TECHNICAL EVALUATION OF THE MAJUBA POWER STATION 10 000 TONNE COAL SILO 20 FAILURE MECHANISMS/FACTORS

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OVERVIEW

This paper presents the failure mechanisms and factors that resulted in the catastrophic collapse of one of the three 10 000 tonne coal silos at Majuba Power Station in November 2014, after 18 years of operation.

The Majuba silo is constructed with reinforced concrete with a dual hopper outlet onto two belt feeders below. The silo is part of the coal sustainability capacity storage system and as such was operated at full or near full level most of the time. Discharge is mainly by means of a single belt feeder, but two belt feeders are operated simultaneously when required.

The material flow patterns inside the silo impose loading conditions which are extremely complex and are still subject to ongoing research. The requirement for the silo design is to combine the field of the evaluation of the material property analysis together with the functional analysis to achieve a successful structural design.

The Majuba silos were designed in the early 90s. Since calculations are not available, it was required to establish if the silo was correctly designed in accordance with the standards and coal properties adopted at that time, thereafter to evaluate its response to more modern design standards in order to better understand its failure mechanism.

For the above reason the initial investigation was performed with the American Standard ACI 313-91 together with the coal properties as defined by Jenike and Johanson (1988), both utilized at that time. Subsequently, the silo investigation was carried out in accordance with the Australian Standard AS3774-1996 and the recent European Standard BS EN 1991-4. The coal properties adopted were those of the present coal.

1. INTRODUCTION

Majuba Power Station, being the last power station built under the previous Eskom build program, is situated between Volksrust and Amersfoort in Mpumalanga. Construction started in September 1993 and the first unit was connected to the grid in April 1996, with the last unit commissioned in April 2001. The dedicated Rand Mines coal mine near Majuba supplied the power station with 1.5 million tonnes of coal before closing down due to complex geology which resulted in a difficult and unsafe mining operation. From then onwards, Majuba's coal had to be sourced from numerous other suppliers, and is delivered by means of road and rail transportation.

Majuba has six boiler units with a total capacity of 4 110 MW and three terrace coal silos. These three silos, namely Silo 10, 20 and 30, have a capacity of 10 000 tonnes each. The daily coal burn at Majuba is in the order of 50 000 tonnes. Each silo supplies coal mainly to two boiler units. Silo 20, the central silo, is serviced by two overland conveyors with inclined head sections and, in turn, supplies coal to the two wing silos by means of four over-silo link conveyors. Silo 20 was the second silo to be commissioned.

Figure 1. Aerial photograph of the Majuba Power Station.

THE INCIDENT

On the 1st November 2014, a vertical fracture developed on the south eastern face of silo 20, approximately two metres above the intersection of the internal hopper and the vertical wall. The vertical crack in the silo wall extended upward for approximately 10 m in height. This vertical fracture was followed by two horizontal fractures which then resulted in the sudden collapse of the cylinder section.

Figure 2. The vertical crack in the silo with coal running from the crack, followed by the horizontal cracks.

Figure 3. The collapsed silo with the bottom part below the 28 m level remaining in situ.

The collapse of silo 20 resulted in the collapse of other structures that were connected to it, including portions of the overland conveyor and over-silo link conveyor gantries.

Since silos 10 and 30 were constructed using the same design as silo 20, a decision was taken to empty these silos and to take them out of service.

2. OBSERVATIONS AND FINDINGS FROM THE SITE INSPECTION OF THE FAILED SILO AS WELL AS THE TWO REMAINING SILOS

The section of silo that failed is the section above the 25.5 m level. This is approximately 1.5 m above the intersection between the internal mass concrete hopper and the cylindrical wall section. The bottom part of the silo below the 25.5 m level remains in situ.

Figure 4. The part of the silo below the 25.5 m level remained in situ.

A large coal build-up, solid as rock, was present inside the standing section of the hopper. The build-up was on the short end of the silo hopper opening which has the shallow hopper angle.

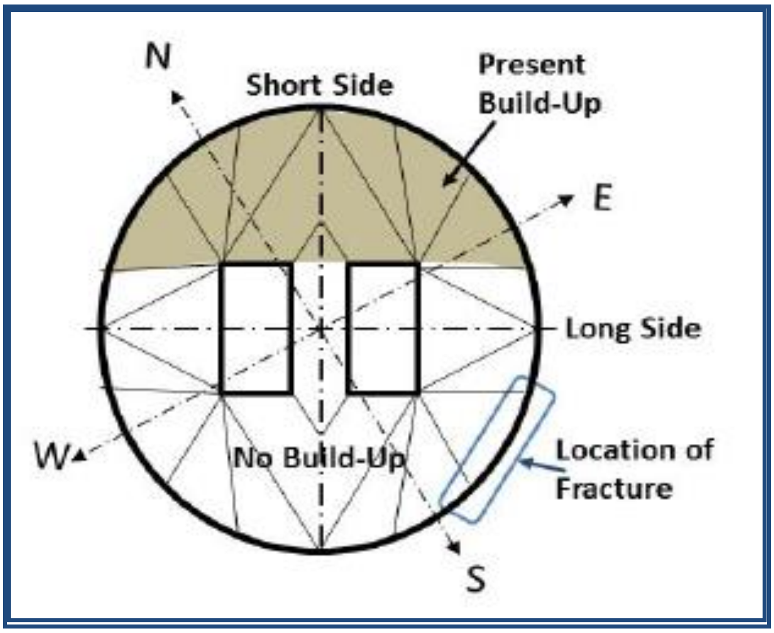


Figure 5. Plan view on silo 20 indicating the location of the coal build-up as well as the location of the origin of the fracture that resulted in the failure of the silo.

The inspected sections of the collapsed cylinder wall lying on the ground showed smooth concrete without any sign of corrosion or erosion. The reinforcement inspected on site was not corroded, eroded or rusted.

Figure 6. Part of the cylinder wall.

Concrete and reinforcement samples were collected from the failed silo 20 remains and sent to Eskom's research department for testing.

Figure 7. Concrete wall sections and reinforcement steel.

The test performed confirmed that the steel reinforcement was indeed 450 MPa high tensile steel and the concrete strength exceeded 30 MPa. By inspecting the reinforcement closely, it showed the classical neck fracture typical of a tensile failure.

Figure 8. Typical tensile failure of rebar.

INSPECTION FINDINGS ON THE REMAINING TWO WING SILOS

Various exterior and interior inspections were carried out on silos 10 and 30 by Eskom’s engineering team as well as a commissioned team of consultant specialists. The first silo inspected was silo 30, it was entered from the top and the findings are depicted hereunder:

SILO No.	SURFACE	BY MEANS	RESULTS
10	Internal	By naked-eye from the silo roof with flood lights.	Some larger cracks visible; smaller ones not visible due to poor visibility. Coal build-up present and visible.
	External	Naked-eye while walking up stairs leading to the roof slab.	Extensive cracks of various sizes.
30	Internal	Skyriders – abseiling from roof slab.	Extensive cracks visible, large and small, and coal build-up present.
	External	Binoculars from ground level.	Cracks not visible due to dark grey color of the silo.
		Naked-eye while walking up stairs leading to roof slab.	Extensive horizontal and vertical cracks present. Visible from approximately level 35.0 m upwards.

Table 1. Findings of visual observations on silos 10 and 30.

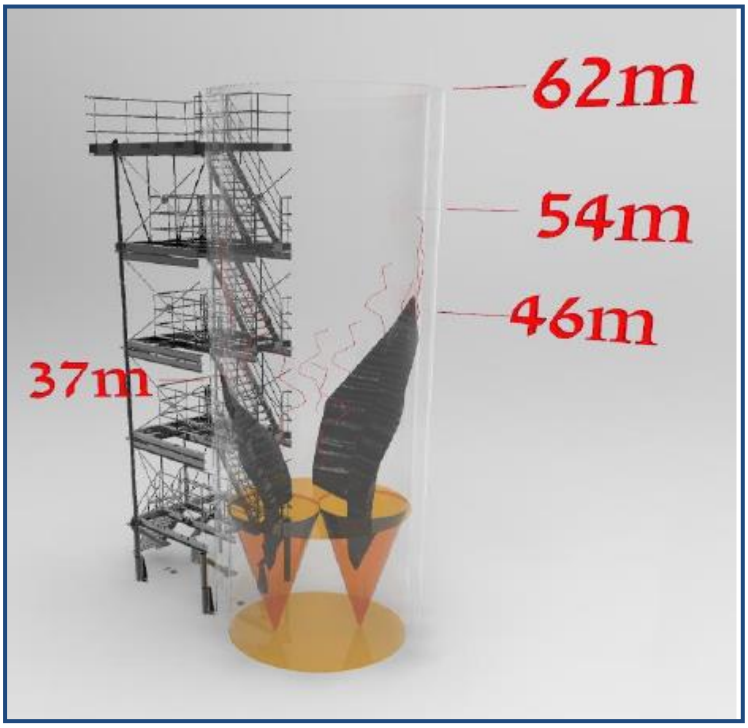


Figure 9. Coal build-up inside silo 30.

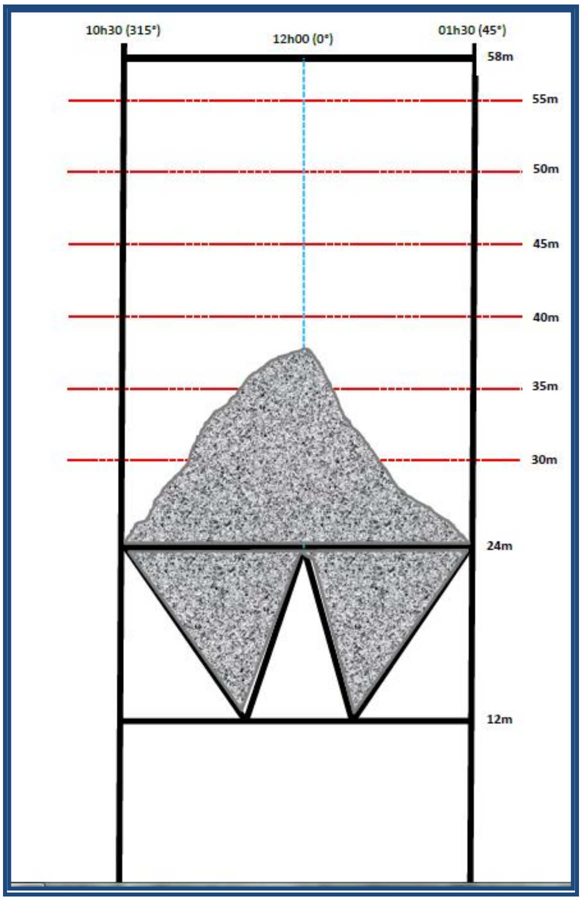
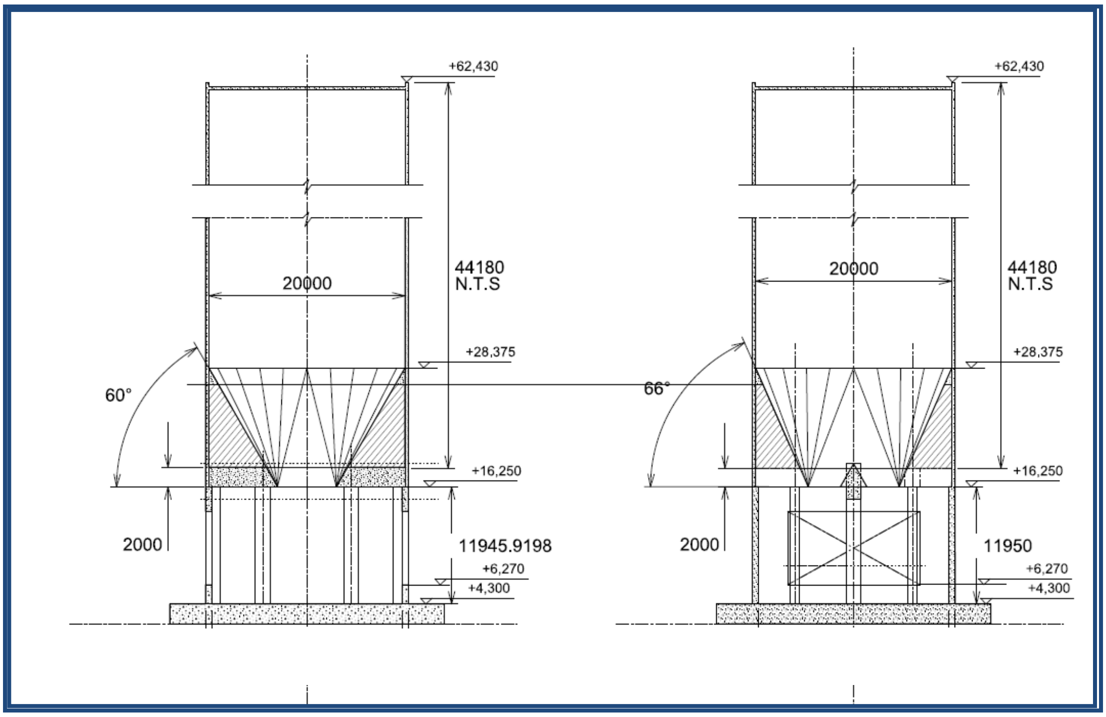


Figure 10. Coal build-up on silo 10.

