Research into Stockpile Performance.

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Research at Newcastle University's Centre for Bulk Solids and Particulate Technologies is continuing on many areas of materials handling. One such area is the behavior of bulk material stockpiles. The accurate prediction of reclaim capacity from a multi reclaim channel stockpile is geometrically complex which lends itself well to CAD methods. Solids based modeling systems can deal with complex geometry and readily compute the quantity of material remaining in a stockpile after draw down has been completed. The geometry of a stockpile reclaim channel is easy to create in a generic CAD form. However the bulk material influences on the basic shape requires further research. Results are presented from a computer model displaying fundamental relationships between material strength and reclaim performance in terms of hopper size and separation for two and 3 hopper systems.

Coupled to the accurate prediction of reclaim capacity is the stress distribution within a stockpile. There have been several papers published in recent years predicting a pressure dip at the center of a conical stockpile resulting in what has been termed the 'M' distribution. Most of the data available is based upon small scale testing rigs with stockpiles up to heights of six hundred millimeters. Many computer simulations have predicted this dip but with limited particle numbers that correspond to a stockpile of, at most, several hundred millimeters in height. The impact of a pressure dip will be discussed in terms of potential reclaim capacity.

INTRODUCTION

The use of gravity reclaim stockpiles in the mining industry is very widespread, however the mechanics of stockpile systems are often underestimated at the design stage. This underestimation can result in less than optimal reclaim performance. Drawings are often produced which show a single angle reclaim channel formed from the top of the discharge hopper through the pile. Although this practice may ease the computation of reclaim capacity for a simple situation, the geometric complexities that are intrinsic with multiple outlet stockpiles negates the simplifications gained with a single angle reclaim channel. The negative side of the single angle reclaim channel is a high probability of overestimating the actual reclaim capacity which can lead to an undersized stockpile. The use of a multi-angle reclaim channel offers a higher degree of confidence in the predicted reclaim capacity without requiring significantly more computer modeling effort. A method of obtaining the reclaim capacity by hand calculation for a two feeder, multi angle reclaim channel stockpile has been presented by Roberts[1], however the expansion to a three feeder situation becomes much more difficult by manual methods. The correct use, of a suitable solids modelling package, can reduce the time for volume calculations to minutes once the model has been constructed. The speed at which different situations can be analysed using computer methods can enable a large number of variations to be tested, and thus the piles reclaim geometry optimised. This optimisation process has been done for a number of material strengths, hopper sizes and stockpile heights, which has produced results that indicate that some simple scaling processes can be used when modifying a stockpile that has been optimised for one set of conditions. These scaling methods and accompanying starting points for optimisation will be discussed later in this paper. This paper also presents a simple graphical means for the determination of the rathole transition point, which is the starting point for all optimisation and modelling methods.

A comparison between a multi angle reclaim channel and a single angle reclaim channel is also presented. It is shown that the results from a single reclaim angle approach can significantly overestimate the reclaim capacity of a stockpile.

Also presented in this paper is an overview of the stress distribution within a stockpile. There have been a growing number of papers looking at the stresses under a conical pile of solids from a Discrete Element Modelling (DEM) view point. It was shown experimentally by Smit and Novasted[2] that a pressure dip at the center of a conical pile occurred. This data was subsequently used by several authors in the production of DEM papers looking at the stress distribution under a conical pipe. Authors such as Wittmer et al[3][4] and Liffman et al have demonstrated that suitable mathematical models can be constructed to predict the experimentally measured pressure dip under a conical pile of solids. If this pressure reduction does occur in full size stockpiles, then the current methods of optimisation need to be reviewed as the results from the current optimisation methods may be incorrect. Other areas in which the effect of a pressure dip would have significant influences include the tunnel design and feeder load predictions.

The results of a model stockpile constructed at Tunra Bulk Solids' laboratory, indicate that for small stockpiles that the pressure dip does exist. However, unlike the Smit and Novasted data in which the normalised pressure peak remains fixed at a given radius ratio, our preliminary data indicates that the pressure peak moves toward the center as the pile height increases. Extrapolating from our data it would seem feasible that once the pile height increased above approximately 2 meters in height, that the pressure distribution assumes a hydrostatic type profile. This may be as a result of larger scale internal shearing redistributing the stresses in the pile or from other mechanics not currently apparent. At this stage the only clear outcome from our scale modeling is the need for more testing on larger models to confirm or deny the size dependence of the pressure distribution.

