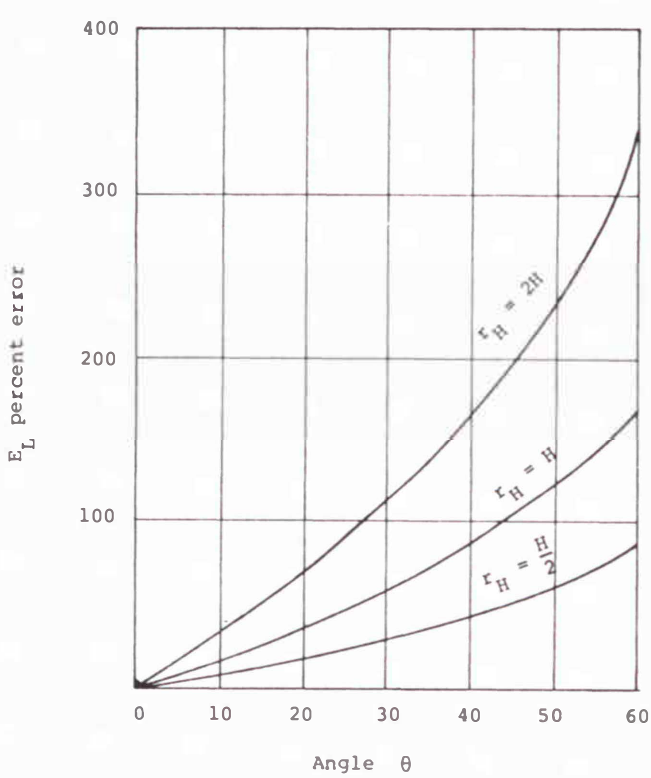


Fig. 3: Errors E_L vs. θ for low levels

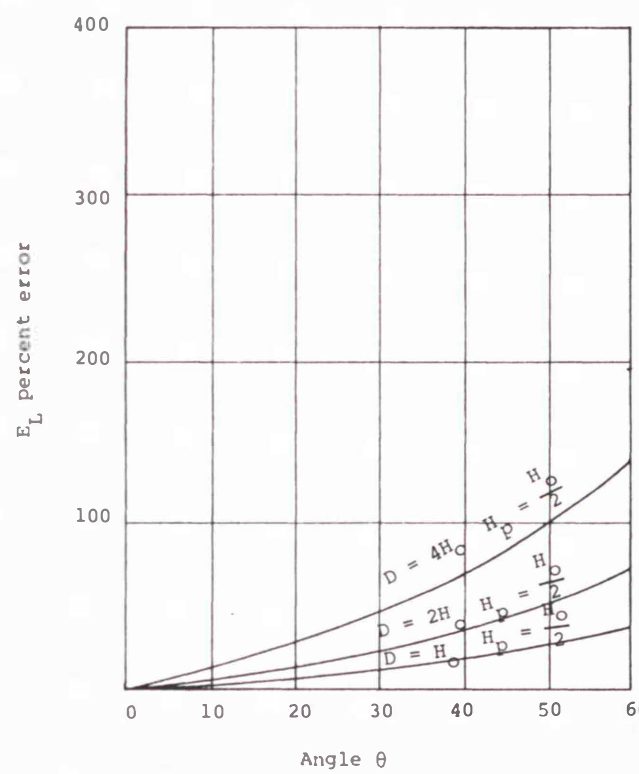


Fig. 4: Errors E_L vs. θ for high levels

the additional problems of material discharging from funnel flow bins and the increased possibility of piping as α increases, further compounding errors.

For high levels as shown in equation (5) we have

$$E_L = \pm \frac{\varrho \pi D^3 \tan\theta}{24}$$

Again E_L may be plotted as a percent of the true quantity of material in the bin at the level being measured. Although the errors are reduced dramatically, for larger diameter bins the errors remain quite significant, and cannot be ignored. The plot of E_L against θ is given in Fig. 4.

As shown here, similar to Fig. 3, three curves are given for conditions where $D = 4H_0$, $D = 2H_0$ and $D = H_0$. Obviously the error increases with an increase in diameter of the bin.

When material is charged into a storage bin the shape of the free surface is fairly consistent for similar material conditions. Repeatable errors as a result of level measurement may be allowed for, and with experiment or experience these could be eliminated.