The visual inspection of the silos (Table 1) and Figures 9 and 10 give a very good representation of what was found during the inspection of silos 10 and 30. The inspection also confirmed that taking them out of production was the correct decision.

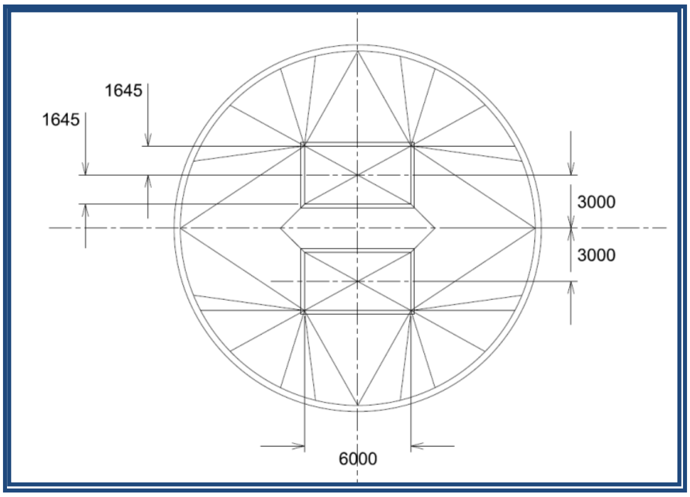
It must be noted that as part of the Eskom inspection policy, the silos were visually inspected the previous year by an external consultant. Besides minor spalling of concrete at the top of the silos, it was reported that the silos were in good structural condition. Furthermore, the silos were functioning quite well, delivering the correct amount of coal to the feeders, never giving any indication of malfunction.

GENERAL ARRANGEMENT DRAWINGS OF THE 10 000 TONNE COAL SILOS



Side View

End View



Plan View on Opening

Figure 11. General arrangement of the 10 000 tonne silos.

Figure 11 shows the general arrangement of the existing silos. The cylinder wall thickness is 350 mm and the inner surface of the cylinder has a smooth concrete finish; the internal hopper is formed using mass concrete with a gunite surface lining; two rectangular openings are provided through the concrete slab from which two external steel hoppers are suspended below. The steel hoppers are lined with 3CR12 liners.

The in-feed conveyor system on the concrete roof of silo 20 feeds coal into the silo from two openings symmetrically placed about the centreline of the silo. The centre of each opening of the in-feed conveyors is 2.0 m offset from the silo centreline. With this configuration the in-feed and discharge presented very little eccentricity.

The out-feed conveyor system at the bottom of the silo consists of two feeders of which one was operating at 100% capacity while the other was standing idle as back-up. This operating philosophy caused constant eccentric discharge loading on the silo wall, for this reason the modus operandi has been changed such that all stations will operate both feeders at 50% thus ensuring a symmetrical discharge.

3. COAL FLOW PROPERTY ANALYSIS

THE ORIGINAL COAL PROPERTIES

In the absence of evidence of the coal properties originally used in the design, it was assumed that the coal properties adopted in the original design were those from the original Majuba Mine, as presented in the Jenike and Johanson report (1988), which amongst other Eskom coal property analysis for that period presents the design's most upper bound values.

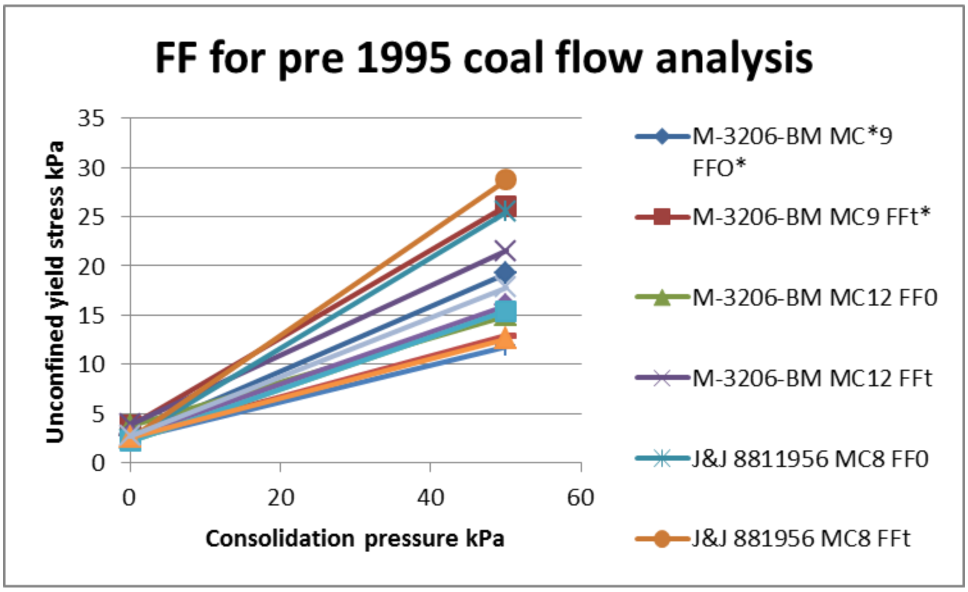


Figure 12. Comparison of the flow functions of coal property analysis information for Eskom coal pre-1995.

*MC Moisture Content by mass, FFt Flow Function for time consolidation, FF0 Flow Function for instantaneous condition.

The Jenike and Johanson (1988) coal property analysis accounts for coal samples tested at a moisture content of 8% and 13% for instantaneous condition as well as for 48 hour consolidation.

ASSESSING THE SILO FLOW TYPE

The hopper has two half angles. On the long side of the opening it is 24° while on the short side it is 30°**.** Since the hopper half angle can also be derived as a function of the hopper opening and vice versa, a series of flow evaluation calculations were performed to assess the flow type for which the silo was originally designed. These calculations were based on the assumed original coal, the present openings, the present hopper angles and the hopper gunite surface. Calculations indicate that the silo geometry meets the requirements on mass flow for the 24° angle and it is just within the boundary for the 30° angle. One can therefore assume that the silo was designed for mass flow.

THE CURRENT COAL PROPERTIES

The current coal, as previously said, comes from a number of different mines; therefore the coal quality is expected to be variable. Four samples of coal were collected after the silo 20 failure at Majuba, one from the live pile at the stockyard, one from the mill feeder that received coal from the silo prior to the failure, one from the strategic stockpile as well as one from the contents of the failed silo. These samples were sent for coal flow analysis.

In the meantime, the design review was performed on the basis of a coal flow property analysis resulting from a more recent sample of coal supplied to Majuba after the mine closure, as presented in the report by Bulk Solid SA Reference BSFA 181 (2003). It should be noted that the coal flow analysis of the four latest samples tested did not differ substantially from the said 2003 report.

The analysis for the current coal shows that the properties of the coal are characterised by its cohesive nature and as such it presents a strong cohesive or sticky coal characteristic.

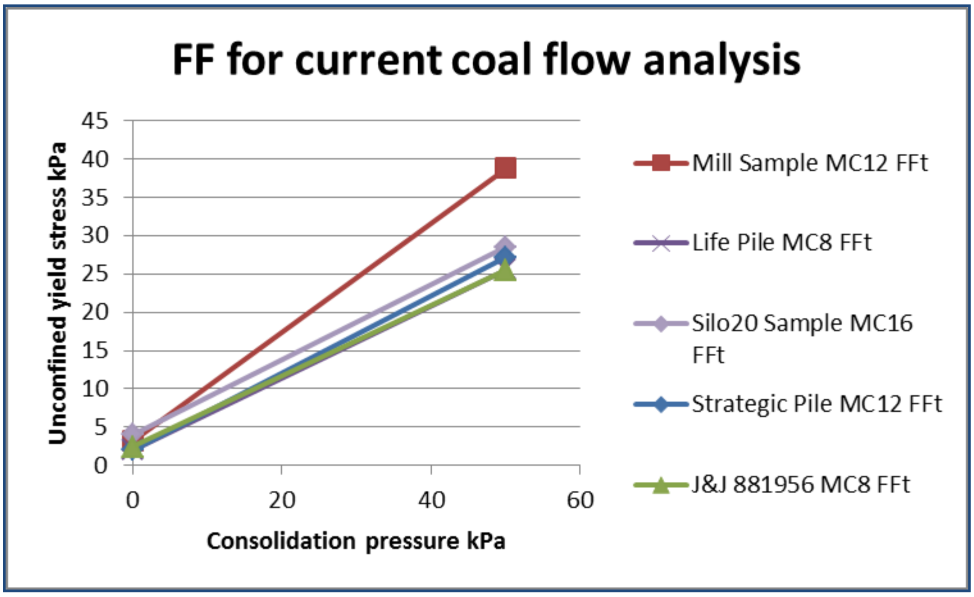


Figure 13. Comparison of the flow functions of coal property analysis information for the current coal in comparison to the original coal.

A series of evaluation calculations were performed on the basis of the current coal in order to determine what type of flow the present silo and hopper arrangement would have been subjected to with the present coal properties.

Calculations indicate that with the current coal properties and the gunite hopper, the silo could not sustain mass flow thus creating stagnant flow zones on the shallow slope. This, in combination with the critical rat-hole criteria, resulted in a very complex mixed flow pattern of mass flow and expanded flow.

The stagnant coal flow zones developed on the short end(s) of the openings would consolidate over time into solid coal build-ups. This has been confirmed by the internal inspection of the silos 10 and 30 and also by the presence of a coal build-up in silo 20.

The build-up of coal on the shallow hopper ends resulted in a permanent change in the hopper geometry as well as contributing to more complex eccentric flow patterns.

Furthermore, the formation of coal build-up, once solidified, changed the internal hopper geometry by moving upward the intersection of the cylinder to the hopper. This caused the switch pressure (Figure 16) to shift upwards, moving up as the build-up progressed upward, while on the side without the coal build-up the switch pressure remained at the correct location. This uneven switch pressure in conjunction with the eccentric wall pressure resulted in additional vertical and horizontal moments for which the silo was not designed.

4. SOME OF THE TECHNICAL CONSIDERATIONS OF SILO DESIGN

The loads acting on the walls of silos are affected by the material properties derived from the flow property analysis and by the flow type. These are:

- The bulk material density
- The material effective angle of internal friction
- The material static angle of internal friction
- The angle of friction between the wall and the material.