MULTI ANGLE RECLAIM CHANNEL, INDEPENDENT HOPPER MODELING

The following pages are intended to assist the reader in understanding the methods currently used in the determination of stockpile geometry which is generally based upon the Jenike theory[5][6].

The formation of a reclaim channel can be thought of consisting of two different sections. The first section tends to be very steep, often in the 2°-10° range (from the vertical) and is designated the rathole. The second section of the reclaim channel has as a typical free surface angle of δ (effective angle of internal friction). This area is designated as the crater. Figure 1 shows a typical cross section through a stockpile with the above parameters indicated.

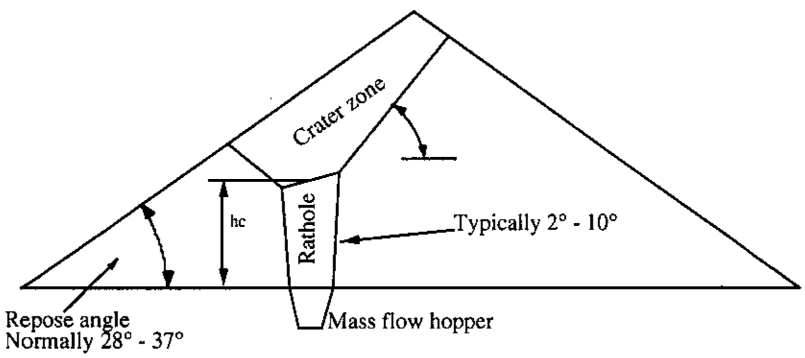

Figure 1 - Stockpile Nomenclature

Rathole Geometry Calculations

The determination of the height of a rathole is based upon the information gained through the normal Jenike bulk strength testing program. Generally these results are used to produce a critical piping diameter graph. This graph is obtained by the application of the following formula.

$$Df = \frac{G(\phi t)\overline{\sigma}_1}{\gamma} \qquad \text{Eqn (1)}$$

Where: Df = Critical rathole diameter

γ = Specific weight of the bulk material

$\overline{\sigma}_1 = f(\sigma_1)$

Figure 2, shown below, presents the critical piping diameter information for two materials. The first is a relatively free flowing material (Beneficiated bauxite) verses a difficult material (ROM Nickel Ore). In general, the lower the curve the more reclaim capacity a stockpile will have with all other conditions being equal. The upper curve of Figure 2 is bordering on being unsuited to a gravity reclaim stockpile situation. However, this is more an economic decision as to achieve a moderate reclaim capacity, say

12%, then three large feeders will be required. These feeders may be in the region of 7m x 2m for a 35 metre high stockpile. The lower strength material may achieve a moderate reclaim, say 25%, with 3 much smaller feeders.

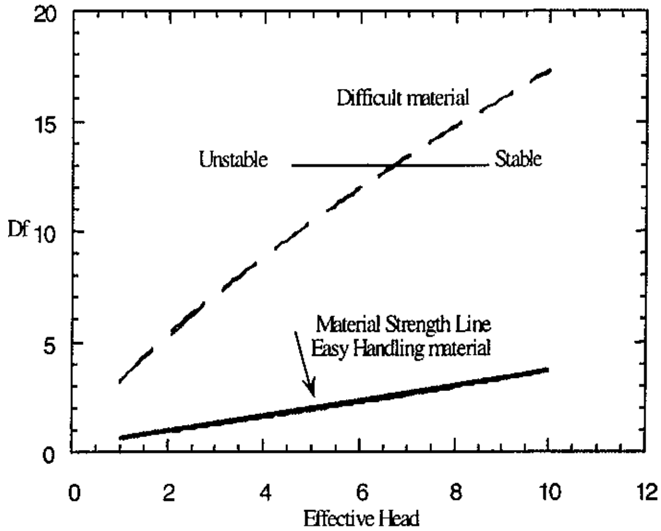

Figure 2 - Critical piping diameter for two materials, Beneficiated Bauxite (lower curve) and ROM Nickel ore (upper curve).