However, when cohesive bulk solid material is discharged from a bin usually erratic behaviour results, making errors completely unpredictable and therefore difficult to eliminate. The angle of the free surface shape will vary within broader limits resulting in much larger errors. The free surface shape angle no longer is the same as the angle or repose for material being charged. In many practical applications this angle can reach a maximum of 90°. Under these conditions the material forms a quasi-stable pipe commonly called a rathole.

4.2 Errors in Weighing

Most process plant operations use weighing as the measurand when carrying out such operations as batching, mixing, packaging or simply just use weighing as a means of accounting for production rates, raw material costing and product sales. Weighing bulk solids directly has many benefits over determination of weight through "level" measurement. There are several sources of error in the determination of weight by direct methods. Some of these are discussed.

a) Distribution of Material

Inconsistent distribution of material within the storage bin can provide a significant error in bulk solids weighing. For normal single outlet bins this problem is relatively minor. However, where storage bins have multiple outlets, particularly in flat bottom bins, material discharge is not evenly distributed and could lead to quite large errors.

Consider the model in Fig. 5 where a storage bin with two discharge hoppers is shown. This is a simplified model of a common practical situation where funnel flow occurs from two discharge hoppers. To keep costs of bin level indication to a minimum, one compression load cell has been installed under the centre support column. Located in this position, the errors are kept as small as possible but are quite significant, usually in the order of 5—15 % depending on storage bin geometry.

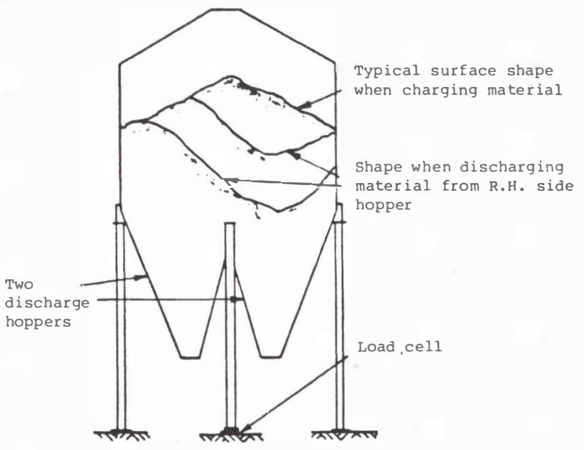


Fig. 5: Model of storage bin with two discharge hoppers

b) Load Bearing of Foundations

Uneven load bearing of column footings, due to settlement of foundations in new installations or to changes in soil conditions for older well established storage bins, have produced errors in weighing in practical situations. These errors can be rectified once discovered and the source isolated. Generally they are not of sufficient magnitude to become significant problems.

c) Conveyor Gantry Live Loads

Most larger types of storage bins such as those typically used for handling and storing coal, support large conveyor gantries which supply coal in the bin. The influence of live loading produced by typical conveyor gantries on bin level systems may be quite large particularly when conveyors are stopped while still in the loaded state. It could be argued that this material, while not yet in the storage bin, is effectively part of the storage capacity even though lying on the belt. Then the effect of its weight on the bin weighing system is neglected and assumed to produce a true indication of bin contents. Whether belt capacity in situations such as this is considered storage capacity and not seen as producing weighing errors, seems to vary from one application to another.

d) Thermal Loads

The thermal stresses induced in large structures will produce significant errors for systems where the bin and support structure is influenced by changing temperatures. These induced stresses will apply apparent loads through the structure to load cells, strain links and displacement transducers. In its simplest form, this problem can be illustrated by considering a storage bin in an exposed environment — simply exposed to the elements. As the earth rotates and the sun falls on different parts of a storage bin structure thermal strains are induced causing thermal expansion and contraction of various structural members. The effect of this problem can be reduced by using multiple transducers so that the thermal effects are averaged. For storage bins simply supported on four columns this can be achieved quite easily at reasonable cost, however the cost becomes prohibitive for many larger storage bins having eight or more support columns. For very large bins with many supports the effect can be reduced by sensible location of the transducers only after careful assessment of each individual storage bin configuration taking full account of the possible thermal problems.