The geometry of the hopper, in the case of a new design, is defined by the material flow properties and the flow type required for the silo operation. In the case of an existing silo, these properties are used to evaluate the actual flow type and the functionality of its geometry.

The potential for the development of coal build-ups that may impose changes to the geometry of the storage container causing wall load conditions that are usually not expected should be evaluated at the design stage assuming potential coal property changes.

For an effective and functional design the determination of the wall loads that will be imposed onto the structure should be calculated from a complete range of the material flow properties, if available, that can potentially apply to a storage facility over its operational life.

The modern design standards give adequate guidance for the calculation of the various wall loads combinations, but it is still essential that the designers are adequately experienced and able to interpret the flow properties and the potential operating conditions to which the structure may be subjected to during its life.

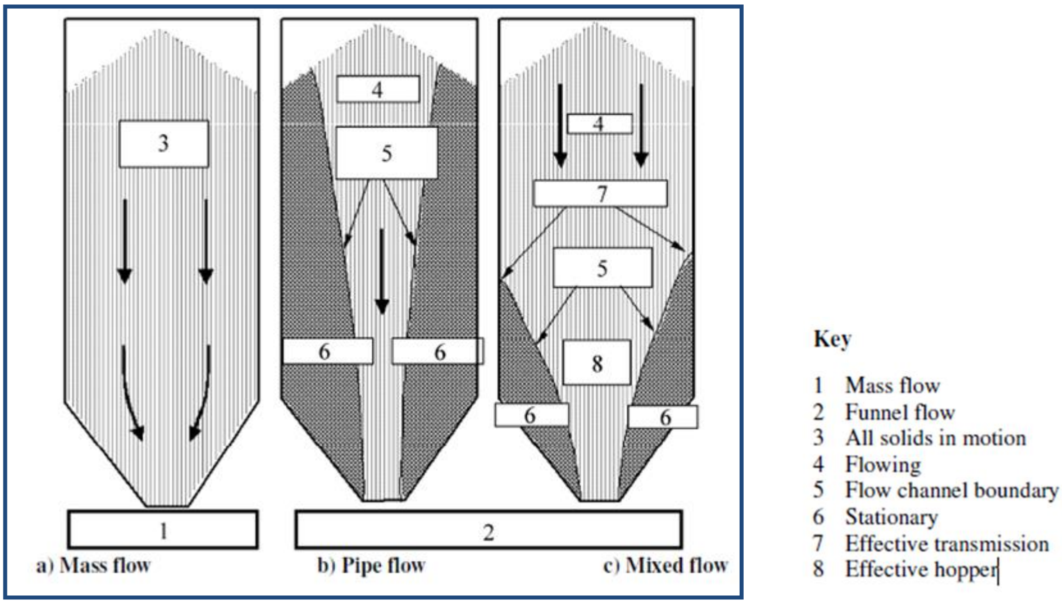


Figure 14. Typical flow conditions.

CYLINDER SECTION

Silo walls are loaded by the filling pressure (active pressure) and by the discharge pressure (passive pressure). Janssen[13], more than a century ago, developed a theory which is still valid and used today to calculate the horizontal radial pressure imposed on the wall of the cylinder section of the silo during the filling or active condition. This pressure is dependent on the factor 'K', the ratio of the mean horizontal pressure to the mean vertical pressure and it is calculated from the angle of internal friction. The greater the factor K, the greater the horizontal pressure against the silo wall. This is a symmetric radial pressure.

The discharge pressure (passive pressure) is calculated by multiplying the filling pressure (active pressure) on the wall by a factor, given in the adopted standard and thus is greater than the filling pressure. This symmetric radial pressure acting on the wall results in a circumferential or hoop tension in the wall. This hoop tension is solely resisted by the circumferential reinforcement. Vertical and horizontal bending moments can also develop at the intersection with the more rigid hopper and by eccentric loading conditions.

HOPPER SECTION

During Filling

The hopper section also experiences two different pressures; the pressure due to filling, the active pressure and the pressure during discharge flow condition, the passive pressure. The diagram of filling pressure, Figure 14, shows the pressure acting in the cylinder and the pressure acting on the hopper. The hopper pressure starts at the transition *(the interface between the hopper and the cylinder)* and increases as it progresses towards the hopper outlet.

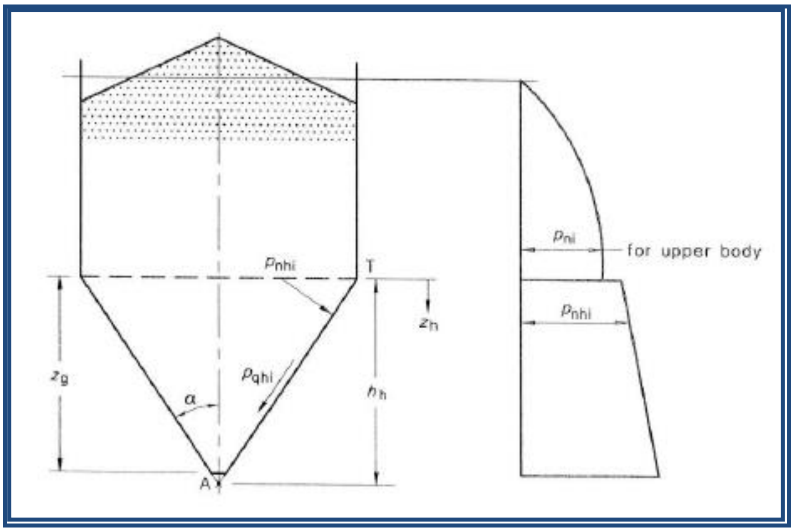


Figure 15. Distributions of initial wall pressures in the container during filling.

During Discharge

The pressure on the hopper wall during discharge has different pressure characteristics than those during filling and both the Eurocode and the Australian standard provide guidance regarding determination of these loads.

Figure 16 shows both the discharge pressure in the cylinder wall and the hopper wall. This pressure acting at the transition, referred to as the 'switch pressure', is generally many times greater than the filling pressure on the wall. The passive pressure acting on the hopper wall is at its maximum at the interface between the hopper and the cylinder wall and decreases as it approaches the outlet.

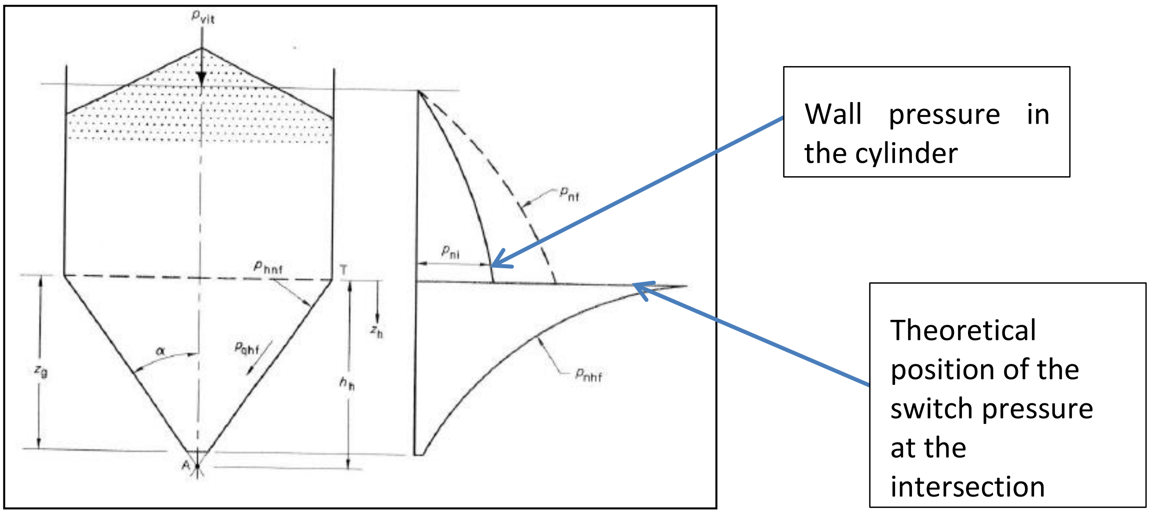


Figure 16. Distribution of wall pressure in hopper with surcharge during flow.

Generally, the design standards and the literature on this subject indicate that the switch pressure is applied at the transition between the cylinder and the hopper. In actual fact, by monitoring various silos, researchers have come to the conclusion that this force spreads over an area above the transition. Jenike and Johanson have proposed (Figure 17), that the switch pressure starts at a point of the cylinder above the transition identified by projecting a line tangential to the arc centred on the theoretical apex of the hopper, passing through the top of the cone.

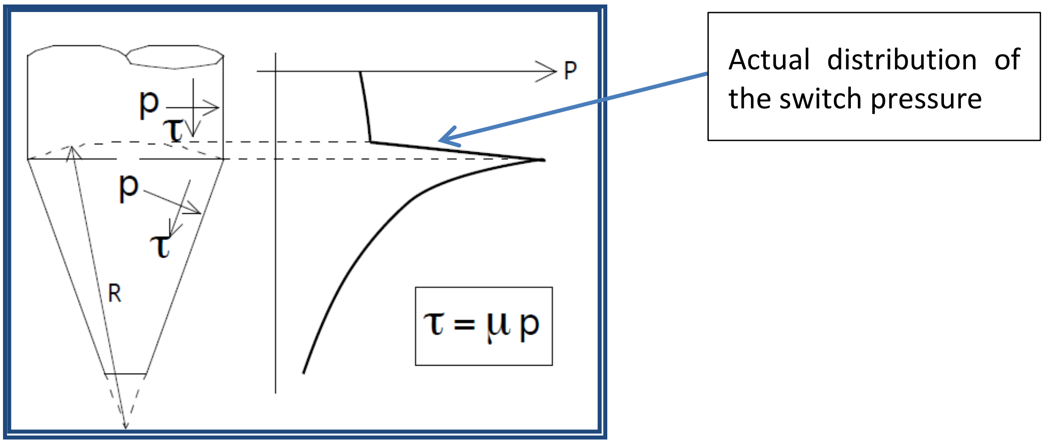


Figure 17. Spreading of mass flow peak into cylinder section.

Carson and Jenkyn (1993) have also shown that with a hopper designed for expanded or funnel flow, the coal could actually develop its own internal flow channel (Figure 14) and this should be considered in the design. Mass flow of material applies inside of this flow channel. If this flow channel intersects the silo's roof, then a funnel flow condition develops. If instead the flow channel intersects the cylinder wall, then the intersection point shifts to this location and with it the switch pressure. Carson and Jenkyn (1993) suggest how to calculate the effect of this switch pressure on the cylinder wall. (Figure 16).

The European Standard BS EN 1991-4: 2006 takes this condition into consideration with the application of the patch loads. Another approach to this could be to consider the intersection load as an overpressure load in accordance with the Australian standard. It could also be predicted as a switch pressure based on the convergence in the flow channel and the stress change from active to passive on that basis.

The book *Bulk Solid* (1982)[4] also discusses this phenomena in the case of silos designed for funnel flow, but it does not give any recommendation how to deal with them.

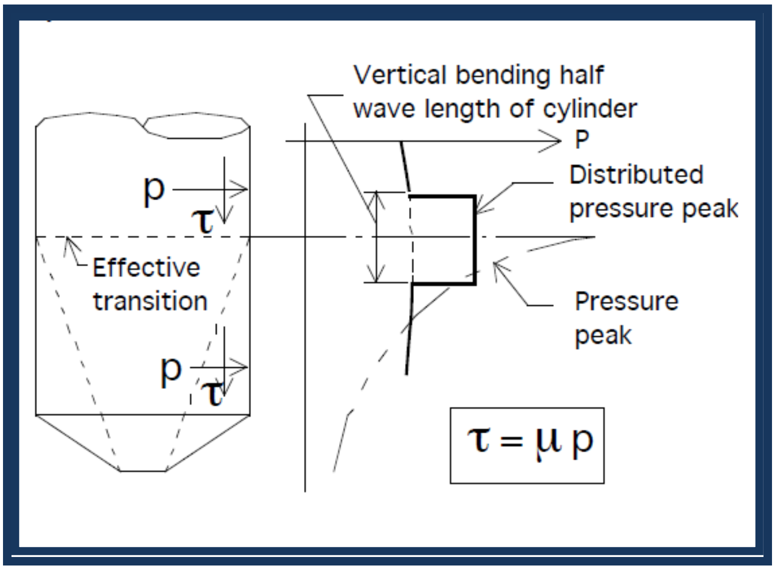


Figure 18. Funnel flow hopper – flow channel intersecting cylinder wall.

