REVIEW
OF THE "SILO QUAKING" PROBLEMS
IN BINS OF VARIOUS GEOMETRICAL SHAPES
AND FLOW PATTERNS

ALAN W. ROBERTS

Emeritus Professor, Centre for Bulk Solids and Particulate Technologies,
The University of Newcastle, University Drive,
Callaghan, NSW, 2308, Australia
engar@cc.newcastle.edu.au

Abstract: The paper reviews the characteristics of pulsating or cyclic flow of bulk solids during gravity discharge in bins and silos. The dynamic load phenomenon is often referred to as "silo quaking" and is known to occur in silos of various geometrical shapes, operating under different flow patterns. Examples include mass-flow, funnel-flow, expanded-flow, multi-outlet bins and bins operating under intermediate-flow. While silo quaking is often associated with tall bins, depending on the flow pattern, the problem can also be experienced in bins of squat proportions. The period of pulsations during flow is influenced by various factors, such as, particle size and size distribution, silo wall material and wall roughness, internal friction, moisture content and discharge flow rate. Of particular relevance is the influence of slip-stick effects during shear flow, and velocity at critical sections in the silo during discharge. The paper presents an overview of silo quaking with case studies to illustrate the range of problems that can occur.

Keywords: gravity flow, flow pulsations, "silo quaking", silo wall loads

1. Introduction

A recurring problem in bin and silo loadings is that due to the phenomenon of "silo quaking". Gravity flow in bins and silos, characteristically, is a cyclic or pulsating type flow which arises as a result of changes in density during flow and by varying degrees of mobilisation of the internal friction and boundary wall friction. The pulsating load problem is more pronounced at low flow rates where the period of pulsing may be from a few seconds to many seconds or even minutes. The consequence of the pulsating loads may range from nuisance value arising from the transmission of shock waves through the ground to disturb neighbouring areas, to structural fatigue failure when the natural frequencies of the silo and structure are excited by the flow pulses. The subject of pulsating flow of bulk solids in bins and silos has been studied by several authors, a selection of papers on this subject being given in [1–15].

Generally speaking, silo quaking refers to low frequency shock loads as described by Roberts *et al.* [7–10]. A variation of the silo quaking problem is silo music and silo "honking" as has been reported by Tejchman and Gudehus [11, 12]. The "honking" phenomenon is known to occur in tall aluminium silos which store plastic powders. In this case the higher frequency components of the flow pulsations can give rise to loud, periodic, "fog horn" type sounds that have a decided nuisance effect.

The discussion that follows has two main objectives. Firstly to review relevant research into the "silo quaking" problem as it occurs in mass-flow, funnel-flow, expanded-flow, intermediate flow and multi-outlet bins. Secondly, to illustrate various practical manifestations of silo quaking problems by reference to four industrial case study examples.

2. Tall mass-flow silos

2.1. Experimental studies

As reported by Roberts *et al.* [7–9], quaking is known to occur in tall mass-flow silos in which the height of fill is above a critical height H_{cr} where $H_{cr} \approx D$, as depicted in Figure 1. Figure 1a shows the test bin or silo of dimensions 1.2m diameter by 3.5m high, the bin being fitted with a stainless steel hopper. Load cells which measure normal and shear stress simultaneously are fitted into the silo walls. Above the height H_{cr}, plug type flow occurs with the velocity profile substantially uniform over the cross-section. Below the critical level in the region of the transition, the flow starts to converge due to the influence of the hopper and the velocity profile is no longer uniform.

The velocity profile is further developed in the hopper as shown. As the flow pressures form in the hopper, dilation of the bulk solid occurs. As a result of this dilation, it is possible that the vertical supporting pressures decrease slightly thus reducing the support given to the plug of bulk solid in the cylinder. This causes the plug to drop momentarily giving rise to a load pulse. The cycle is then repeated.

Examples of wall pressure and shear stress records depicting the pulsating load in the cylinder are shown in Figure 2. The pulsing was quite pronounced at location 14 well up the cylinder, but was less evident further down the cylinder. Virtually no pulsing was shown to occur at location 5 near the transition.

2.2. Dynamic load model

The dynamic load model proposed by Roberts [8] is shown in Figure 3. Following the work of Wensrich [13–15], it is known that in tall mass-flow silos, slip-stick effects give rise to shock waves which travel upwards through the silo from the transition. While it was recognised that multiple shock planes may exist, the assumption of an averaged single shock plane model has been shown to provide a good practical predictor of loads in industrial silos experiencing quaking problems. Whereas Roberts had assumed the averaged shock plane is located at the critical height $H_{sh} = H_{cr} \approx D$ measured above the transition, subsequent studies have indicated that the shock plane is located higher up the cylinder at a height $H_{sh} \approx 1.5D$ to $2D$.
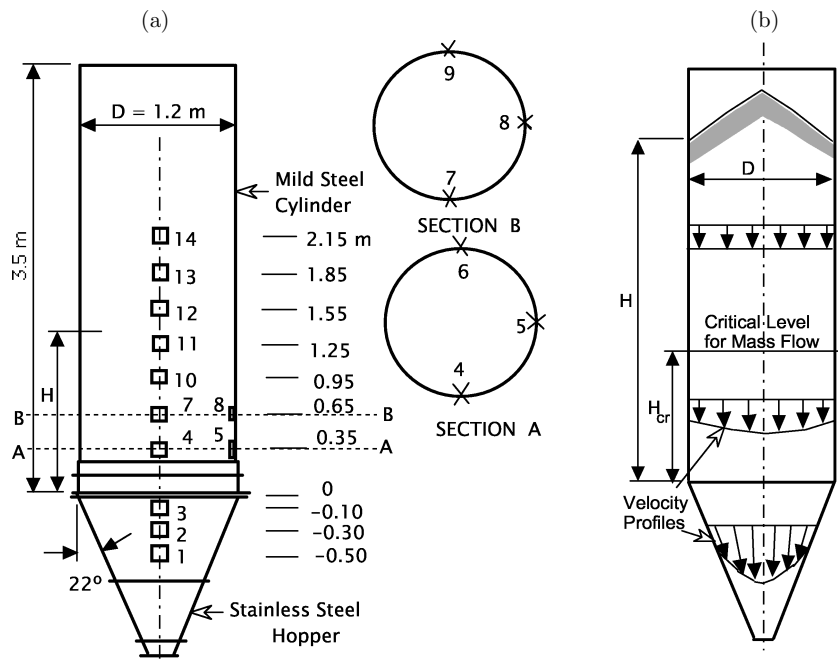
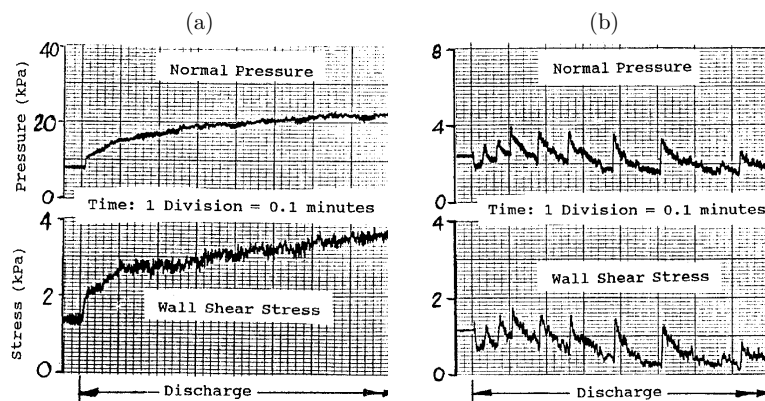**Figure 1.** Mass-flow test bin: (a) test bin showing load cell locations, (b) velocity profiles