In Figure 2, the area above the material strength line represents the unstable area for the rathole, the area below the material strength line represents a stable area. This is best illustrated with the horizontal line shown on the graph, crossing over the difficult material. It can be seen from figure 2 that as the amount of head increases on the material, it's ability to hold a rathole of given size increases and thus a rathole of given size becomes more stable. The effective head of material can be thought of as the effective consolidating stress the material experiences within the stockpile. In general, the value of effective stress used is the Rankine pressure head, which is hydrostatic pressure multiplied by the cosine of the repose angle, which is normally equates to approximately eighty percent of the hydrostatic value.

In order to determine the collapse point of any given rathole the critical piping diameter graph is used, this graph is derived from equation 1. The critical piping diameter graph is an indication of the materials bulk strength which forms one constraint. The second constraint is imposed by the geometry of the rathole itself. Providing that the reclaim hopper is correctly designed then the rathole will form from the top of the hopper and expand upwards at a small angle (typically 2 to 5 degrees from the vertical). If these two constraints are plotted on the same graph an intersection point can be determined which indicates the collapse point of the material. As an example, take a 22 metre high stockpile using a single, central feeder with a stockpile repose angle of 35°. The effective head of material above the feeder can be calculated from [eq 2] shown below. The computed value of effective head (18m) is plotted onto the critical piping graph as a vertical line, see Figure 3. The hopper diagonal dimension is used as a starting point for a rathole geometric constraint line. The geometric constraint line is simply the diameter of a cone expanding at a given angle [eq 3]. As discussed above the intersection point between the material constraint and the geometric constraint indicates the collapse point of the rathole.

$$He = H * \cos(Ør) \qquad \text{(eq 2)}$$

$$Drg = Do + 2 * \tan(Øex) \qquad \text{(eq 3)}$$

Where He = the effective head of material

Ør is the repose angle of the stockpile

Drg is the geometric rathole diameter

Do is the hopper diagonal dimension

Øex is the rathole expansion angle.

In summary the process for predicting rathole heights is:-

- Determine the amount of material above the feeder in question

- Plot a vertical line at the equivalent head position for the value determined above.
- After selecting a suitable rathole expansion angle, plot the 'geometric' rathole constraint on the graph. This is determined from the expansion angle and simple trigonometric relations. (eq 3)
- The intersection point between the material and geometric constraints provides the collapse point of the rathole in question.

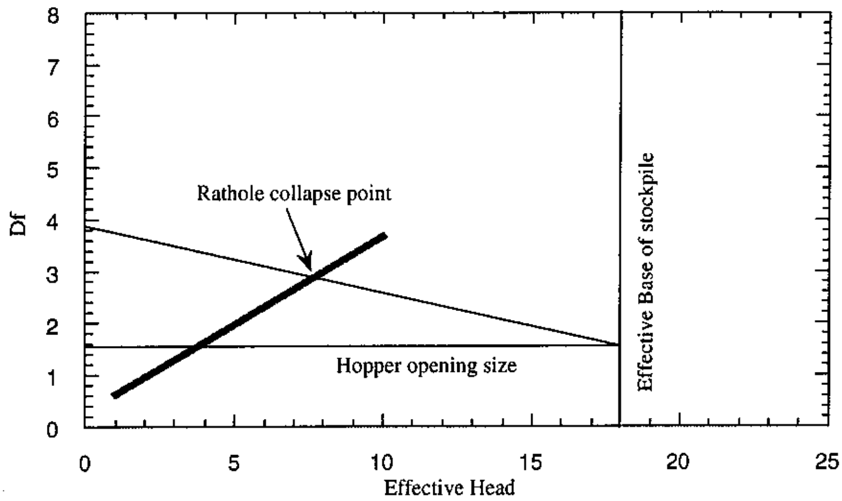

Figure 3. Typical graph showing the intersection point between the geometric rathole constraint and the material strength lines.

It should be obvious from Figure 3 that an increase in bulk strength or stockpile height will increase the height of the rathole. In contrast, an increase in the opening size of the feed hopper will lower the height of the rathole.