It is good practise to consider that coal may build up due to possible changes of the material properties, causing changes in the flow pattern.

5. INVESTIGATION OF THE WALL LOADS IMPOSED ON SILO 20

THE IMPOSED LOADS DERIVED FROM THE ORIGINAL DESIGN AND THE INITIAL COAL FLOW PROPERTIES

The first phase of the investigation was to establish to which standard the silos were designed and what coal properties were adopted in the design. After extensive research it was found that the design was carried out in accordance with the ACI 313-91. Since no evidence could be found on the coal properties adopted, it was decided to adopt the coal properties from the flow analysis of Jenike and Johanson (1988). This, amongst a number of flow analyses, yielded the more onerous properties.

It must be emphasized that:

- ACI 313-91 focuses on symmetric loadings and does not give any guidance on how to deal with eccentric loadings, although Clause 4.4.2.4 states: 'pressure increase or decrease due to concentric and eccentric discharge openings shall be considered'.
- We do not know if the design engineer at that time did consider this case, however we tested this case by adopting the algorithm in AS 3774-1996 and the discharge pressure was calculated with ACI 313-91.
- ACI 313-91 calculates the K value for the Jansen algorithm using the Rankine static pressure K= 1-sinΘ/1+sinΘ which gives wall load pressures far less than the pressures calculated with AS 3774-1996 or indeed with EN 1991-4:2006 which uses the pressure at rest.

The silo was analysed with the original coal properties using the American design code ACI 313-91 to assess if the design was executed correctly at that time. The silo was also analysed with the current coal properties with the ACI 313-91 in order to assess what the reinforced steel stress would have been had the original engineer checked for this.

In the second phase of the investigation, two analyses were performed adopting the Australian Standard AS 3774 1996; one with the original coal in order to investigate the reinforcement stress should the coal properties have remained the same, and the second with the current coal in order to investigate the stresses and to compare and investigate the level of safety for the two cases.

Independent design reviews were also conducted by Professor A. Roberts from the University of Newcastle, Australia as well as by Jenike and Johansen Inc. from Massachusetts, USA as verification.

Wall Reinforcement

The reinforcement drawings show that the cylinder wall was reinforced with two layers of horizontal reinforcement to resist the hoop forces. The area of reinforcement per metre height of wall is greater at the intersection of the cylinder with the hopper and reduces as it progresses towards the roof. The vertical reinforcement is constant throughout the height of the cylinder wall and it appears to be nominal.

The internal hopper section was constructed with mass concrete, cast against the cylinder wall after the construction of the cylinder. At the top of the hopper there is a 2 m high heavily reinforced ring beam. This ring beam was built within the hopper concrete and the cylinder wall is not part of it. The ring beam was placed strictly in accordance with the theory that it should be placed at the location where the switch pressure is expected to be.

DESIGN REVIEW CALCULATIONS IN ACCORDANCE WITH THE AMERICAN STANDARD ACI 313-91

The ACI 313-91 standard gives the designer the option to calculate the initial filling pressure either by means of the Janssen's algorithm or alternatively by Reimbert's[3] method. The discharge pressure has been calculated by multiplying Janssen's active pressure by a factor given on Table C.1 of the standard.

The eccentric load condition was also considered adopting the algorithm in the Australian Standard AS 3774-1996 by applying the vertical discharge pressure calculated with the ACI 313-91; the results indicate that the amount of reinforcement required is still less than that of which the silo was constructed.

The vertical reinforcement was also checked for the horizontal moment and found to be adequate. Calculations indicate that the design of the silo was carried out with the state-of-the-art standard and the knowledge available at that time and it fulfils the requirement of the standard. The calculation of the wall loads was performed taking into consideration the hopper geometry, i.e. along the long ends of the hopper openings as well as along the short ends of the silo openings.

Figures 19 and 20 below give an indication of the loads calculated with ACI 313-91 for the original and current coal qualities respectively.

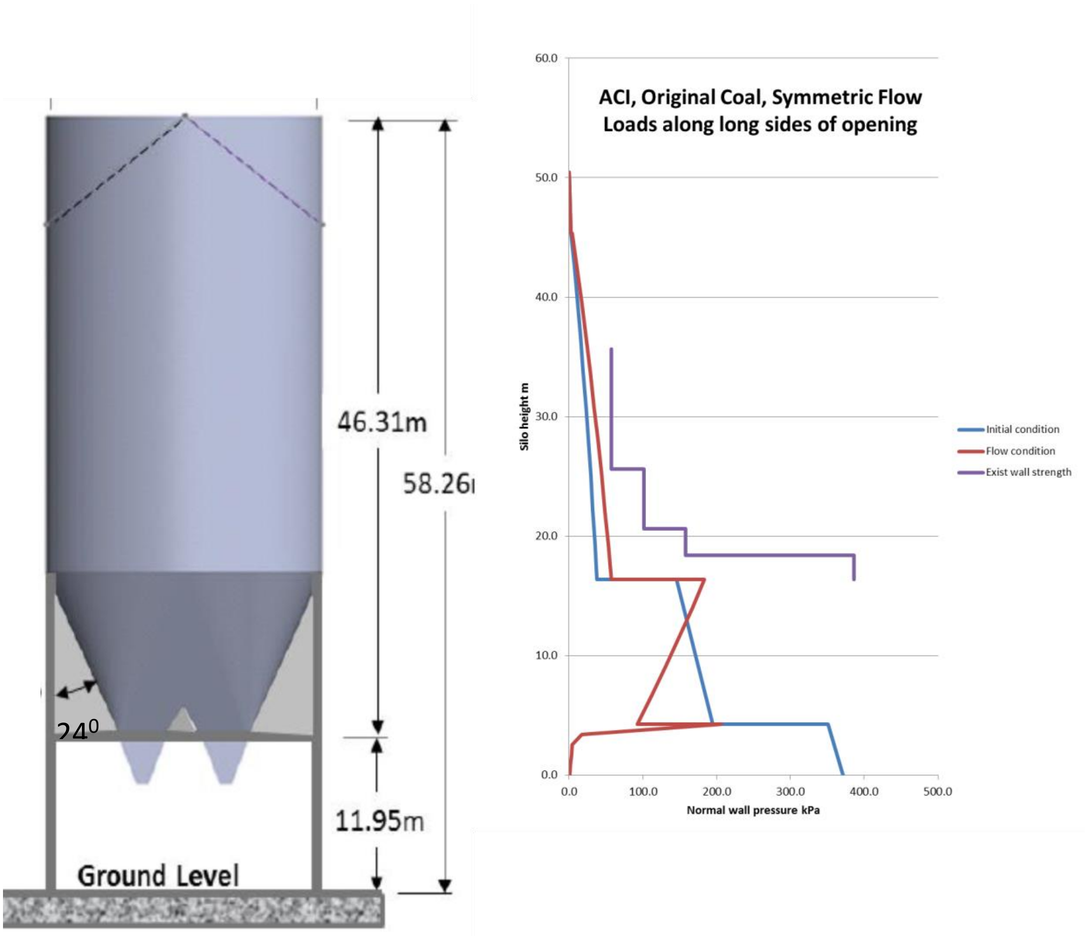


Figure 19. Wall load for the original coal base on the ACI 313 standard.

Figure 19 shows that the amount of reinforcement provided in accordance with the ACI 313-91 is more than sufficient.

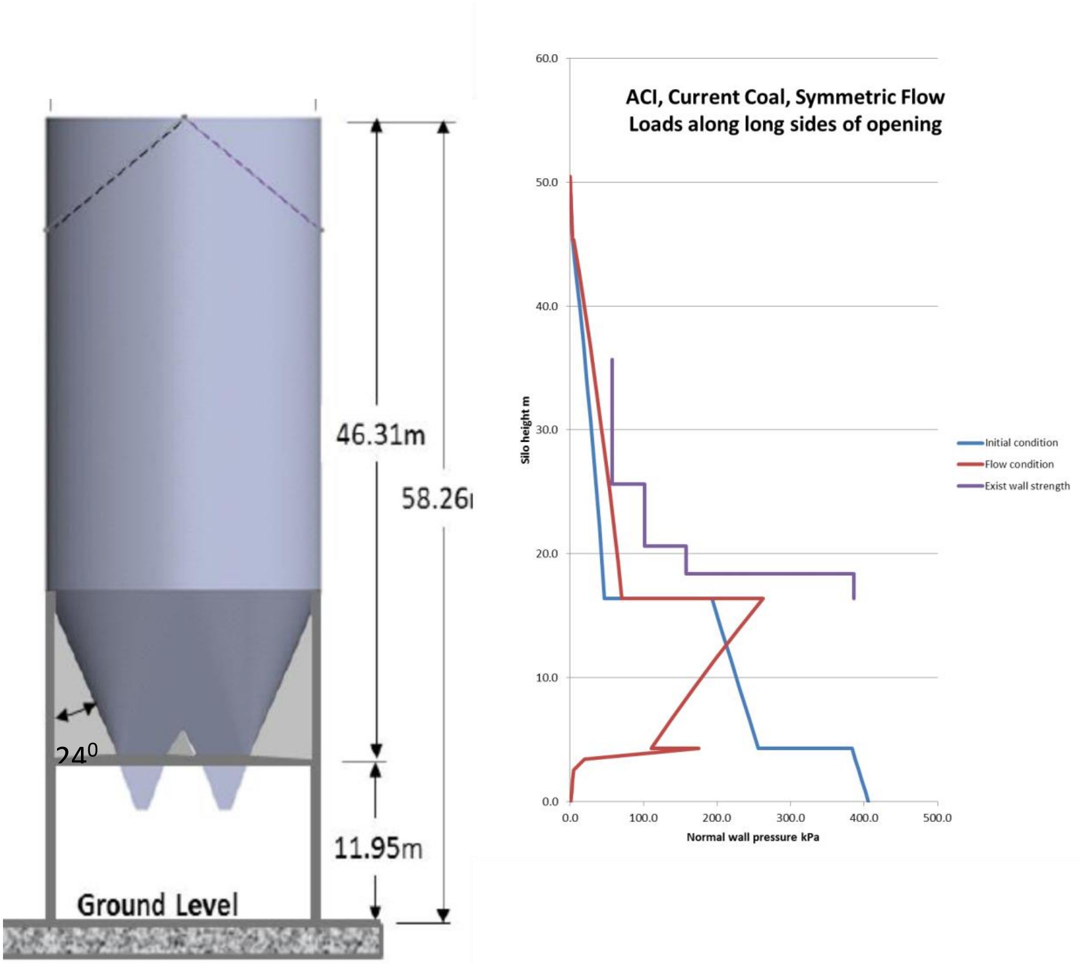


Figure 20. Wall load for the current coal based on the ACI 313-91standard.

Figure 20 shows that the amount of reinforcement provided for the current coal adopting ACI 313-91 is still within the standard requirement.

DESIGN REVIEW CALCULATION CARRIED OUT WITH THE AUSTRALIAN STANDARD AS 3774-1996

The Australian Standard AS 3774-1996, *Loads on Bulk Solid Container,* is more advanced than the ACI 313-91; and provides for concentric and eccentric conditions.

For this reason the analysis was also performed in accordance with this standard.