Figure 2. Sample of normal pressures and shear stresses at two locations:
(a) results for location 5, (b) results for location 14

The maximum increment in the average vertical pressure, Δp_{vo}, due to the shock load is:

$$\Delta p_{vo} = k_d \gamma \left[\left(1 - e^{-\mu K h/R} \right) \left(\frac{R}{\mu K} - h_s \right) + h_s \right]. \tag{1}$$

The corresponding maximum increment in lateral wall pressure due to the shock load is:

$$\Delta p_{wo} = K \Delta p_{vo}, \tag{2}$$

where, effective radius
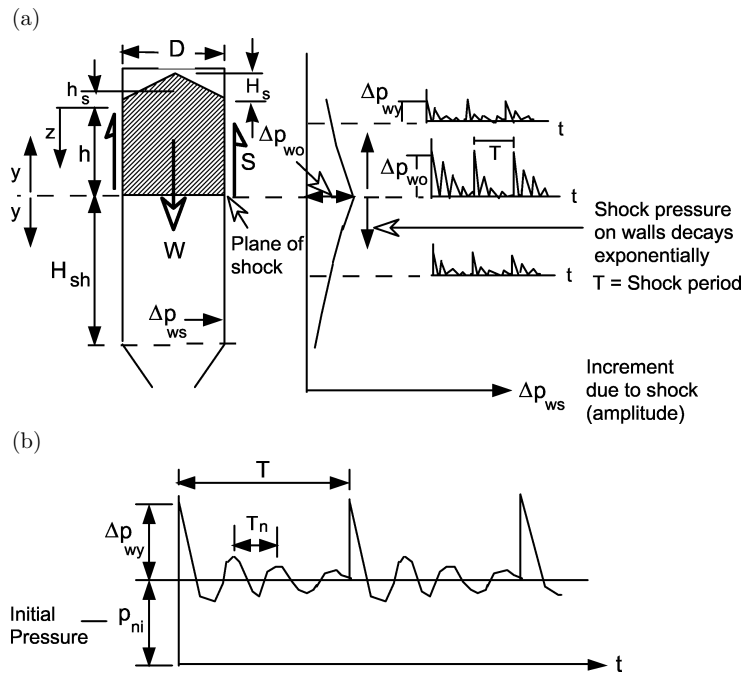
$$R = \frac{D}{2(1+m)}, \tag{3}$$

Figure 3. Dynamic loads induced in silo: (a) dynamic pressures due to shock, (b) shock waves at location z

effective surcharge head

$$h_s = \frac{H_s}{m+2},\qquad(4)$$

where $\gamma = \rho g$ – bulk specific weight, ρ – bulk density, h – head, K – ratio of lateral to vertical pressure, H_s – actual surcharge head, D – diameter or width of flow channel, $m = 0$ for rectangular silo, $m = 1$ for circular silo, $\mu = \tan\phi$ – coefficient of wall friction, ϕ – wall friction angle.

Based on the results of shown in Figure 3 an exponential distribution for the stress or pressure amplitude is assumed. The variation in the maximum amplitude of the pulse pressure Δp_{wy} on each side of the shock surface is given by:

$$\Delta p_{wy} = \Delta p_{wo} e^{-\mu K y/R}.\qquad(5)$$

As $y \to h$, it is assumed that Δp_{wy} "tails off" to approach the flow pressure at the top surface in the cylinder. It is noted that Δp_{wy} is the additional wall pressure applied to the initial or static pressure.

2.3. Comparison of predicted and measured wall pressure amplitude

Figure 4 shows the measured values (plotted points) and calculated (full lines) wall pressure amplitudes for the wheat silo of Figure 1a. The calculated values are based on Equations (1) to (3) using the following values: $H_{sh} = 2.14$m (location 14 of Figure 1a), $\phi = 30°$, $\rho = 0.85$t/m^3, $D = 1.2$m, overall fill height above transition, $H_{sh} + h = 3.0$m, $K = 0.4$, $k_r = 0.29$, k_r – ratio of shear to normal stress amplitude.
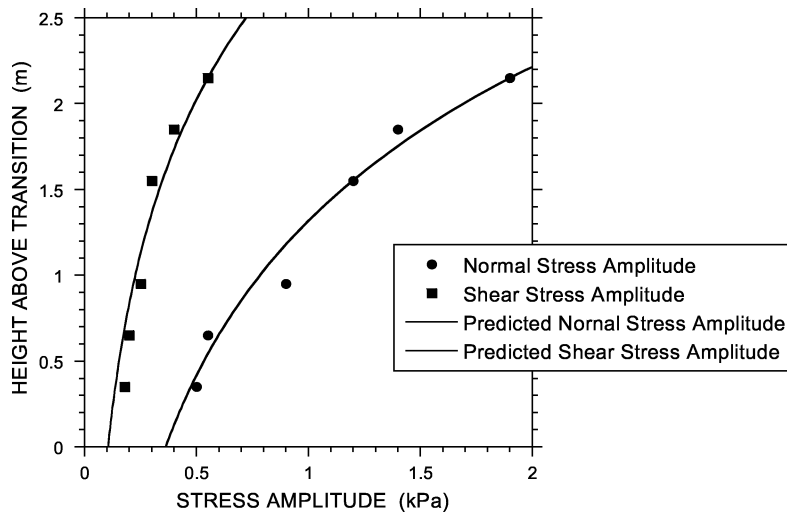
Figure 4. Computed and measured normal and shear stress amplitudes
for experimental wheat silo

The agreement between the measured and calculated normal and shear stresses is considered very satisfactory. The exponential form of the pressure amplitude distribution of Equation (3) is confirmed.