The method used in constructing figure 3 can be applied either graphically, or numerically by using curve fits to the critical piping diameter graph. Care must be used with numerical methods to ensure the validity of any extrapolation. Extrapolation is often required as the maximum pressure that can be obtained with the standard Jenike shear testing apparatus is approximately 150 kPa. It should be noted that a pressure of 150 kPa with a bulk density of 2 t/m^3 occurs at a depth of only 7.5 metres.

OPTIMISATION OF DRAW DOWN CAPACITY USING COMPUTER MODELLING

The results presented here, are of modeling work conducted using the flow properties of Beneficiated Bauxite and a ROM Nickel ore. The results are presented to indicate the influence of three variables, material strength, stockpile height and hopper size on the reclaim potential and what, if any, functional parameters exist for optimization of reclaim potential.

The CAD package used for the modeling work was Pro Engineer. This package allows for a solids model to be constructed and mathematical relationships between components to be set. This allows an alteration in, for example, the height of the stockpile to ripple through the other items of the model and allow for rapid analysis of a particular configuration.

A section of a typical Pro-Engineer relations file for a two feeder model is presented as table 1.

Table 1. Typical relations file

RELATION	PARAMETER	NEW VALUE
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/*** Relations for A-STOCKPILE:		
expansion=D15	expansion	8.000000e+0
opening=D13	opening	7.000000e+00
crater=D16	crater	5.500000e+01
repose=D2	repose	4.000000e+01
hm=((D1/tan(repose))-1.2*opening)* tan(repose)	hm	1.095156e+01
solve		
d=2.8*h^0.73569		
d=opening+2*tan(expansion)*(hm-h)		
for d,h		
	D	8.754619e+00
	H	4.709181e+00
D14=(hm-h)		
Symbolic constant	X-refs	Current value
EXPANSION	Local	8.000000e+00
OPENING	Local	7.000000e+00
CRATER	Local	5.500000e+01
HM	Local	1.095156e+01
D	Local	8.754619e+00
H	Local	4.709181e+00
K	Local	1.000000e+00
REPOSE	Local	4.000000e+01

From Table 1 it can be seen that there is the ability with the CAD software to evaluate simultaneous equations, these are shown in bold italics for clarity. This allows some simplification of the pre-CAD computation process. It should be noted that the model this file was chosen from was a symmetric, two feeder, conical stockpile. The second feeder obtains the rathole geometry from the first feeder and as such there is no need to repeat the computations for the second rathole. If the feeders were not symmetrical, or a different size, then a second evaluation section would be required.

Note that the variables labelled D(x) are default computer model parameters related to the solids model.

RESULTS OF COMPUTER MODELING

The first product, beneficiated bauxite, consists of basically spherical particles greater than 3 mm in diameter and less then 10 mm diameter. The beneficiation process removes a large amount of the clay materials that otherwise render this product extremely difficult to handle.

The second material chosen was a ROM Nickel ore with a top size of 250 mm. Other than possessing a high strength there was nothing special about this material.

For the purposes of the analysis three hopper sizes were chosen, these had diagonal dimensions of 2, 4 and 8 metres. Table 2 gives the length and width of the feeders as used which maintained an aspect ratio of 3:1

Table 2. Feeder geometry used in the computer modeling.

Diagonal (m)	Length (m)	Width (m)
2	1.9	0.65
4	3.8	1.25
8	7.6	2.5

Figures 4 through 9 show the results of this investigation into the effects on reclaim capacity of hopper separation, hopper size and stockpile height. It can be seen that there is a point at which reclaim is maximised. However an economic decisions regarding reclaim tunnel length, hopper size, and the number of hoppers verses the extra reclaim potential must be considered.

The normalising factors used using in presenting the data are as follows:-

Normalised separation distance = Outer hopper separation distance / stockpile radius.

Normalised reclaim potential - % reclaim at a given separation distance and stockpile height / maximum % reclaim at given height and separation.