e) Dynamic Loading and Discharging

The dynamic effects of loading and discharging material from storage bins is not normally considered a significant source of errors in bin weighing. In many situations where dynamic forces are noticeable the effects are generally transient in nature and do not usually produce any significant errors under static conditions.

f) Wind Loading Effects

The effect of wind on large storage bins and support structures can be quite noticeable in some applications. On a simple model for a bin of circular cross-section supported on columns as shown in Fig. 6, the error due to wind loading may be simply expressed as a function of bin geometry and the applied wind force [3].

$$W_s = \frac{1}{2}\,\varrho\left[\int_0^{H_0} \pi r_H^2\, dH + \frac{\pi D^2}{4} H_p\right] \pm P H_e D H_c \tag{10}$$

where

W_s = weight sensed = W/N, kg
N = number of supporting columns
ϱ = average bulk density, kg/m³

(The free surface shape is neglected in this analysis).

The error due to wind loading, E_W, can be expressed simply as a percent of total bin capacity for a cylindrical bin of height H, diameter D and equivalent area with centroid H_c above terrain.

H_e = effective height of bin parallel section seen by the wind, m
H_c = height of centroid of area of bin as seen by the wind, m
H_0 = height of hopper section of the bin, m.

To simplify the model further, the wind force P was determined from a wind velocity with a 100 years return cycle for terrain category 3 from Australian Standards Association. This assumes most severe conditions, so for normal conditions wind effects would be much lower than the results plotted in Fig. 7, where E_W is plotted against aspect ratio H_c/D.

It should be understood that this simplified approach to error analysis is aimed at achieving only relative magnitudes of errors and the author appreciates that for individual bin or silo geometries a much more detailed approach is necessary to obtain more accurate estimates of errors.

The plots are given for values of average bulk density 200 kg/m³, 700 kg/m³ and 1,200 kg/m³. It is obvious from Fig. 7 that tall narrow bins storing low average bulk density material will be most affected by wind loads.

The effect of wind loads on weighing systems may be eliminated in one of two ways. Multiple transducers and the use of averaging techniques is usually the most common method used. This method could increase the cost of bin weighing systems beyond budgetory allowances. Another less expensive method, and a much simpler one, is to filter the effects of wind loading using electronics. Wind usually comes in gusts with a frequency generally much higher than bin charging and discharging rates and the effects of wind loading can therefore be filtered without reducing the sensitivity of the system to weighing bin contents.