2.4. Pulse period

Pulsating flow has been studied by several authors [1–4]. For instance, Shinohara *et al.* [1] recognised the existence of a dynamic arch and studied the flow of both sand and glass beads from a PVC bin of $H/D = 3$. It was noted that the location of the arch was higher for glass beads than for sand, this being due to the difference in the void fraction of the particles. In both cases the arch was well inside the hopper. The authors derived an expression to predict the frequencies of the pulsating flows. Firewicz [4] proposed an improved solution to that presented by Shinohara *et al.* [1].

However, the work of Shinohara *et al.* and Firewicz refers to the flow from the hopper and the influence of this pulsating flow on the behaviour in the main body of the bin is difficult to predict. The problem is made more complicated by the variability in bin shapes, variability in the properties of the bulk solid, particularly when mined products such as coal are handled where there are a wide range of particle sizes, moisture contents and impurities such as clay.

The following equation, proposed by Roberts [8] has been shown to be a good predictor of the pulse period:

$$T = \left(t_0 + \frac{v}{a}\right) + \sqrt{\frac{v}{a}\left(2t_0 + \frac{v}{a}\right)}, \tag{6}$$

where

$$a = \frac{\Delta p_{vo}}{\rho(h + h_s)}, \qquad v = \frac{Q}{\rho A}, \qquad t_0 = \frac{\Delta \varepsilon_y}{v},$$

a – acceleration of upper mass during pulse motion, v – average velocity of bulk solid in the cylinder during discharge, Q – discharge rate, A – cross-sectional area of

cylindrical section of bin, t_0 – time for motion of upper mass to be initiated, $\Delta \varepsilon_y$ – dynamic displacement of consolidated mass in vertical direction.

In many cases the average velocity is quite low. For example, consider the discharge of a bulk solid of bulk density $\rho = 1 \mathrm{t/m^3}$ from a tall, 10m diameter cylindrical silo fitted with a conical hopper. The discharge rate is $100 \mathrm{t/h}$. The average velocity in the cylindrical section of the silo is $v = 0.0004 \mathrm{m/s}$. It is also necessary to gain some appreciation of the magnitude of the accelerations occurring during pulsating flow. In general, the pulse accelerations lie in the range $0.1g \leq a \leq g$. It follows that for most practical cases:

$$T = \frac{\Delta \varepsilon_y}{v}. \tag{7}$$

The parameter $\Delta \varepsilon_y$ is dependent the average particle size, void ratio and properties of the boundary surface of the flow channel. A plot of pulse period versus average discharge velocity in the cylindrical section of a silo is presented in Figure 5.
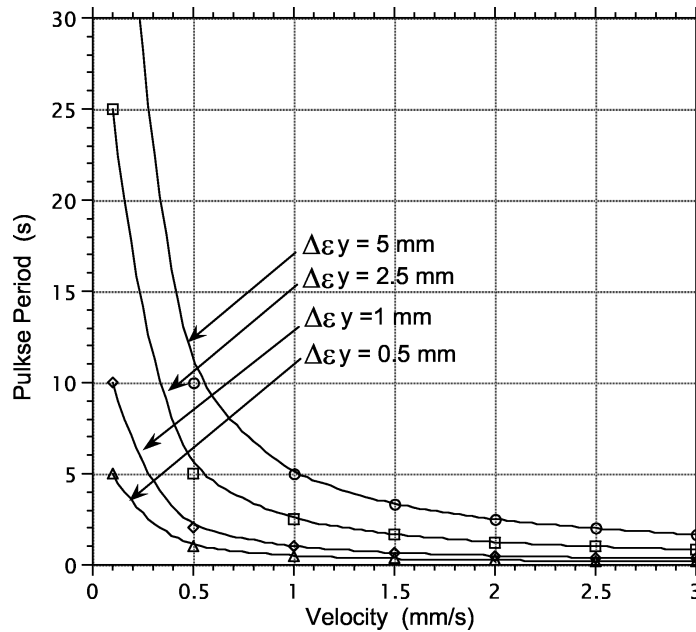

Figure 5. Pulse period versus velocity

It is interesting to observe that Roberts [9] conducted wall friction tests for sand on perspex using the Jenike shear tester for a range of shear strain rates from 0.004 to 0.085 mm/s. Slip-stick was quite pronounced with the period decreasing with both increase in strain rate or shear velocity and decrease in normal stress. The relationship for T was confirmed. It was also shown that:

$$\Delta \varepsilon_y = \frac{\sigma_n}{K_T}, \tag{8}$$

where K_T – contact stiffness [kPa/mm] and σ_n – normal stress [kPa]. The value of $K_T = 333$ for sand on perspex, but it is believed that this value was influenced, to some extent, by the stiffness of the load cell of the shear tester.

2.5. Silo quaking studies performed by Wensrich

More recently, a comprehensive fundamental study of the silo quaking problem in tall mass-flow silos has been performed by Wensrich [13–15]. He examined slip-stick motion of bulk solids discharging by gravity and used continuum models employing hypo-plasticity theory to analyse the wave motion. His models clearly show the exponential growth of various wave amplitudes up the silo.