The calculations were carried out for the original coal, the current coal without taking the eccentricity into account and the one taking the eccentricity into account.

The analysis with current coal shows the reinforcement is overstressed between the 25 m and the 35 m level. The analysis with the current coal without and with the eccentricity shows that the reinforcement is overstressed.

For all three cases this is because of the K factor, the ratio between the horizontal and vertical pressure is 0.35, about three times that calculated using the Rankine theory. It is also interesting to see that the eccentricity does not have a major effect although it has some contribution to the magnitude of the wall loads.

It must also be noted that the eccentricity calculated did not take into account the coal build up, it is purely calculated taking the opening eccentricity into consideration.

Figures 21 to 24 present the wall loads calculated for the original coal for symmetric loading as well as for the current coal for various load conditions.

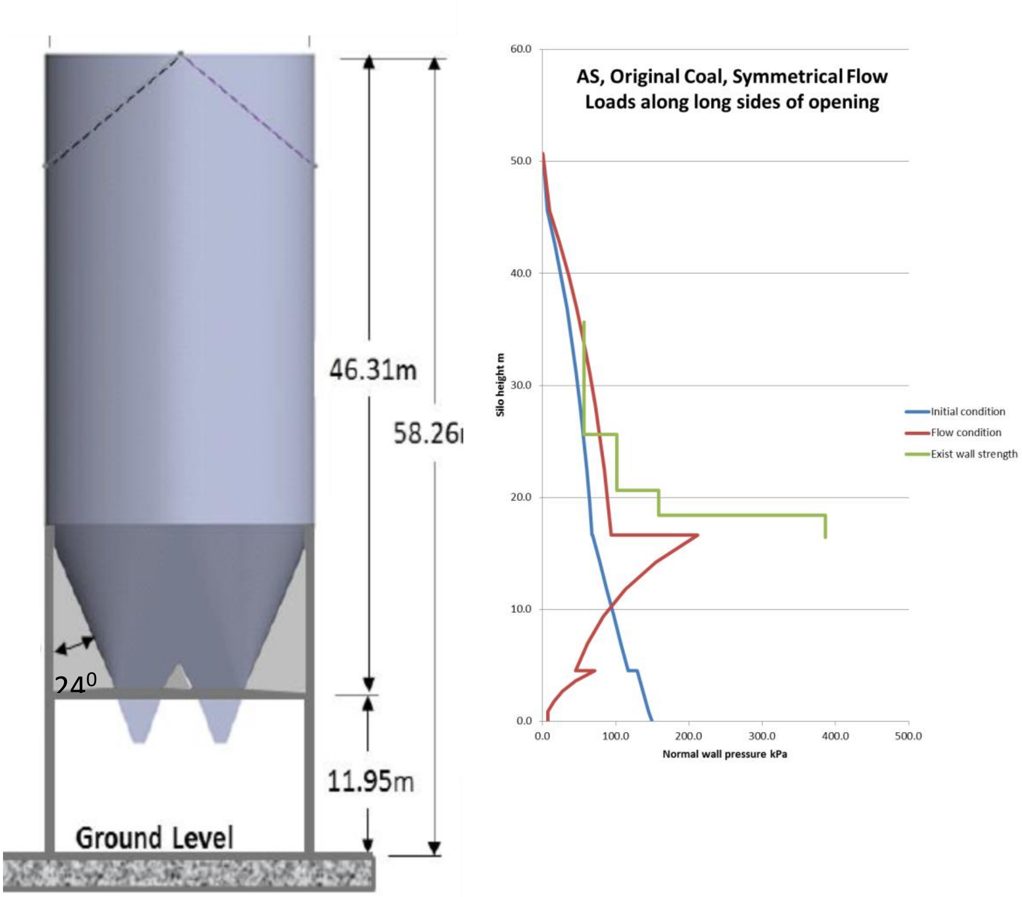


Figure 21. Wall load for the original coal based on AS 3774-1996.

Figure 21 shows that the amount of reinforcement between elevation 25 m and 35 m is not sufficient when checked with original coal and the AS 3774-1996. The wall strength at the 25 m level is in the order of 57 kPa compared with the calculated applied wall loads in the order of 60 kPa and 84 kPa for the initial and flow condition respectively.

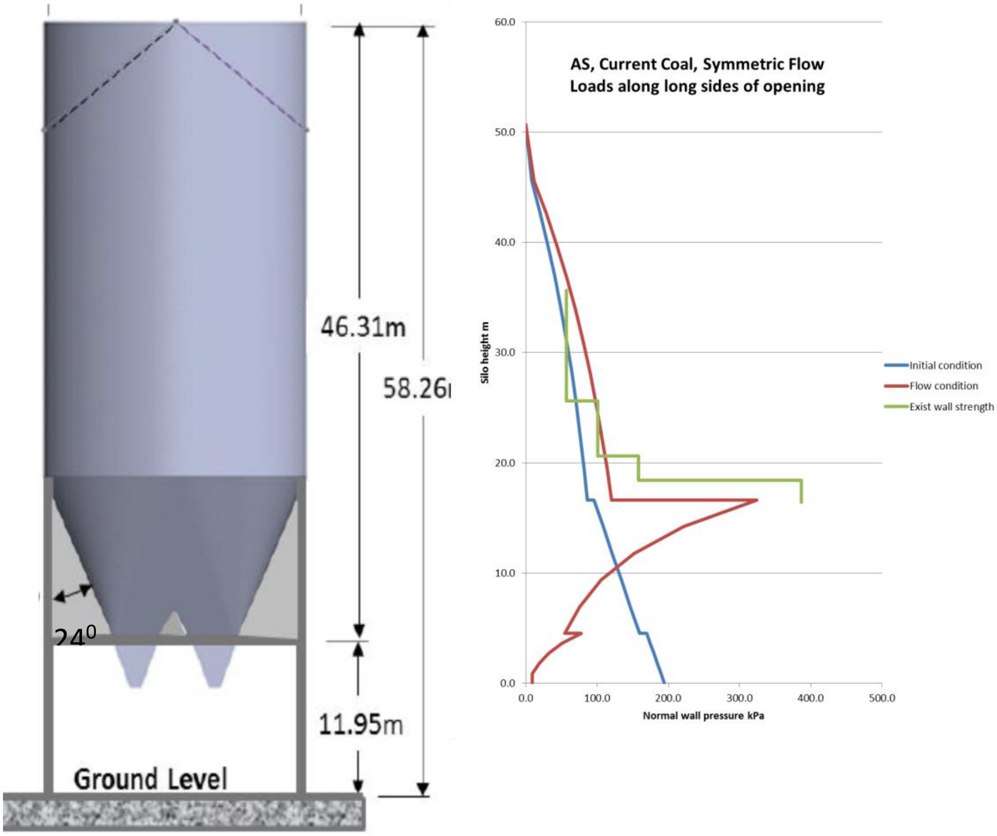


Figure 22. Wall load for the current coal based on the AS3774-1996 – excluding eccentricity.

Figure 22 shows that the amount of reinforcement between elevation 21 m and 35 m is not sufficient when checked with current coal and the AS 3774-1996. The wall strength at the 25 m level is in the order of 101 kPa compared with the calculated applied initial wall loads in the order of 107 kPa.

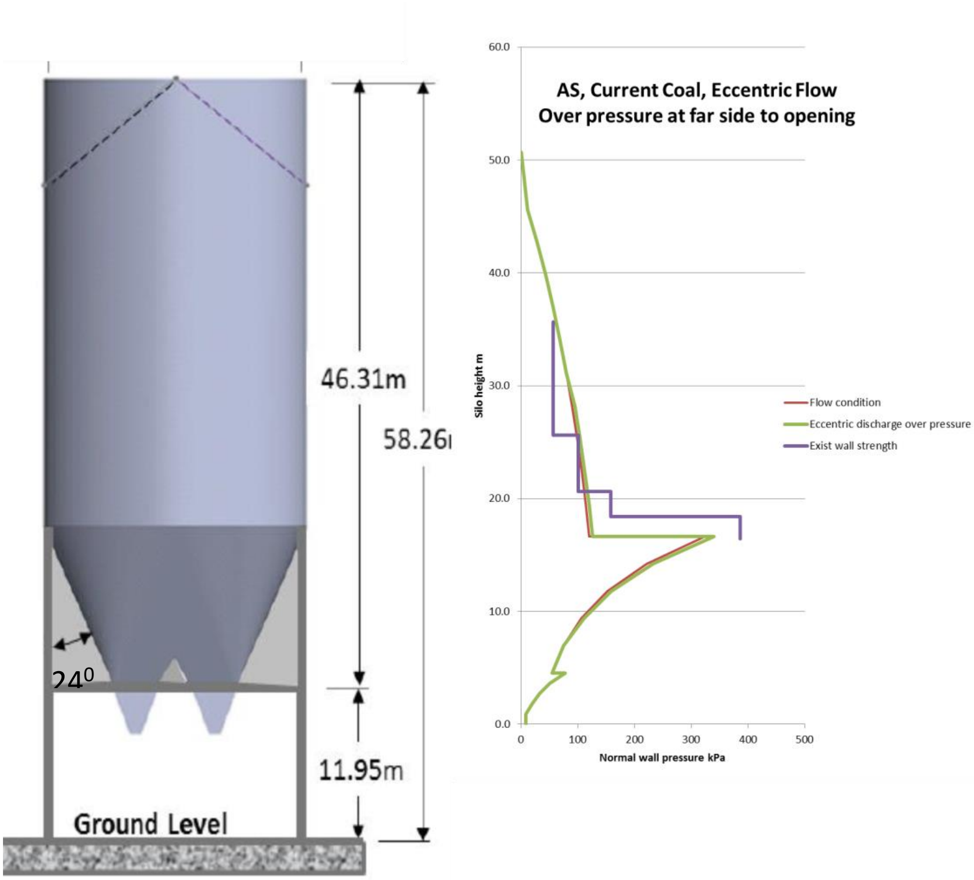


Figure 23. Wall load for the current coal based on the AS 3774-1996 – eccentricity included.

Figure 23 shows that the amount of reinforcement between elevation 21 m and 35 m is not sufficient when checked with current coal and the AS 3774-1996 including the eccentricity. The wall strength at the 25 m level is in the order of 101 kPa compared with the calculated applied wall overpressure load in the order of 120 kPa.