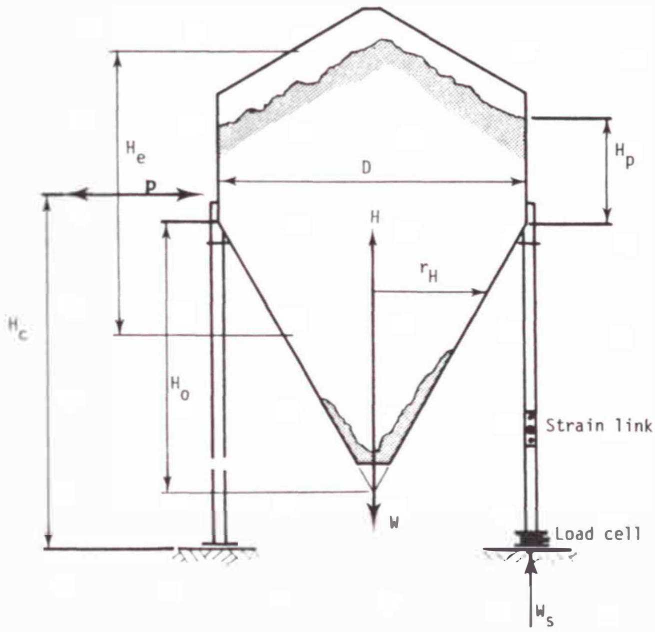


Fig. 6: Simplified model of storage bin with applied wind forces

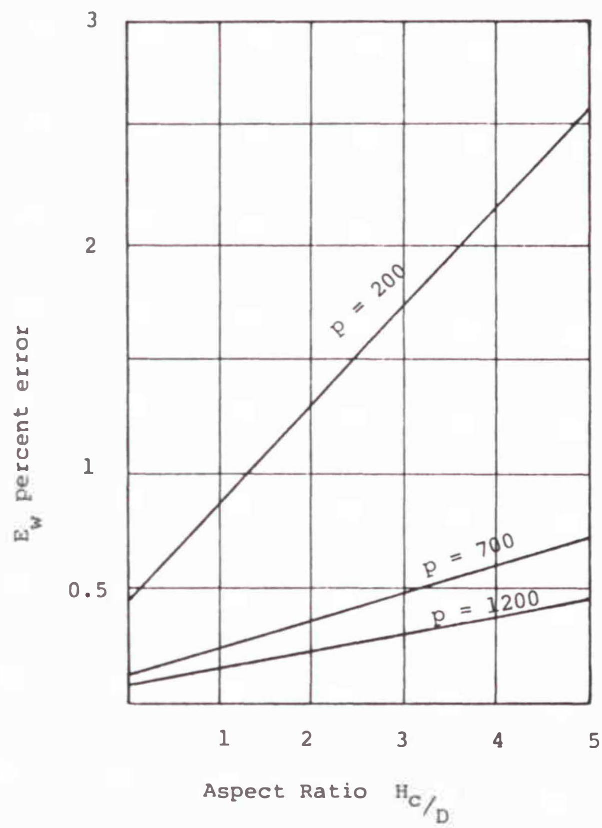


Fig. 7: Wind load errors E_W vs. bin aspect ratio

In many applications where the contents of storage bins must be known there are basically two sensible alternatives.

(i) To Measure Volumetric Capacity

True "level" sensors are ideal in these applications so that full volumetric capacity of storage bins may be realised at all times. Where variations in average bulk density occurs, weighing techniques are not recommended when full volumetric capacity of bins is required.

(ii) To Measure Weight Capacity

If the weight of bulk solid material in a storage bin must be known then generally direct weighing techniques are recommended. Unless the bulk solid to be stored is generally free flowing, and variations in average bulk density are small, "level" measuring techniques are not recommended for measuring bin contents in terms of weight capacity.

It is quite common for these two basic systems and their approach to determining bin contents to be confused resulting in gross errors and general dissatisfaction with the bin level equipment used.

5. Special Problems and Solutions — Case Studies

By way of illustration, several practical case studies are discussed. The chosen situations should adequately illustrate most of the problems commonly encountered when determining the quantity of bulk solid material in a storage bin.

5.1 Large Capacity Free Standing Storage Bin

A large capacity free standing storage bin exposed to the elements and storing cohesive bulk solid material, for example coal, can provide many problems when seeking a simple straight forward solution to determination of contents.

In many applications such as this, the information sought is generally the quantity of material held within the space. For various reasons the answer is generally wanted in tonnes. Traditionally mining management has used intrusive level measuring devices to obtain this information. There are several reasons for not using intrusive devices in an application of this type.

(i) The nature of coal as a material, particularly run of mines coal, prohibits the use of any type of intrusive level transducer particularly for use in low level determination. The size and mass of particles has an extreme destructive effect on low level fixed probes. In some instances substantial mechanical protection has been used to protect the device, but this has only managed to provide minimal extension in life of the installation.

Flexible intrusive devices, such as resistive probes mounted on chains and supported from the top of a bin and used as high level probes, have had some success in the coal industry. These devices operate with reasonable reliability, if maintained effectively. However, extreme forces are exerted on these devices when slight overfill occurs, burying the probe. Many transducers have been lost with the product as a result of this action.

Ultrasonic transducers have been installed in applications of this type but with limited success. Problems generally stem from the excessive dust which is released inside the bin during charging. The immediate effect is a reduction in accuracy, but a more serious long term effect is damage to the device by contaminants from the bin environment.

(ii) For run of mines coal (raw coal) the possible variation in average bulk density is quite staggering. Variations in excess of 30% are not uncommon in Australia for the contents in a storage bin of 2,000 tonnes capacity. Weight determination from "level" measuring techniques for conditions like this will produce large errors. "Level" measuring techniques will therefore not provide reliable information of weight or mass contents of a bin.