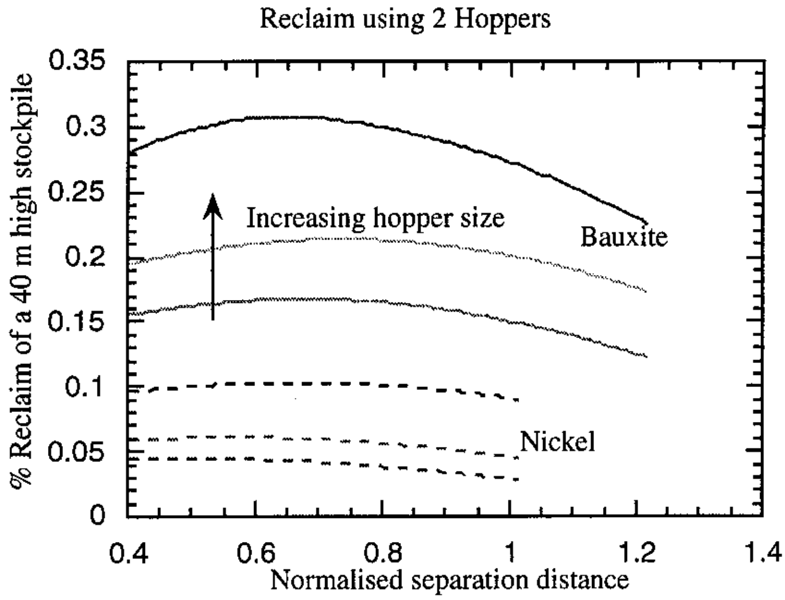

Figure 4 Reclaim potential verses opening size with two feeders.

It can be seen from Figure 4, as expected, that an increase in hopper size results in an increase in the reclaim potential. However, an increase in hopper size seems to have little influence on the optimal hopper separation distance.

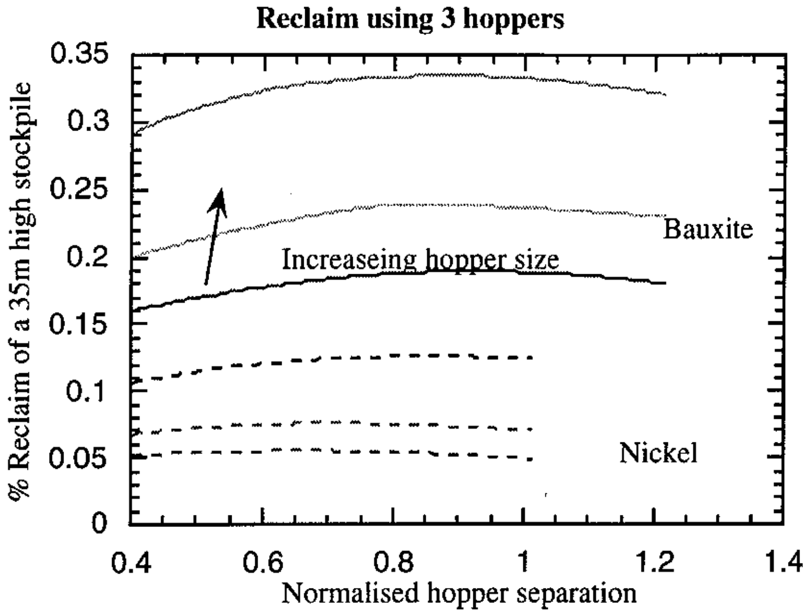

Figure 5. Reclaim potential verses opening size with three feeders.

Figure 5 shows the increase in the reclaim potential as a function of hopper size for a 3 hopper system. In a way similar to Figure 4, the optimal separation of the hoppers is not significantly affected by hopper size. The optimal separation distance is larger for a three hopper system compared to a two hopper system.