To confirm the analytical predictions, Wensrich conducted experimental studies using a small scale "silo" simulation model. The model, together with typical test results, are shown in Figure 6. The model comprised a perspex tube 90 mm diameter and approximately 1 m long. A plunger or piston was used to control the downward movement of the bulk material. The piston is retracted at pre-determined velocities by means of the DC motor connected to the piston by means of a screw. Sand at approximately 0.5% moisture content was chosen as the bulk material particularly since sand on perspex displays pronounced slip-stick behaviour. To measure the induced accelerations in the flowing sand tiny accelerometers were employed.
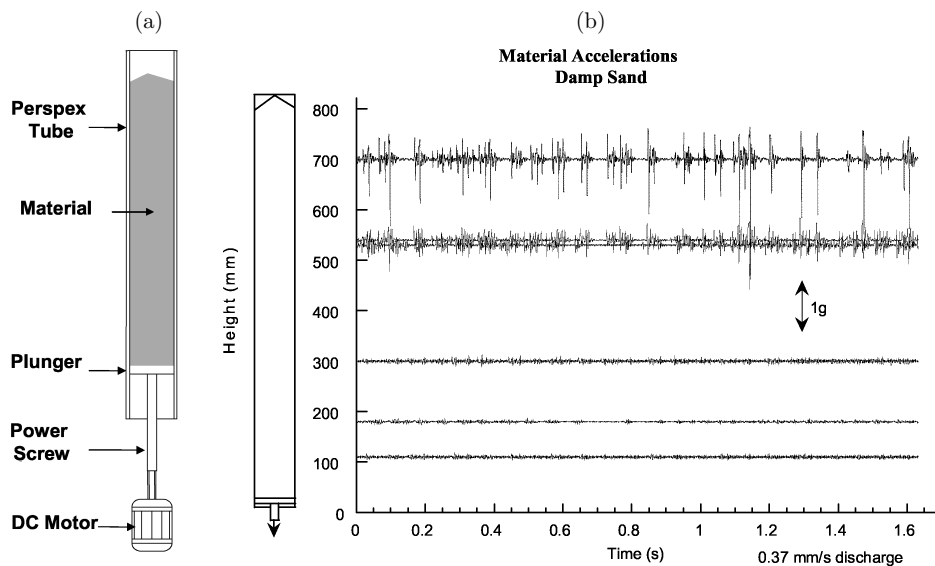

Figure 6. Experiments performed by Wensrich [14]: (a) test rig, (b) set of typical test results

By way of example, Figure 6b presents the accelerations within the material at various heights for the discharge velocity of 0.37 mm/s. The results clearly show that the amplitudes of the accelerations increase with height up the tube owing to the slip-stick effect. Towards the bottom of the tube the accelerations are practically zero. The results confirm the predictions of Roberts [8] as summarised in Section 2.

3. Other types of bins and silos

3.1. Funnel and expanded-flow bins

A similar action to that described for mass-flow bins may occur in tall funnel-flow bins where the effective transition intersects the wall in the lower region of the

silo. As a result, there is flow along the walls of a substantial mass of bulk solid above the effective transition.

Pulsating flow and dynamic loads may occur in funnel-flow and expanded-flow bins of squat proportions as illustrated in Figure 7. During funnel–flow with no flow along the walls, as depicted in Figure 7a, dilation of the bulk solid occurs as it expands in the flow channel. As a result some reduction in the radial support given to the stationary material may occur. If the hopper is fairly steeply sloped, say $[\theta \geq \delta]$, then the stationary mass may slip momentarily causing the pressure in the flow channel to increase as a result of the 'squeezing' action. The cycle then repeats. A similar behaviour may occur in expanded flow bins, such as the bin depicted in Figure 7b.
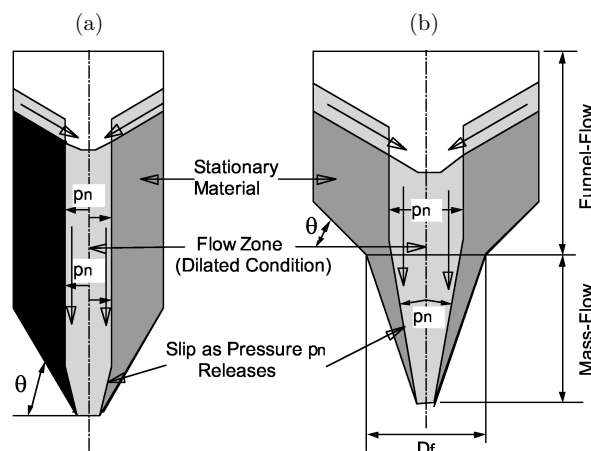

Figure 7. (a) Funnel-flow and (b) expanded-flow

3.2. Intermediate-flow

Benink [16] identified an additional flow regime, namely, intermediate-flow, which occurs between mass-flow and funnel-flow. Intermediate-flow is illustrated in Figure 8. Whereas the radial stress theory of Jenike [17] ignores the surcharge head, Benink has shown that the surcharge head has a significant influence on the flow pattern generated.

For mass-flow to occur in the hopper, the surcharge head of material in the cylinder (Figure 1) must be greater than the critical head H_{cr}. For squat bins in which $H < H_{cr}$ and for which the hoppers are close to the borderline between mass and funnel-flow, discharge will be characterised by intermediate-flow. Such flow is defined by a rapid flow in the central region of the hopper, and a slower flow in the outer regions as illustrated in Figure 8a. Funnel-flow is really the special case of intermediate-flow in which the outer region is stationary.

Based on observed flow patterns in model and full size bins, an estimate of the dynamic loads may be made. The effective dynamic mass of bulk solid in the central flow channel of the hopper section is the total mass in this section less the frictional support due to shear at the boundaries between the central and outer flow channels. This is depicted in Figure 8b.
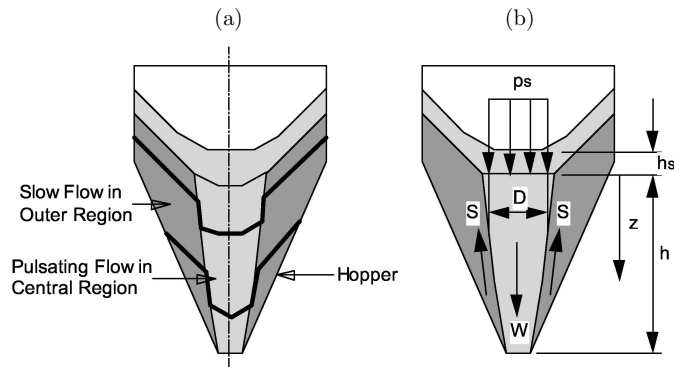
(a)   (b)

Figure 8. Intermediate-flow illustrating pulsating flow regime:
(a) folw patterns, (b) effective mass

Here the analysis is similar to that presented in Section 2 for tall bins, except in this case the flow pulsations are generated in the lower hopper section. The pulsating mass is as indicated in Figure 8b with the substitution of $D_f = D$ – width or diameter of flow channel, and μ – coefficient of internal friction. Normally

$$\tan\phi_t \geq \mu \geq \sin\delta, \tag{9}$$

where ϕ_t – static angle of internal friction, δ effective angle of internal friction defining upper bound of shear stress.