When a storage bin such as this is designed, the required volume to contain 2,000 tonnes of coal is provided. A quantity of rock from underground mines conveyed to the pit head and into the storage bin to fill the same space to the required "level", produces extra loads on a storage bin shell and structure. Rock may be as much as twice the density of coal. The occurrence of significant overloads is common and under these conditions it is possible to achieve double the maximum design load. This is bad practice, particularly where storage bins have been in service for a number of years and some wearing of the shell and subsequent weakening of the stucture has occurred. There have been several bin collapses possibly as a result of this practice.

For an application such as this, a non-intrusive weighing device overcomes both problems. A non-intrusive device is unaffected by the material stored while the weighing technique produces direct determination of weight for auditing and provides a useful overload protection.

The type of weighing transducer best suited for this application is a strain link. The expense of installing load cells is generally prohibitive for installations of this magnitude. Installation costs alone would be quite high. Displacement transducers can provide problems in harsh dusty environments where some types with moving parts will be affected.

Strain links are relatively cheap and easy to install. For improved accuracy a number of these may be located around the storage bin structure to average the effects of thermal and wind source loads at very competitive cost. Strain transducers usually use well established strain gauge techniques and are solid state devices. For structures with low values of live strain an amplifier type strain transducer is recommended. By mechanical amplification of structural loads [3] errors caused by thermal strain and temperature induced errors from electronic amplification may be reduced.

(iii) One other problem that could produce large errors is the thermal effects from long conveyor gantries fixed to storage bins. Conveyor gantries are generally supported to the tops of storage bins through "hinged fixtures". However when the conveyor gantry increases in temperature the theoretical "hinged" joint imparts an overturning force to the bin as shown in Fig. 8.

On storage bins ranging in capacities from 500—2,000 tonnes, strain transducers of the mechanical amplification type produce accuracies generally better than $\pm$ 3% for single transducer installations. If increased accuracy is required, multiple transducers may be used to achieve system accuracies of up to ± 0.5 %.

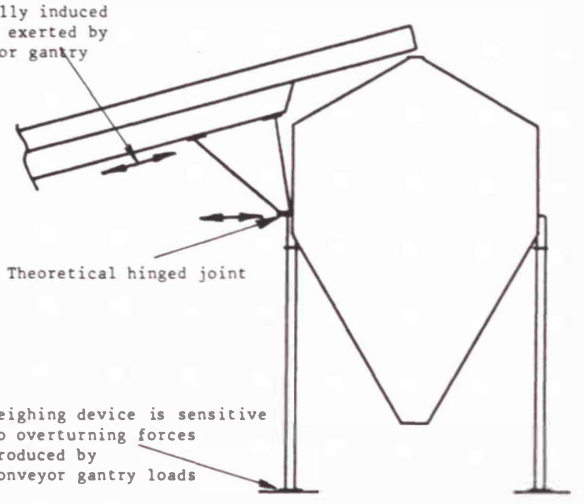


Fig. 8: Typical large bin with conveyor gantry

5.2 Multiple Bins on Common Supporting Structure

Quite often, for economic reasons, several storage bins are located on a common support structure. In some cases the material stored suits the use of intrusive level measuring transducers. In some applications, however, intrusive devices have been installed and have failed for one or a number of reasons. In one recent application with stored alumina, an ultrasonic transducer failed due to excessive dust inside the storage space. In another application, the transducers simply corroded or air jets used to locate the "level" were blocked. In yet another application the stored material, being abrasive in nature, simply caused mechanical damage or excessive wear to the transducer where frequent expensive replacement was necessary.

Non-intrusive weighing devices are sometimes difficult to apply in this type of application. Nuclear devices usually meet with some resistance either from industrious unionists or from the local governing authorities. In some instances, the regulations and precautionary measures necessary, make nucleonic devices an unattractive proposition.

For an application as shown in Fig. 9 load cells or load beams may be installed. While the cost of the transducers themselves are reasonable, installation costs of load cells in existing storage bins usually makes load cells a less attractive proposal.