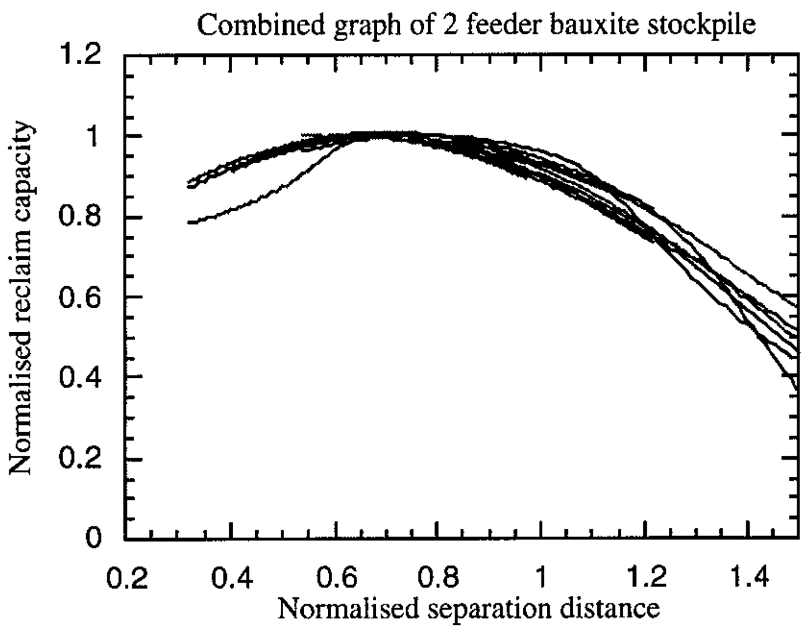

Figure 6. Combined plot of normalised reclaim verses normalized hopper separation for Bauxite

The interpretation of Figure 6 highlights some interesting points. Figure 6 consists of twelve data sets of a 2 feeder system handling bauxite.

The data sets are divided into three sets of data for each opening size. What is most relevant is that the peak in reclaim capacity is coincident at the same separation ratio. From figure 8 it appears that for a two feeder system the optimal separation distance in independent of hopper size. It also indicates that the optimal hopper separation can be approximated by a linear function of stockpile height.

The same trend was seen with the Nickel ore.

DEPENDANT FLOW CHANNELS

In the preceding section each hopper was assumed to act independently, and, in this situation a drop in the reclaim capacity was noted if the hopper separation was reduced below 0.6 normalised separation for a two feeder case. A normalised value of 0.6 on a 30 metre stockpile represents a hopper separation of some 25 metres. If the hopper separation is reduced below the 0.6 value, then the reclaim capacity will continue to drop until a point of dependence occurs. If two independent ratholes intersect at some distance below the natural transition point, a new transition point will be formed. For most material the intersection of two ratholes will cause an immediate transition to the crater section. This should however be confirmed by using the critical piping diameter graph. Figure 7 indicates the reclaim capacity of a two feeder, thirty-meter conical stockpile using a typical gold ore.

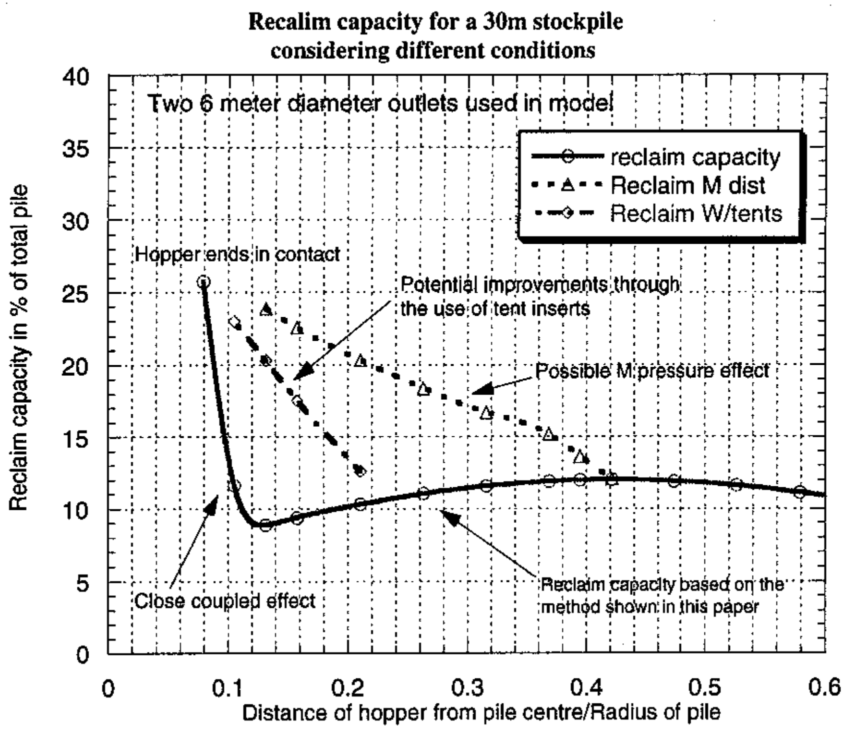

Figure 7 – Reclaim capacity for 30m pile with two feeders

From this graph it can be clearly seen that as the hopper separation increases from a dependant state that the reclaim capacity drops rapidly until the reclaim channels return to fully independent operation. From a practical point, the positioning of hoppers with a negligible separation is difficult in respect to providing suitable access for feeder maintenance. As a means to achieve a reasonable feeder separation whilst ensuring dependant operation of the flow channels, the use of passive flow promotion tents between hoppers has provided good results.