4. Tall coal bins with chisel hoppers-case study

Severe silo quaking problems were experienced in an installation of three, 12 700 tonne, reinforced concrete coal silos. The silos, which are shown schematically in Figure 9, stand 58 m above the ground; the height above the base is 52 m, the internal diameter is 21.4 m and the wall thickness is 0.3 m.
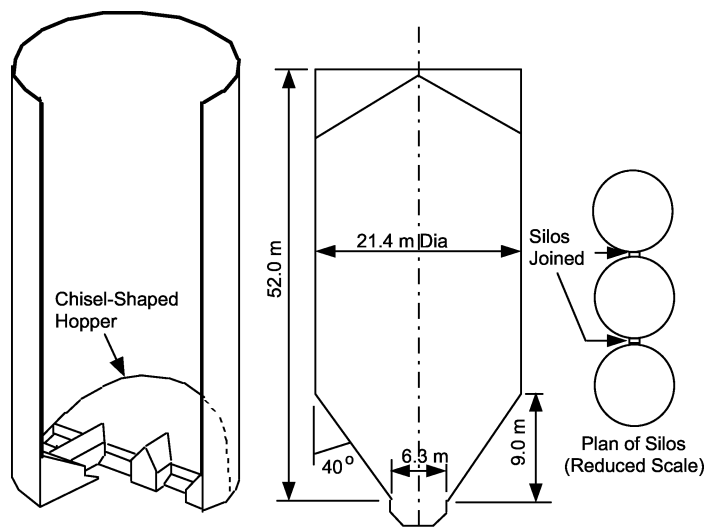

Figure 9. Tall coal silos

Adjacent silos are connected by concrete along the vertical lines of intersection. The silos have chisel-shaped, plane-flow hoppers lined with carbon steel plate, the half-angle α being 40°, this being the angle with respect to the vertical. The hopper splits into three outlets, the lower hoppers being lined with stainless steel. The maximum discharge rate is 2 700 tonne/hr through vibratory feeders.

The reported period of the shocks was 3 to 5 seconds, the shock loading being most severe when the silos were substantially full. After several years of use, severe damage started to occur, with sections of concrete being dislodged.

4.1. Computation of shock loads

The shock plane is assumed to be located at a height of 26 m above the base of the hopper. The head of coal above the shock plane is $h = 22$ m. Using the procedures presented in Section 2, the estimated amplitude of the dynamic pressure is $\Delta p_{wo} = 56$ kPa.

Equation (3) has been used to compute the locus of the shock pressure amplitude, the results being illustrated in Figure 10. Also shown are the static and flow pressures. In view of the curved transition of the chisel-shaped hopper with the cylinder, the pressure profiles will vary around the periphery of the bin. Figure 10 applies to the side of the bin where the chisel-shaped hopper has its highest intersection point with the cylinder wall.
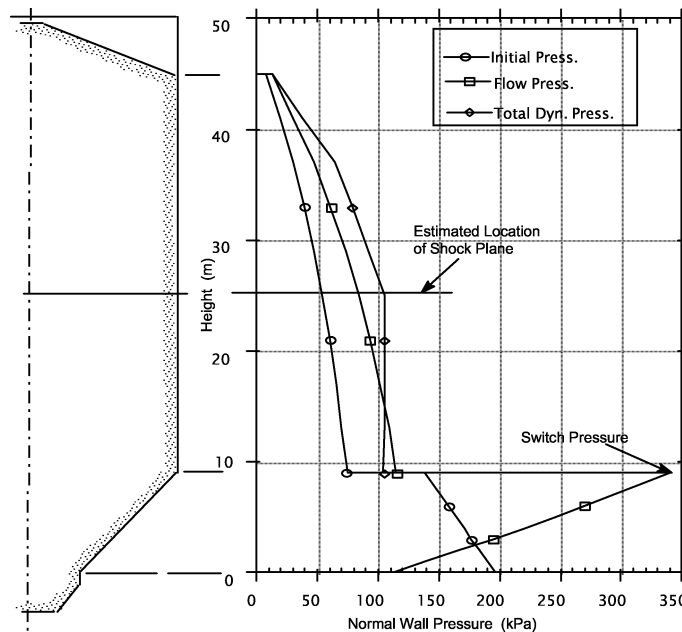

Figure 10. Pressure distributions for bin

4.2. Estimation of pulse period

The application of Equation (7) gives the following predicted values of the pulse period:

– for discharge rate $Q = 2\,700\,\text{t/h} - T = 2.4$ seconds,

– for discharge rate $Q = 1\,500\text{t/h} - T = 4.4$ seconds.

These values, which are based on $\Delta\varepsilon_y = 5\text{mm}$ for the coal, are in general agreement with the approximate values of 3 to 5 seconds as reported for the actual silo.

4.3. Vibration of structure

A critical factor in the operation of the silos is the influence of the dynamic characteristics of the overall structure. Noting that the silos were supported on columns on a base, which, in turn, was supported on piles, a simplified dynamic model of the silos is shown schematically in Figure 11. There will be vertical and lateral stiffness due to the columns and piles as well as vertical and lateral stiffness due to the concrete connecting adjacent silos. In view of the significant variation in the silo mass from the full to the empty condition, there is a significant variation in the natural frequencies.
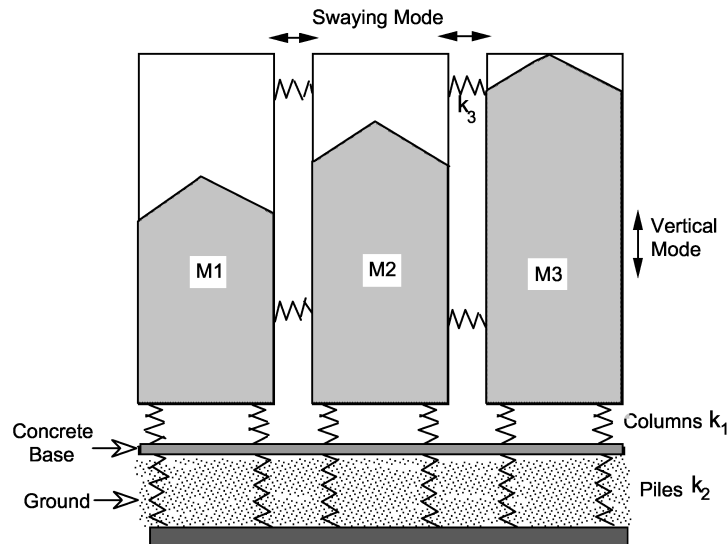

Figure 11. Simplified dynamic model of silos

The natural frequency for the fundamental mode is given by:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}}. \tag{10}$$

Noting the variation in mass, the natural frequency of each silo will change as follows:

$$\frac{f_{n,full}}{f_{n,empty}} = 0.56. \tag{11}$$

The natural frequency of the full silo is only 0.56 of the empty silo. While the various stiffnesses of the structures are not known, it is possible that the load pulse frequency of 3 to 5 seconds could excite one of the silo modes.