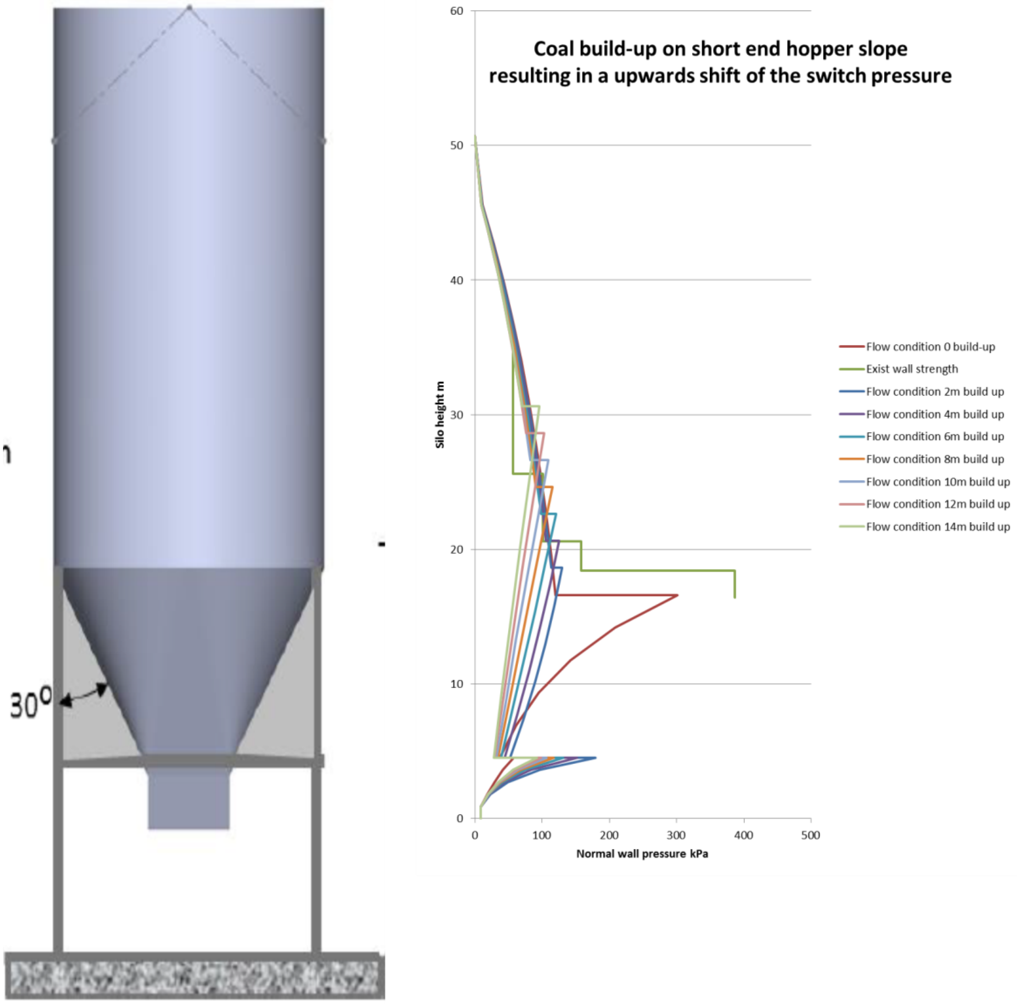


Figure 24. Switch pressure along build-up development based on the AS 3774-1996.

Figure 24 shows the development of the build-up together with the shift of the switch pressure checked with current coal and the AS 3774-1996 including the eccentricity. In this case the calculated applied wall pressure exceeds the wall strength ability for the silo vertical wall for the height range between approximately 2 m and 12 m above the hopper to vertical wall intersection.

Figure 25 presents a comparison of the calculated wall loads.

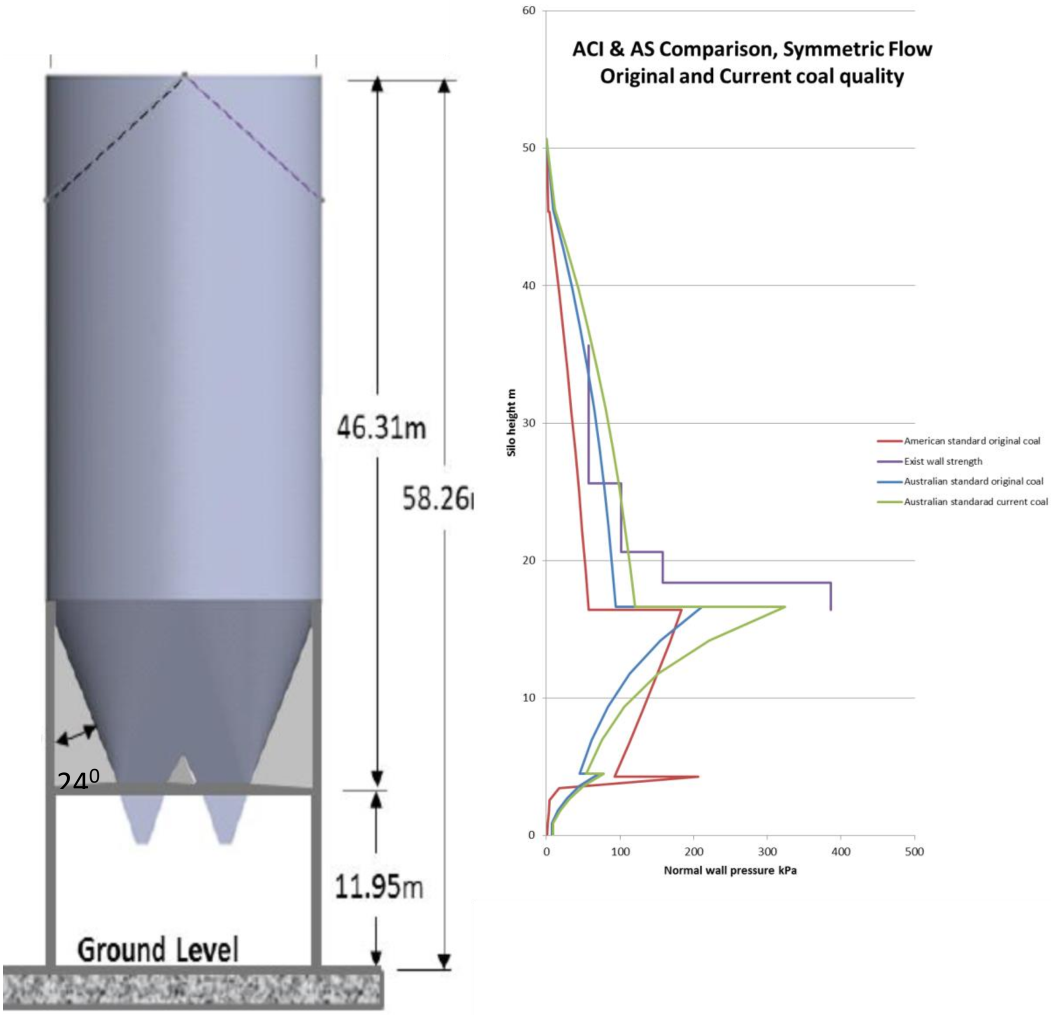


Figure 25. Comparison of the symmetric loads for the AS 3774-1996 and the ACI 313-91.

CONCLUSIONS ON THE ORIGINAL DESIGN

The calculation for the original coal indicates that the silo was correctly designed at that time and it fulfils the requirement of the adopted ACI 313-91. It also clearly shows that the reinforcement was not overstressed, but indeed was more than it was required to be. It is also interesting to notice that the calculations adopting the current coal and the ACI 3213-91 indicate that the reinforcement is still within limits.

The main deficiency of the ACI 313-91 when compared with the more modern standard is that it considers symmetric or concentric load condition only and the K factor *(the ratio of the horizontal to the vertical load*) is calculated with the Rankine formula. The modern standards include conditions for the eccentric loads and the K factor is calculated either with the pressure at rest or with a different algorithm giving much higher values than the ACI 313-91 standard when it is introduced in Jansen's algorithm.

THE CAUSE OF THE SILO FAILURE

It is not possible to pinpoint one single reason for the silo failure. The silo failure occurred for a number of reasons acting over an extended period of operating time, such as:

- The inadequate amount of reinforcement resulting from an inadequate standard used for the original design.
- The continuous eccentric discharging condition which created additional loading on the wall also causing vertical and horizontal bending moment.
- The presence of coal build-up over time which caused a continuous upward shift of the switch pressure during its progression, thus causing additional forces and moments.
- The lack of distribution of the switch pressure to the cylinder wall.
- It must also be noted that due to the different hopper half angles the switch pressure around the silo is not constant, thus creating vertical bending moments.

Inadequate Amount of Reinforcement

- From the Australian standard the reinforcement provided in the cylinder wall of the silo is inadequate in the most critical area for the original coal and more so for the current coal properties when checked at Ultimate Limit State (ULS). The stress of the reinforcement in the critical area at Serviceability Limit State (SLS) is very close to the yield stress for symmetric wall loads, but it is exceeded during eccentric loads conditions. This was also exacerbated by the presence of the coal build-up.

Coal Discharging onto Feeders

- In accordance with past operating procedures, the Majuba silo was mainly discharging on one feeder, thus causing a sustained eccentric load pressure on the wall. This modus operandi has now been changed on all stations and both feeders are operating simultaneously, thus discharging symmetrically.

Coal Build-Up

- The build-up of coal on the short side hoppers applied during the life of the silo. This build-up, solid as a rock, contributed and intensified the effect of the eccentric loading on the wall creating a complex load system.

Therefore it is the opinion of the authors that the switch pressure followed the formation of the build-up of coal on the shallow end of the hoppers imposed high additional non-symmetrical pressure in the cylinder. This pressure together with horizontal pressure on the sides of the wall facing the long side of the opening was likely to have caused high hoop stresses together with high vertical and horizontal moments. Clearly, the amount of reinforcement provided was not, in the long run, capable of sustaining these additional loads.

Standards

Based on the above findings it can be concluded as follows:

- The original design of the silos was carried out in accordance with the state-of-the-art standard at that time adopting the American Standard ACI 313-91 and the coal properties in accordance with the Jenike and Johanson (1988) report and meets the requirement of the standard. Furthermore, when checked with the current coal properties, it still just meets the requirements of the ACI 313-91.
- Calculations carried out for the current coal properties with the Australian Standard AS 3774-1996 with a minimum value K=0.35, the reinforcement does not meet the requirements of the standard and the reinforcement is overstressed by the complex eccentric wall load condition which over a long period of time and by the cyclic loading and unloading fatigued the reinforcement to failure.

Therefore it can be stated that:

The non-symmetrical and excessive coal build-up, together with the eccentric discharge and the different coal properties, resulted in the situation where the inadequate reinforcement had been over-stressed over a period of time. Cyclic loadings were partially responsible for this, not only by membrane stresses (hoop stresses) but also by high vertical and horizontal moments, thus causing cyclic stresses in the reinforcement above the yield stress leading to fatigue and eventually steel rupture.

These findings regarding the mechanism of failure of silo 20 were confirmed by the independent investigation conducted by the University of the Witwatersrand (Wits)[10]. Wits, via their international link, TUNRA Bulk Solids, assigned the task of reviewing the silo wall loads prediction to Professor A. Roberts from the University of Newcastle, Australia as well as to Jenike and Johansen Inc[11] from Massachusetts, USA for the design assessment of the silo structure.

THE INVESTIGATION FINDING BY PROFESSOR A. ROBERTS

The eccentric discharge from the silo by means of operating only one of the two feeders generates high eccentric wall loads that in turn results in complex bending stresses along the circumference of the silo at various levels on the silo vertical wall. This would cause the vertical crack development in the walls.

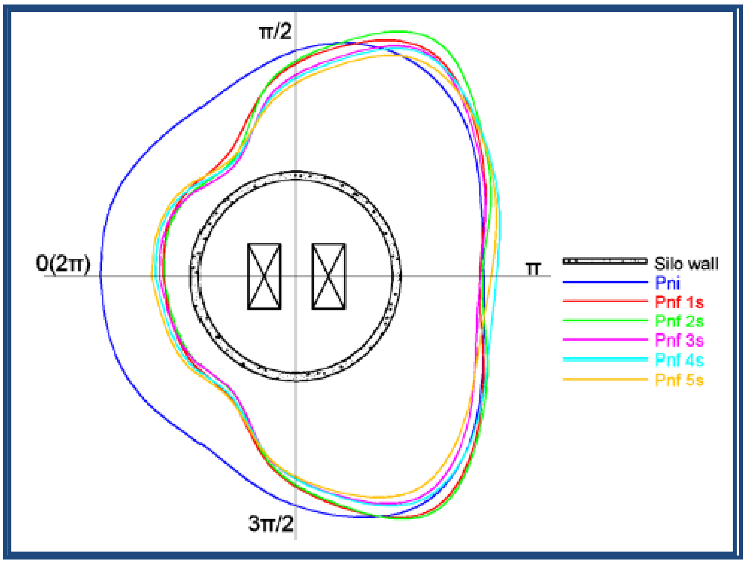


Figure 26. Wall load above the transition for eccentric discharge while filling coal at the same time.