FLOW TENTS

Flow tents, if correctly implemented, can provide the benefits of dependant hopper operation whilst providing maintenance room around the feeders(ref Figure 7). The use of flow tents needs to be assessed on an individual basis. The optimal form of a flow tent comprises a sharp top with the lower edge shadowing a small portion of the hopper. In this way the minimum amount of flow resistance is offered to the material and as such the maximum potential is realised. If a ledge exists between the flow tent and the hopper there is a chance that material can cement in this area and prevent the tent from shedding material. Figure 8 shows a sketch of a good flow tent installation. It is imperative for the flow tents to be designed similar to a hopper, if the wall angle is too shallow the tents will fail to shed material correctly and render their inclusion useless.

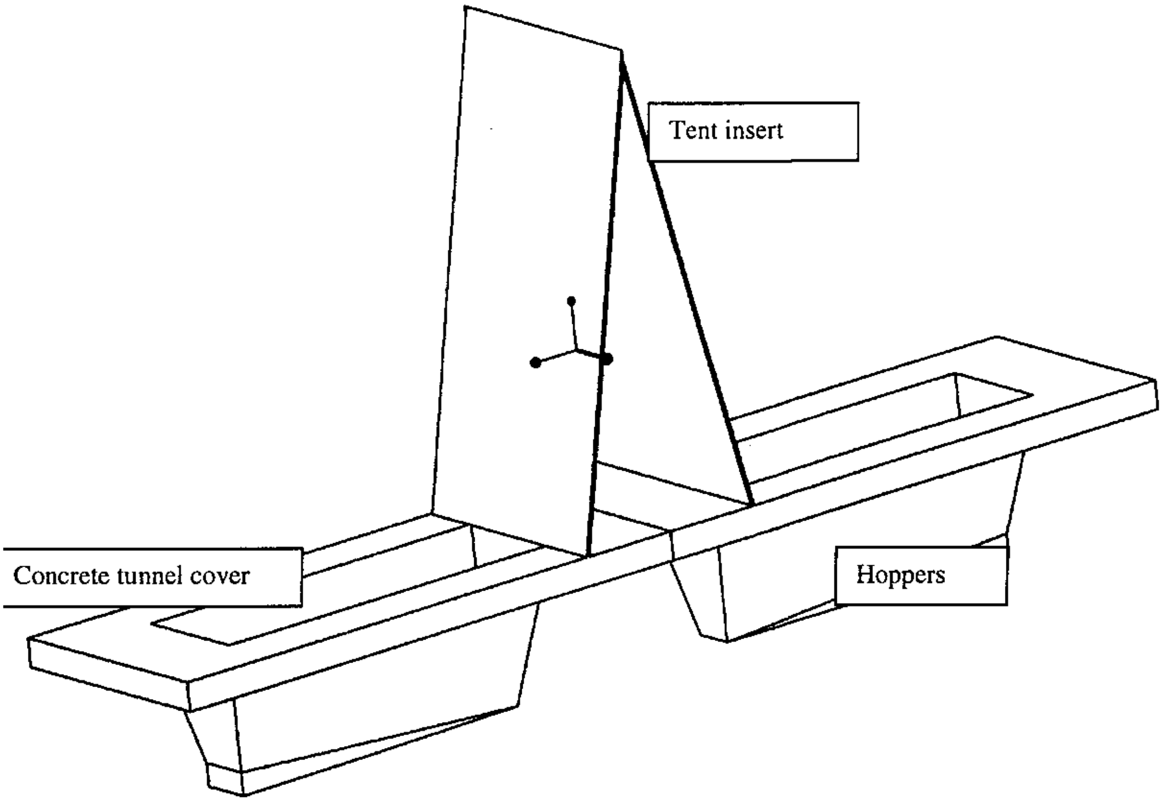

Figure 8 – Optimal flow channel to hopper interface

SINGLE ANGLE RECLAIM CHANNEL APPROXIMATION

The use of a single angle reclaim channel for the determination of reclaim capacity can be considered as a first order approximation only and should be confirmed with a multi angle reclaim computation when flow properties become available. Figure 9 shows data obtained using a single angle reclaim angle, still with two hoppers, compared with the reclaim prediction as obtained using the method presented in this paper.

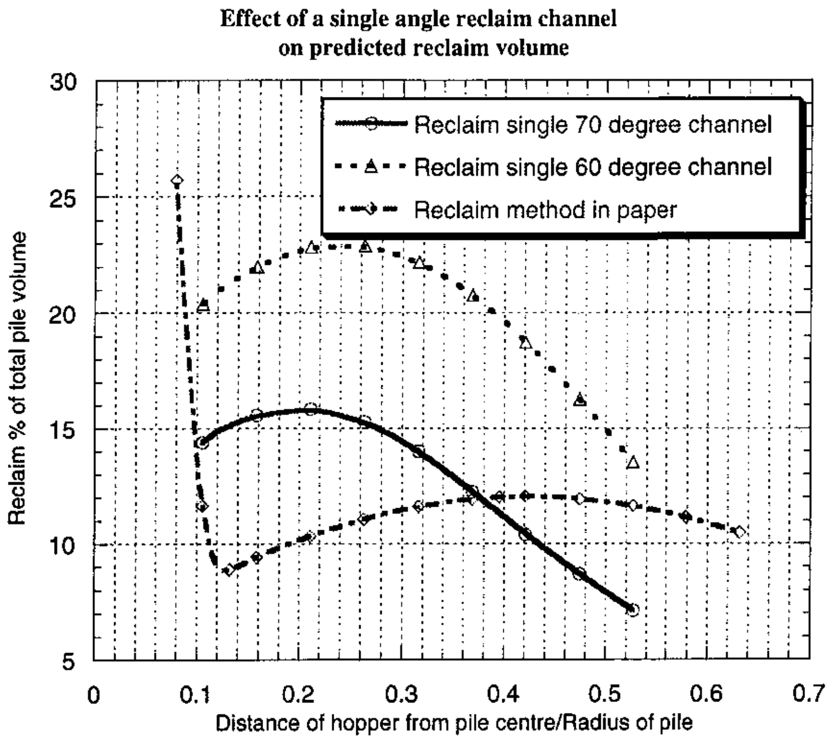

Figure 9 – Single angle V Multi angle reclaim channels for a two channel stockpile