As each silo fills and empties, there will be different mass contents and, hence, different frequencies for adjacent silos. As a result, there will be dynamic coupling between adjacent silos which could impose significant loads on the concrete connecting

these silos. The modes of vibration, while complex, would involve a combination of vertical and sideways swaying motion, the latter induced by non-symmetrical loadings of coal in the silos as well as variations in ground stiffness in the zone of the supporting piles.

5. 200 tonne wheat conditioning silo – case study

5.1. Problem description

This case study is concerned with the "silo quaking" problem being experienced with the 200 tonne wheat conditioning silo shown in Figure 12.

Figure 12. 200 tonne wheat conditioning silo

Wheat is dosed with water prior to being fed into the top of the silo, the objective being to bring the wheat to a uniform moisture content of around 16% prior to discharge for the subsequent milling process. The magnitude of the shock loads were quite severe, particularly when the silo was full or near full. Observation showed the shock loads were transmitted through the ground into the neighbouring concrete silo structure leading to some cracking.

Calculations showed that the vertical dynamic load for the full silo when discharging grain amounted to 30% of the full static load, thereby increasing the total vertical load to 130% of the static load, The load analysis indicated that if the silo is operated at reduced head or fill, the shock loads are significantly reduced. For instance, at 60% full, the dynamic load is 46% of its maximum value, whereas at 50% full, the dynamic load is only 21% of its maximum value. Obviously, operating at 50% full would be the preferred option provided the residence time of the wheat in the silo is still sufficient to achieve good conditioning.

The vibration frequency of the silo structure due to the vertical motion and swaying varies with the degree of fill. The fundamental natural frequency of the silo
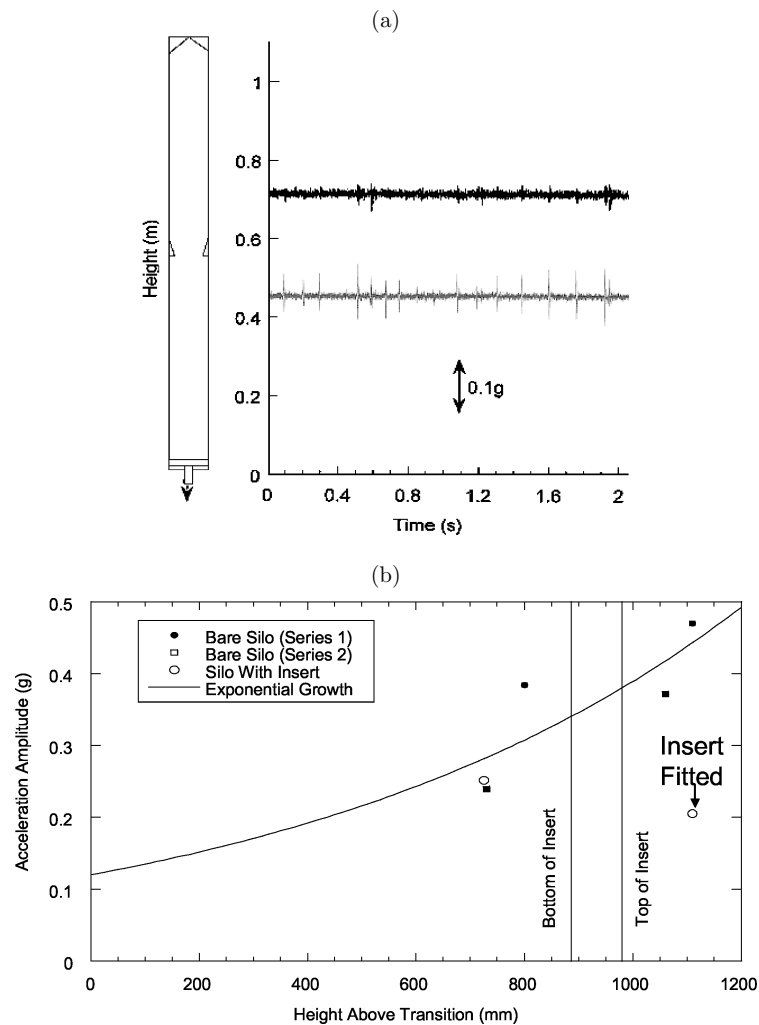
(a)

(b)

Figure 13. Influence of hopper insert in reducing acceleration during discharge:
(a) measured accelerations above and below inserts, (b) amplitude of acceleration

when 100% full is estimated to be 40% of the corresponding frequency when the silo is empty.

5.2. Recommended solution

In order to attenuate the growth in shock wave amplitude up the silo, Roberts and Wensrich [18] conducted experiments using a hopper insert, as depicted in Figure 13a. In effect, the insert divides a tall mass-flow silo into two squatter mass-flow silos. As the results of Figure 13b show, the acceleration amplitude above the insert is reduced by approximately 50%.