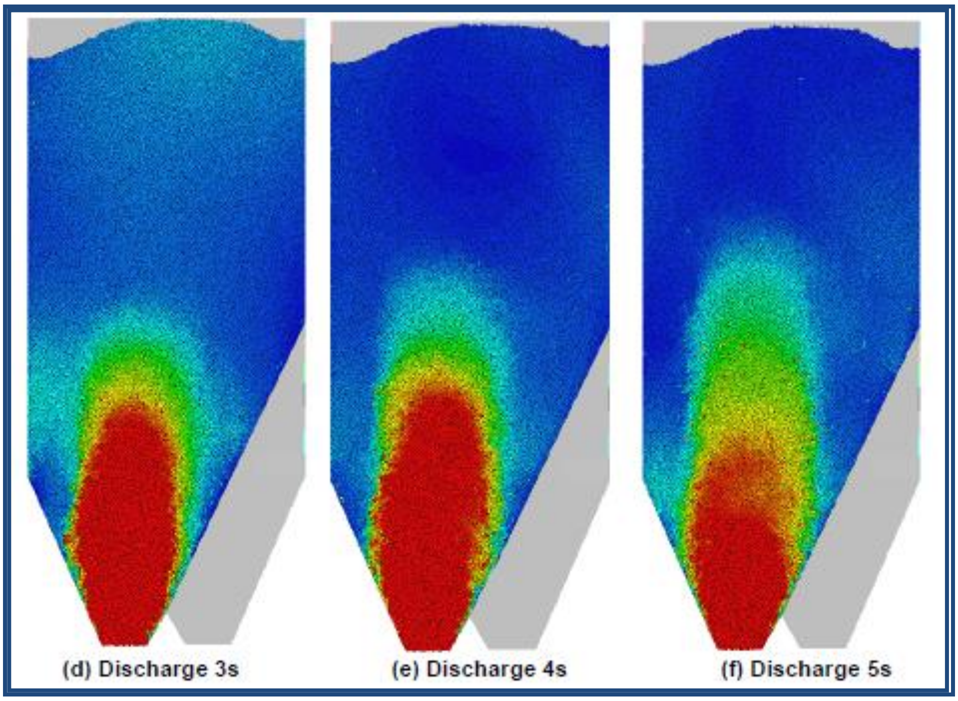


Figure 27. FEM (finite element modelling) presentation of simultaneous filling and discharge under eccentric condition.

The FEM confirms that as a result of the presence of coal build-ups on the hopper short ends, due to the hopper larger half angle, the development of a switch pressure at the convergence of the coal build-up and the vertical wall where the active pressure in the coal changes to passive pressure.

The complex stresses in the wall caused by these loads result in vertical and the horizontal bending moment for which the silo was not designed, causing vertical and horizontal cracks in the wall.

Figure 28 below was extracted from Professor Robert's report and shows the very complex loadings applied to the silo walls due to the presence of coal build-up.

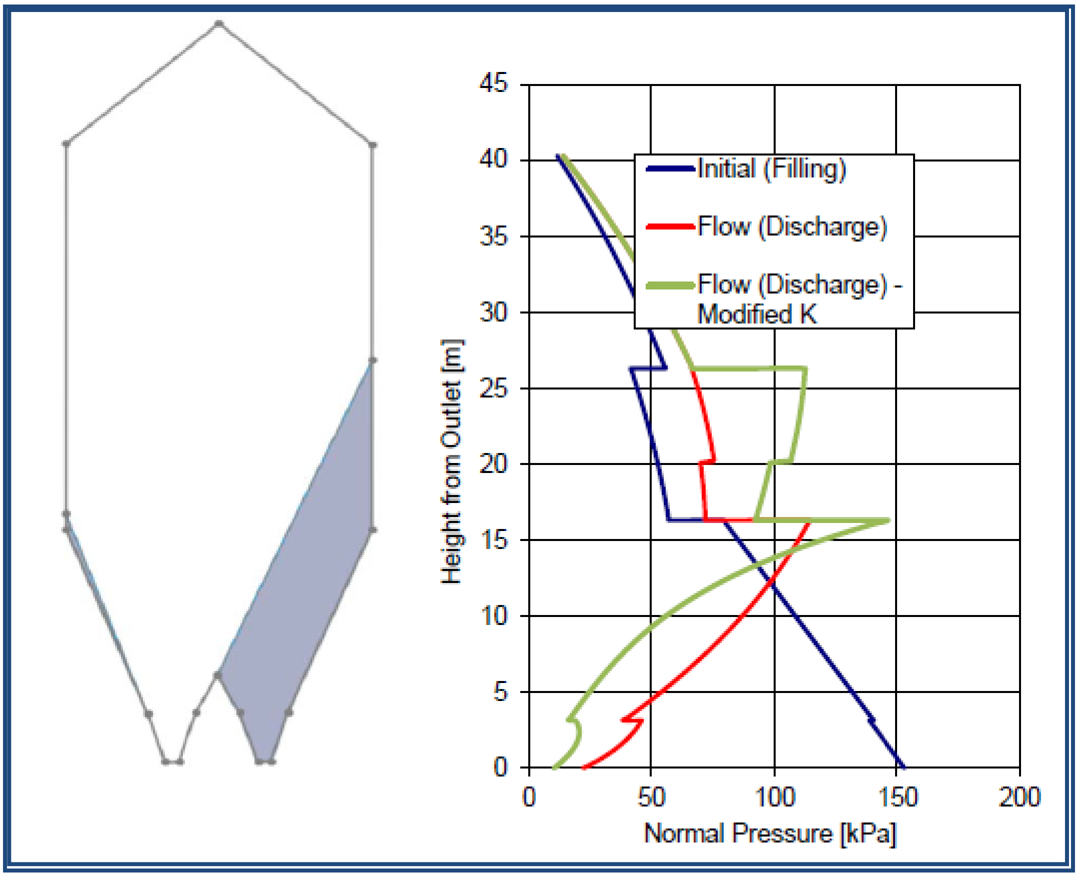


Figure 28. As a result of the stagnant coal in the silo, a switch pressure develops at the convergence point of the flow channel to the vertical wall.

Professor Roberts concluded that the silo experienced a very high eccentric pressure load caused by the presence of the build-up and the modus operandi of the silo. These high eccentric pressure loads contributed to the failure of the silo.

THE INVESTIGATION FINDINGS BY JENIKE AND JOHANSON INC.

Jenike and Johanson performed a structural assessment of the silo. They performed this assessment on the basis of the modern European Standard EN 1991-4:2006. Symmetric as well as eccentric load conditions were evaluated. For this analysis the current coal flow properties were used.

The conclusion of this specialist report as quoted is that:

- 'Assuming eccentric loading as mentioned in Load Case 1 of Section 5 (solids-induced loads), plus roof loads, our FEM shows that steel horizontal reinforcement in the cylinder in silo 20 are not capable of carrying tension and bending due to non-uniform pressures.'
- 'Assuming concentric loading as mentioned in Load Case 3 of Section 5, plus roof loads, our FEM shows that steel horizontal reinforcement in the cylinder in silo 20 are not capable of carrying tension due to uniform pressure with patch load.'

Based on analyses, it is concluded that the cylinder wall of silo 20 was in a compromised condition to carry the combined solids-induced loads per BS EN 1991-4:2006 and roof loads.

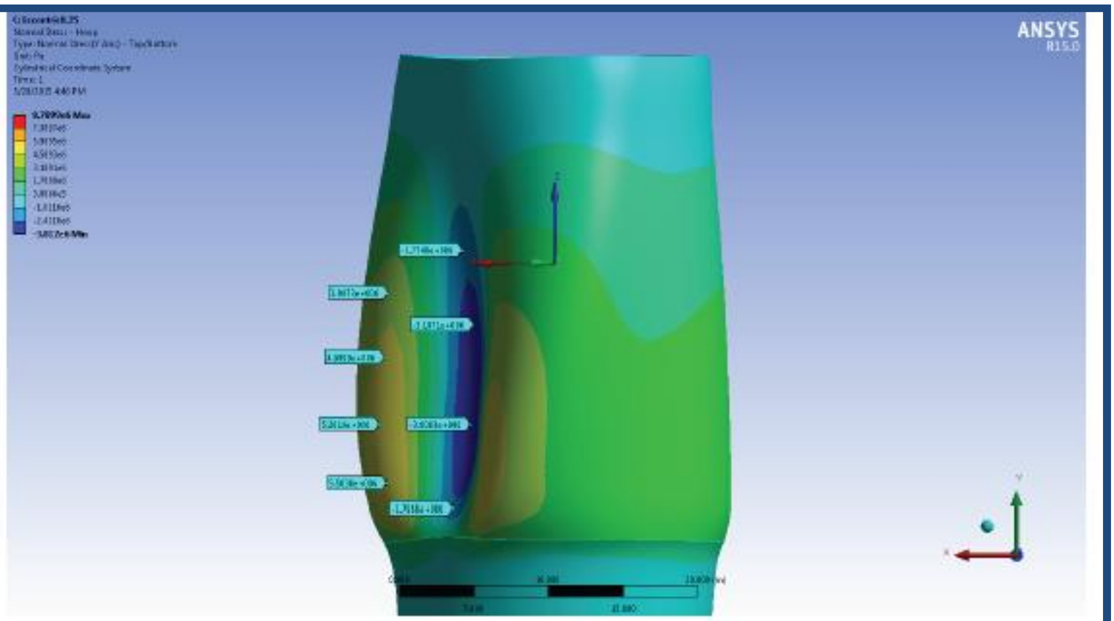


Figure H: Normal Stresses in circumferential direction due to eccentric flow, outside ($r_c = 0.25\,r$)

Figure 29. Extract from the Jenike and Johanson investigation.

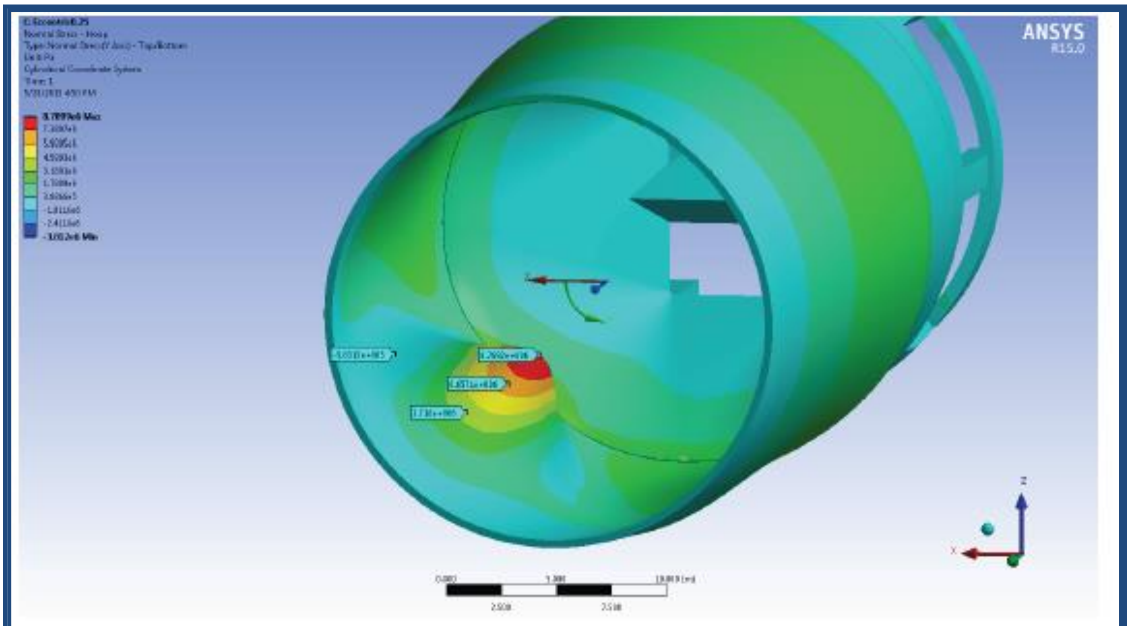


Figure I: Normal Stresses in circumferential direction due to eccentric flow, inside ($r_c = 0.25\ r$)

Figure 30. Extract from the Jenike and Johanson investigation.