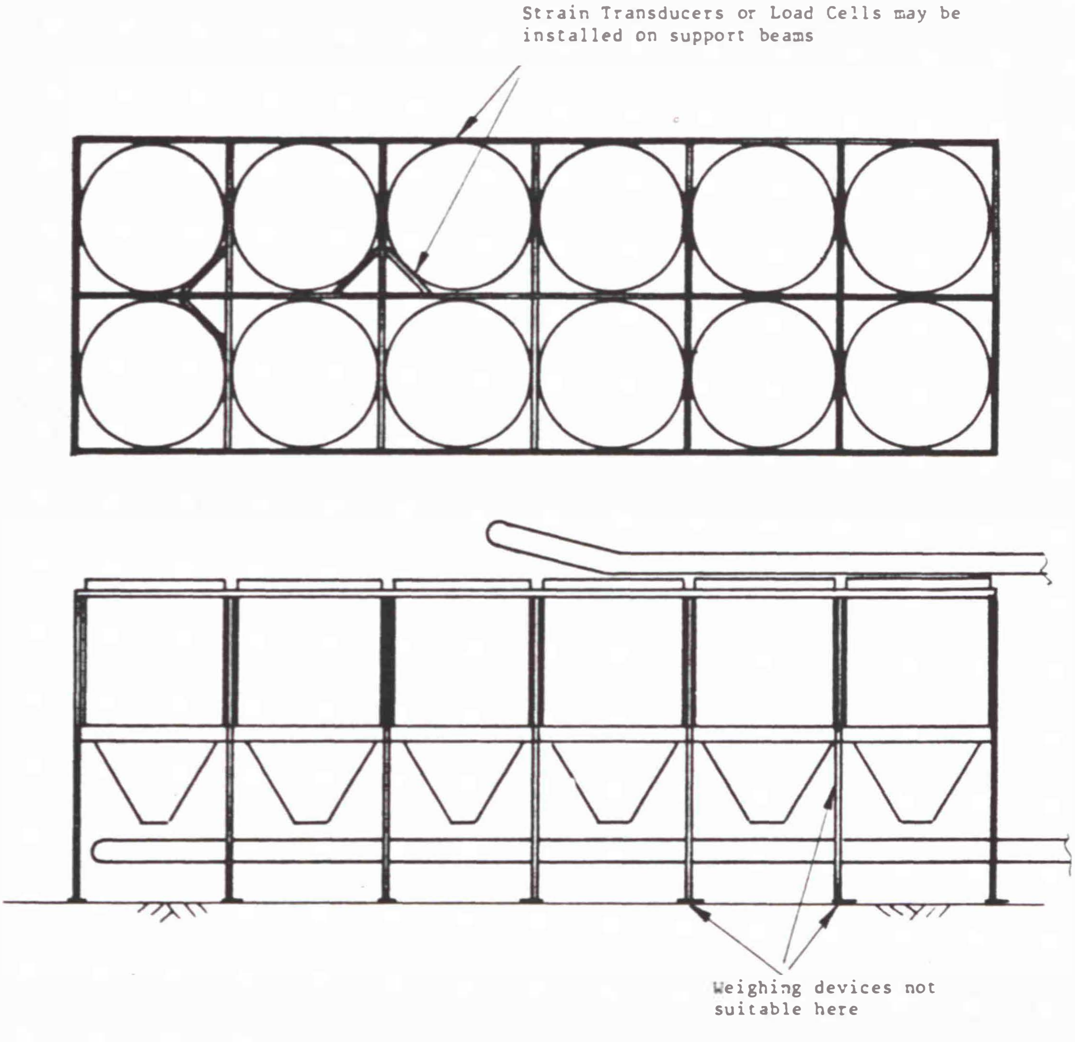


Fig. 9: Typical structure supporting many bins

Strain transducers may be installed on beams, as shown in Fig. 9, or to any other structural member generally influenced only by the load in the bin under investigation.

The errors from this type of application depend on the various conditions as discussed earlier but should generally be similar in magnitude to those in larger single bins. Similar sources of error apply. The cost of installing strain links to supporting structure is usually a fraction of the cost of load cell installation. An additional advantage in using strain links is that they do not carry any load and therefore are not subjected to any impact loading as load cells are.

5.3 Two Bins and Integral Common Supporting Structure

Some designs of multiple storage bins incorporating integral support structure used to handle a material such as coal, as in the practical example, provide real problems for the determination of bin contents. It is generally not recommended to use an intrusive device in coal storage bins. Apart from providing limited accuracy in funnel flow bins, the forces exerted in protuberances in mass flow situations prohibit the use of intrusive devices, particularly for low "level" determination. Fig. 10 shows an application of this type. Evaluation of the mass inside the storage space using level devices will produce errors in the order of 20—30% for funnel flow bins as shown.