The proposed solution for the silo of Figure 12 is shown in Figure 14. It needs to be noted that the insert will cause an increased normal, switch type pressure on the silo wall and consequently, the silo wall may need to be strengthened in this region. This is illustrated by the stiffening ring shown in Figure 14.
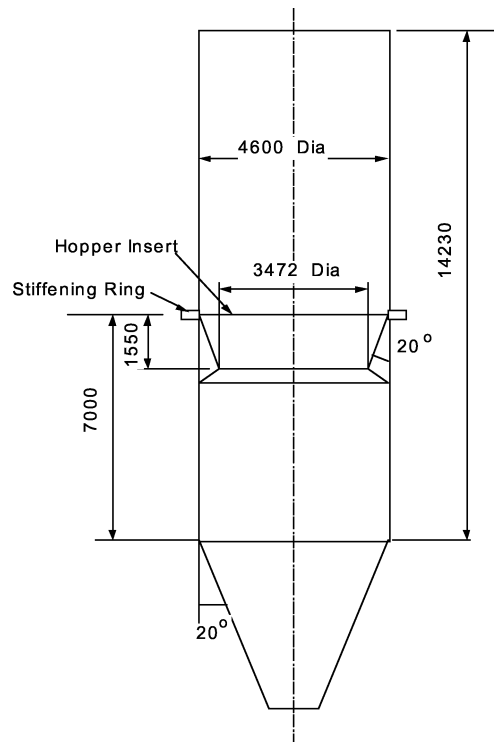
Figure 14. Modified silo showing hopper insert

6. 6 000 tonne multi-outlet coal bin − case study

6.1. Problem description

Silo-quaking problems have been known to occur in bins with multiple outlets. By way of illustration, the case study referred to in [8] concerning a 6 000 tonne is reviewed. The bin is illustrated in Figure 15. The bin has seven outlets and the hopper geometries provide for reliable flow permitting complete discharge of the bin contents. Coal was discharged by means of seven vibratory feeders onto a centrally located conveyor belt. When the bin was full or near full, severe shock loads were observed at approximately 3 second intervals during discharge. The discharge rate from each feeder was in the order of 300 t/h. When the level in the bin had dropped to approximately half the height, the shock loads had diminished significantly. With all the outlets operating, the effective transition was well down towards the bottom of the bin walls and the critical head H_m was of the same order as the bin diameter and greater than D_F. Substantial flow occurred along the walls, and since the reclaim hoppers were at a critical slope for mass and funnel-flow as determined by flow property tests, the conditions were right for severe "silo quaking" to occur.

6.2. Field trials

Confirmation of the mechanism of silo quaking was obtained in field trials conducted on the bin. A set of dynamic strain results is shown in Figure 16. In one series of tests the three feeders along the centre line parallel with the reclaim conveyor were operated, while the four outer feeders were not operated. This induced
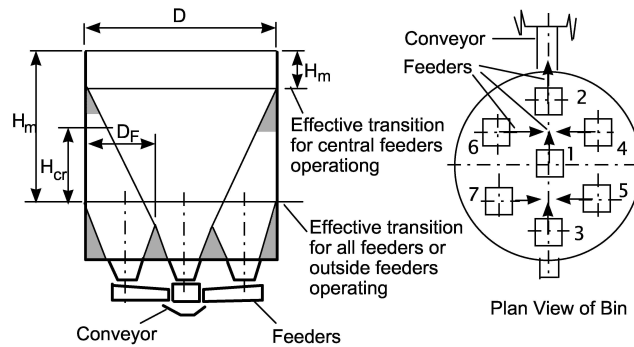
Figure 15. 6 000 tonne multi-outlet coal bin

funnel-flow in a wedged-shaped pattern as indicated in Figure 15, with the effective transition occurring well up the bin walls, that is $H_m < H_{cr} (= D_F)$ or $H_m \ll D$. The same was true when only the central feeder (Fdr. 1) was operated. In this latter case the stationary material in the bin formed a conical shape. Under these conditions, the motion down the walls was greatly restricted and, as a result, the load pulsations were barely perceptible.
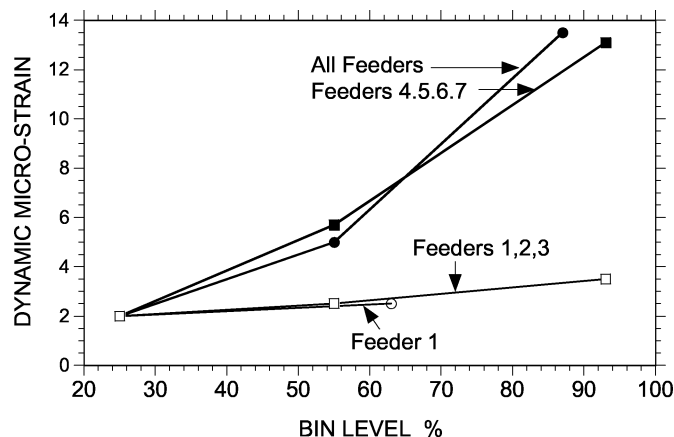

Figure 16. Variation in dynamic micro-strain in bin column (peak to peak measurement)

In a second set of trials, the three central feeders were left stationary, while the four outer feeders were operated. This gave rise to the triangular prism shaped dead region in the central region, with substantial mass-flow along the walls. The load pulsations were just as severe in this case as was the case with all feeders operating.

A critical factor in the operation of "quaking" silos is the dynamic stability of the overall structure. The silo in question is supported on columns from a concrete base which, in turn, is supported on piles as illustrated in Figure 17. In view of the significant decrease in total mass of the silo from the full to empty condition, there will be a corresponding increase in the natural frequencies of the silo during the emptying process. The modes of vibration involve combinations of vertical, swaying and twisting modes which are induced as a result of non-symmetrical loading of the
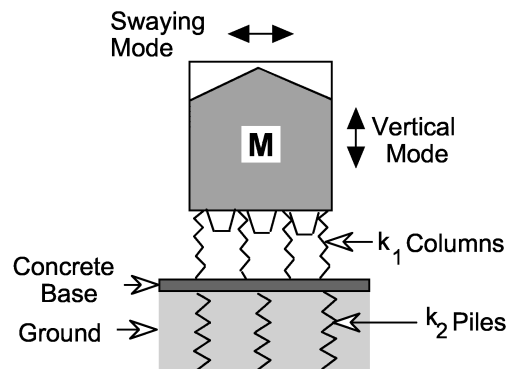
Figure 17. Silo dynamic model

silo, the pulsating flow during discharge and variations in the ground stiffness in the zone of the supporting piles.