Figures 29 and 30 show the normal stress distribution in the circumferential direction (hoop stress) for eccentric load Case 1 for a flow channel radius r_c = 0.25 r. Stress values are shown along the height of the cylinder in the flow channel (blue colour region along the height) and at the edges of flow channel (yellow colour region along the height). For example, in the flow channel (circumference width about 3.5 m) at approximately 8 m from the bottom of the cylinder, the circumferential stress on the outside face is -3.8083 MPa (compression), and at the same elevation the circumferential stress on the inside face is 8.7692 MPa (tension). From this the uniform tension stress due to hoop tension is ft = 2.4805 MPa and the bending stress is fb = 6.2888 MPa.

From the above bending stress, the calculated moment is 218.27 kN-m/m widths, which is greater than the capacity 176.483 kN-m/m width

Similarly, the calculated tension of 1475.9 kN is greater than the tension capacity of 1268.4 kN at an elevation of approximately 8 m from the bottom of the cylinder. The tension capacity of the horizontal reinforcement in the flow channel, the edge of flow channel, and the static zone is less than the actual tension due to applied loads; therefore, it does not meet the requirement of BS EN 1991-4:2006.

The calculated maximum vertical compression stress of 6.4 MPa at the bottom of the cylinder (Figure 31) is well below the allowable compressive stress (11.547 MPa); therefore, it meets the requirement of BS EN 1991-4:2006. Given these results, one can conclude that compression is not the governing case in this eccentric load analysis.

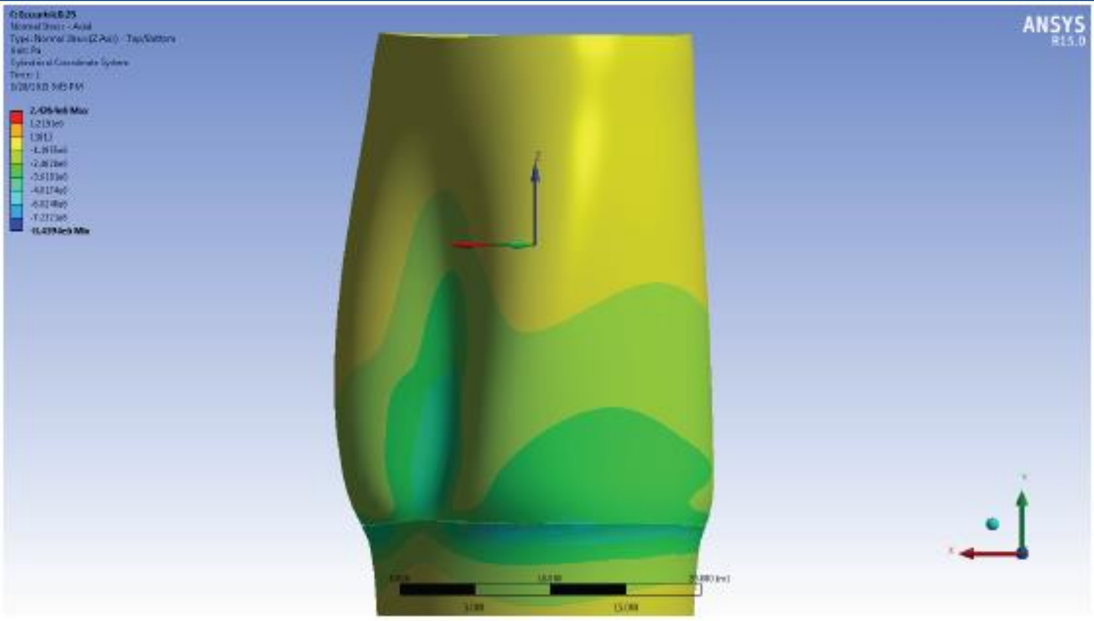


Figure J: Normal Stresses in axial (vertical) direction due to eccentric flow, outside ($r_c = 0.25\,r$)

Figure 31. Extract from the Jenike and Johanson investigation.

THE COMPARISON AND OPINIONS ON THE WALL LOAD DESIGN STANDARDS APPLIED IN THE DESIGN REVIEW OF THE FAILED MAJUBA SILO 20

The Australian Standard AS3774-1990, which first appeared in 1990, broke new ground in the level of detail and comprehensive coverage of the subject of bin and silo loads. It included a methodology for dealing with non-symmetrical loadings due to discharge from eccentric openings. A revised version, AS3774-1996 was issued and remains as a valid standard for bin and silo load determination and analysis.

More recently, the Eurocode EN 1991-4 has appeared and is now widely accepted in view of its extensive, very detailed coverage of this complex subject of silo and bin loads. It does, however, contain a level of empiricism in the design procedures and equations presented. In effect, this may be regarded as a way of building in suitable factors of safety to ensure safe design and operation.

The Eurocode, to some extent, is not very user friendly. It contains a level of empiricism in the design methodologies and equations that are presented. For example, there is often a mismatch between the angles of internal friction recommended that are lower than the angles determined by flow property tests, and, in some cases, lower than the angle of repose, the physical significance of which is difficult to understand.

One particular area of possible confusion centres around the selection of the so-called pressure ratio K values which express the normal pressure or stress acting on the silo wall to the average vertical pressure or stress over a horizontal cross-sectional layer of bulk material. Different K values will apply to the cylinder and to the hopper. Also, the K values will vary in accordance with the stress field set up within the contained material, the stress fields being ‘active’ for the initial filling case and 'passive' for the flow case. By way of illustration, for coal, Table E1 of EN 1991-4 lists the mean internal friction angle as 31° and angle of repose 36°, whereas the flow properties of the coal shows the effective angle of internal friction reaching a steady state value of 52°. For most coals, the asymptotic value of the effective angle of internal friction is usually around 50°. Table E1 lists the mean value K_m= 0.52, while equation (4.7) of EN 1991-4 gives 0.53, which compares quite well. On the other hand, AS3774-1996 specifies that K should not be less than 0.35. It needs to be noted that recommendations and empiricism have in-built safety factors to ensure safe load to handle funnel-flow.

For the calculation of symmetric wall loads (Figure 32) the Eurocode yields greater wall loads than the Australian standard. The reason for this is that the Eurocode presents a more conservative K value than the Australian code.

In the case of the eccentric discharge with the coal build-up as presented in Figure 33, the modified Australian code presents the greater wall loads.

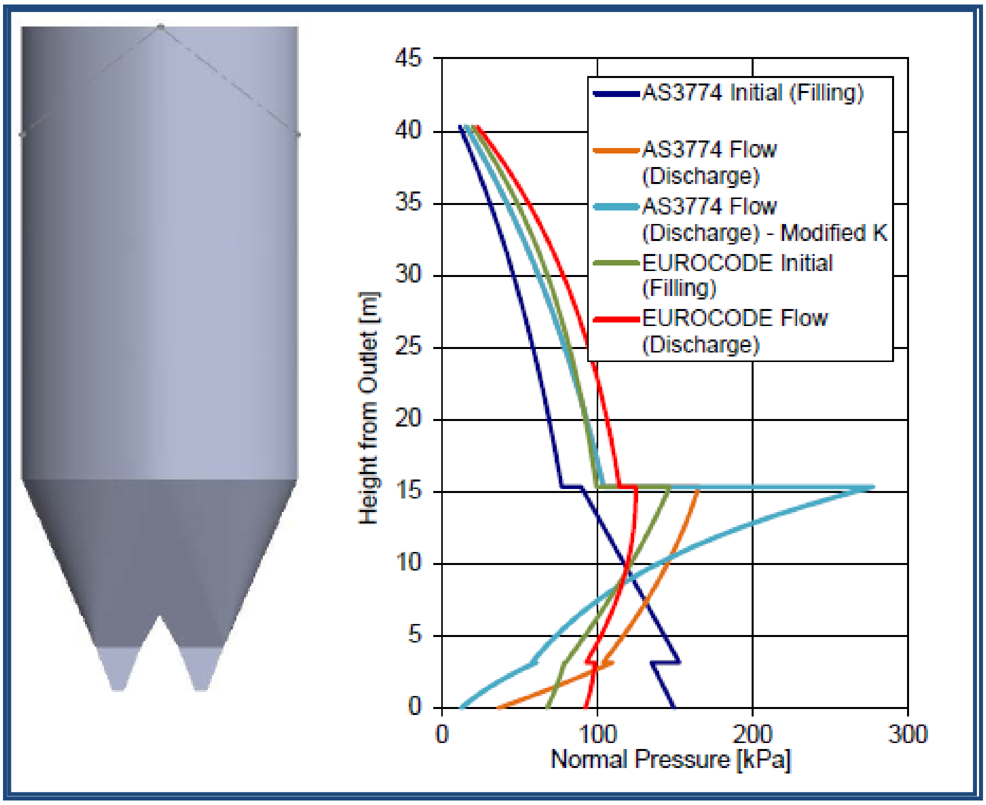


Figure 32. Comparison of the derived wall loads along the long side of the hopper opening for symmetric flow condition.

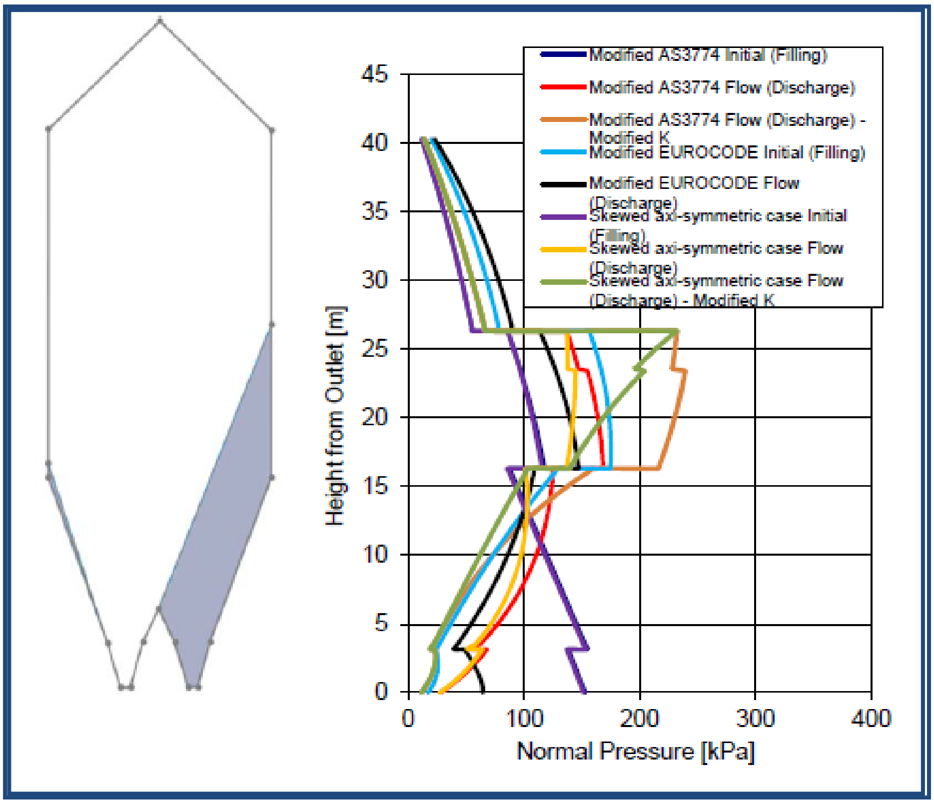


Figure 33. Comparison of the derived wall loads along the long side of the hopper opening for eccentric flow condition at the far side to the opening under operation.

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