In this application where the storage space and support structure are one and the same, it is not possible to find a point of the structure where direct measurement of weight can be obtained without also measuring the influence of changes in contents of the adjacent bin. It appears then that intrusive devices, even with their problems when used with coal, are the only suitable solution.

It is possible to reduce the effect of interactions by measuring the effects and electronically conditioning the signal to eliminate the problems of interaction. As shown in Fig. 10 four bolt-on strain transducers are located in the corner columns. The outputs from transducers 1 and 2 and 3 and 4 are summed electronically. Each has its own excitation and amplifier so that the gain for each transducer may be tuned individually.

Fig. 11 shows a block diagram of an analog system applicable to this situation. The gain factors $C_1 — C_5$ are found on site during commissioning, although analysis of the structure will give results within 10% prior to installation.

Strain transducers with mechanical amplification were chosen for this bin structure and similar to most larger structures values of live strain were low. Also, as for previous example, strain transducers are extremely cost competitive and reliable compared to alternatives.

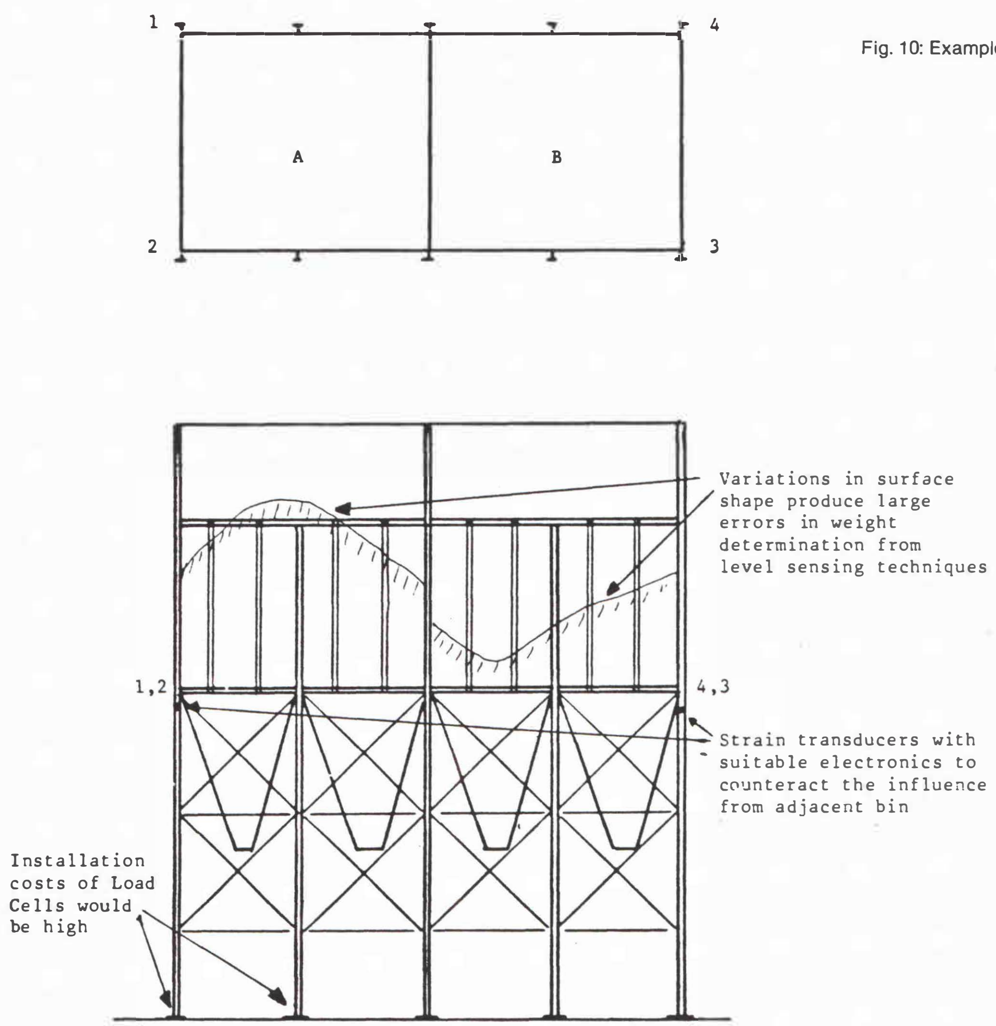
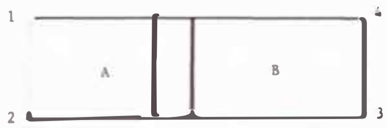