7. Expanded-flow bin with twin intermediate-flow hoppers – case study

Figure 18 shows a 2 800 tonne coal bin of steel construction, which operates under expanded-flow. The lower chisel shaped hopper splits into two outlets from which flow is controlled by vibratory feeders. The maximum discharge rate is 2 500 tonne/hour.
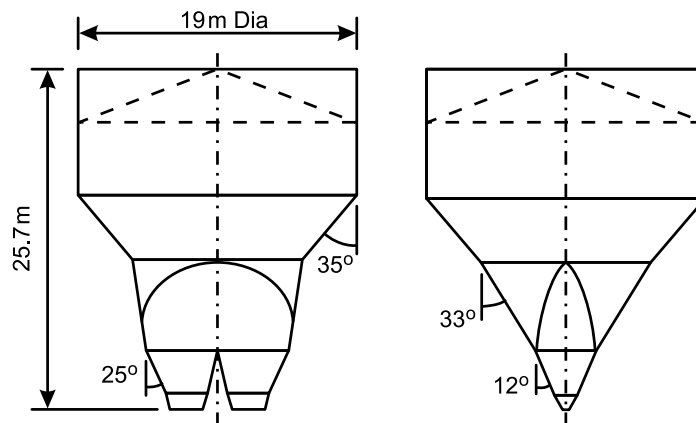

Figure 18. Expanded flow bin with twin intermediate-flow hoppers

Severe silo quaking was observed and unlike the previous case study examples where the quaking diminished significantly when the bins discharged half their contents, in this case the shock loads were still quite substantial even when the bin level had dropped below 50%. The load pulsations were more pronounced when wet coal was handled.

7.1. Dynamic loads and stresses

Using a scale model of the coal bin constructed of clear plastic confirmed that the pulsating loads were due to the flow patterns developed in the lower chisel-shaped

hoppers. Flow was characterised by rapid flow in the central region and slow flow in the outer region. Flow instabilities were observed at the interface of the flow zones giving rise to slip-stick type motion. The pulsating flow was most pronounced when moist, cohesive coal was used; when dry coal was used, the problem was not observed. It is quite apparent that the curved interface geometry of the chisel-shaped hopper, combined with the large plane-flow hopper half-angle and higher friction of the moist coal on the hopper surface, render the hopper marginal for mass-flow. In fact, the flow is more characteristic of intermediate-flow as defined by Benink [16]. This flow mode is illustrated in Figure 8.
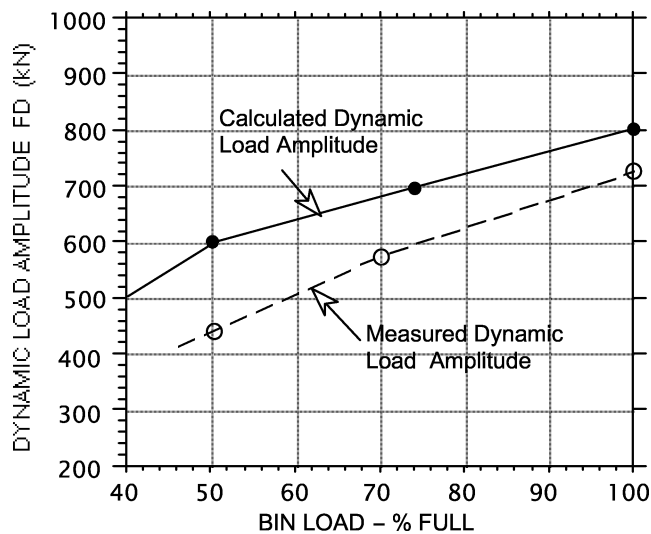

Figure 19. Estimated and measured dynamic loads

The dynamic loads due to pulsing were computed for various levels of fill, these values being converted in the estimated dynamic stresses in the bin support columns. Strain gauges were mounted on the support columns of the full scale bin and the dynamic strains were recorded during several loading cycles. Figure 19 shows the predicted and measured results. The measured dynamic loads are slightly lower than the predicted values, but the comparison is considered to be quite reasonable.

7.2. Natural frequencies of the bin and structure

It is contended that flow instabilities giving rise to pulsating loads or "silo quaking" are present in most bins or silos; whether the dynamic loads are experienced depends on the stiffness of the structure as a whole. In the case of the bin in question, the structure is quite flexible when the support columns and wooden piles are taken into consideration. The vibration modes of interest are the vertical and lateral swaying modes as shown in Figure 20.

The dynamic motion is a combination of both modes. However, in view of the observed non-symmetrical loading of the bin, it is more likely that the swaying mode dominates. The fundamental natural frequencies were determined for the vertical and swaying modes both for the full and empty conditions. The results are presented in Table 1.
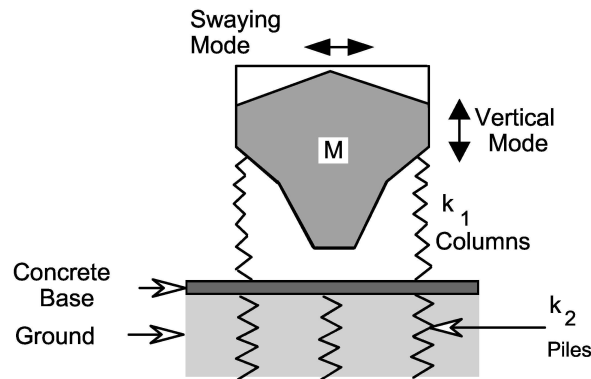
Figure 20. Vibration modes

Table 1. Natural frequencies of bin

Mode	Bin load	Natural frequency [Hz]	Ratio f_{full}/f_{empty}
vertical	full	3.4	0.23
	empty	14.78	
lateral	full	1.82	0.27
	empty	6.84	

8. Conclusions

This paper has examined the phenomenon of self-excited dynamic loads in bins, often referred to as the "silo quaking" problem. Mechanisms under which pulsating flow and dynamic loads may occur in tall mass-flow and funnel-flow bins and silos and in squat funnel-flow, expanded-flow, intermediate-flow and multi-outlet bins have been described. Based on laboratory and field studies, theories have been presented to describe the characteristics of the dynamic loads that are generated during discharge. The shock load amplitude is shown to increase exponentially with height measured above the hopper and cylinder transition. The pulse period is found to be inversely proportional to the average velocity of the discharging bulk solid in the cylindrical section of the silo.

Studies of slip-stick motion provide a great insight into the "quaking" phenomenon. Current research on this topic involves the application of lumped mass models and continuum models based on hypo-plasticity theory to describe dynamic flow behaviour. For tall mass-flow silos, the results confirm the exponential growth of the shock pressures from the lower to the upper regions of the cylinder.

It is believed that flow pulsations occur in almost all bins. Whether the corresponding dynamic loads induced are observable depend on the degree of severity of the pulsations and on the natural frequencies of the bin and supporting structure as well as to geotechnical characteristics of the ground providing the foundation support for the structure as a whole. It is important that bin designers become fully aware of the "silo quaking" phenomenon and ensure that the natural frequencies of the overall bin structure avoid the frequencies due to the flow pulsations.

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