Fig. 10: Example of bins with integral support structure



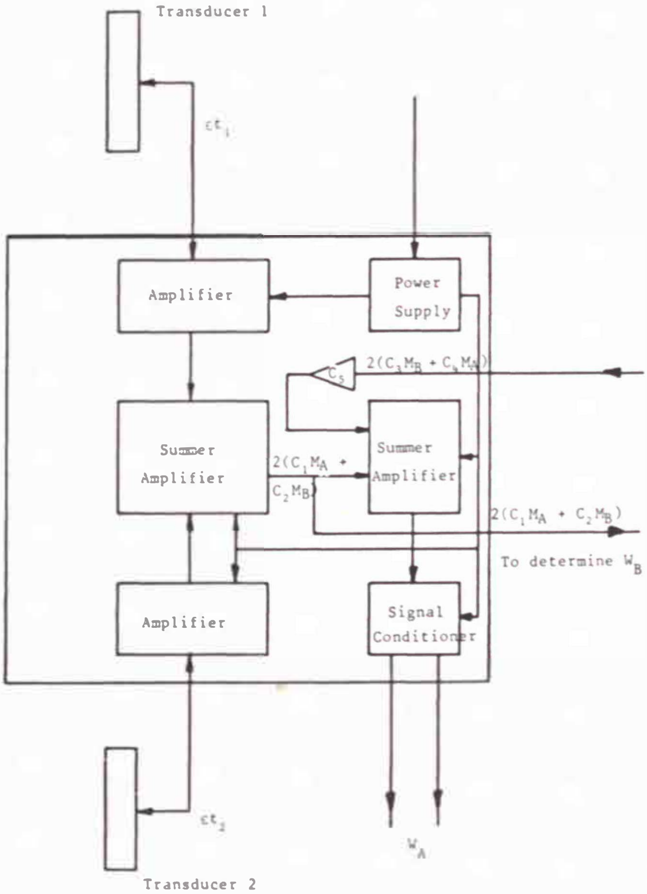


Fig. 11: Block diagram of simplified solution to problems of interaction in weighing

A simplified analysis for a practical situation follows from Fig. 10.

Assuming uniformly distributed loads in storage spaces A and B for all conditions

$$\epsilon t_1 = \epsilon t_2$$
$$\epsilon t_3 = \epsilon t_4$$

where ϵt_1 = strain in transducer No. 1 etc.,

$$\epsilon t_1 = C_1 M_A - C_2 M_B$$
$$\epsilon t_3 = C_3 M_B - C_4 M_A$$

where M_A = Mass in bin A,
M_B = Mass in bin B.

Determination of the weight contents within storage space A.

$$W_A = 2(C_1 M_A + C_2 M_B) + 2C_5(C_3 M_B + C_4 M_A)$$

and to determine the weight of contents within storage space B.

Fig. 11: Block diagram of simplified solution to problems of interaction in weighing

$$W_B = 2(C_3 M_B + C_4 M_A) + 2C_5(C_1 M_A + C_2 M_B)$$

$C_1 = C_3$ = direct influence factors proportional to quantity of bulk solid stored.

$C_2 = C_4$ = interaction influence factors proportional to quantity of material stored.

To minimise interaction influence

$$C_1 = \frac{C_2}{C_3} = \frac{C_4}{C_5}$$

The values of $C_1 - C_5$ are simply gain factors in the electronic circuit as shown in Fig. 11.

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[3] Scott, O.J. and Ooms, M., "A Bin Level Indication System by Mechanical Amplification of Structural Loads", Powder Europa '80 Conference, Wiesbaden, West Germany, 22—24 Jan., 1980.