It should be obvious from the above graph that the modeling of a stockpile reclaim with a single angle reclaim channel can lead to significant overestimation of the reclaim capacity of a stockpile. The amount of error induced by the single angle reclaim approach is dependent upon the material strength and on the hopper size. A low strength material with large hoppers may compare favorably the multi angle reclaim approach and the single angle approach.

INFLUENCE OF LARGE PARTICALS

It has been shown that once the level fines, material less than four millimeters, in a sample of ore exceed twenty percent that the coarse fraction plays little role in the bulk strength of the product. The benefit of the coarse fraction is at best a scouring effect on the hopper walls which will tend to reduce the build up of fines at the liner plate joins. The disadvantage of the course fraction is from an impact perspective with the large particles having a much smaller contact area per unit mass to dissipate the impact energy when contacting hoppers or other hard structures. In terms of the reclaim capacity of the stockpile, initially there may be a higher reclaim capacity with a low fines material due to a lower bulk strength. Over a period of time the fines entering the pile will fill the voids of the dead material making the reclaim capacity of the pile as though constructed from all fines.

STRESS DISTROBUTION UNDER A BULK SOLIDS STOCKPILE

All of the above volume reclaim analysis work was completed under the assumption of a hydrostatic or hydrostatically shaped vertical stress field. Until a more detailed stress analysis work has been completed, including the gathering of field data, little progress can be obtained in the rathole modelling area.

If reclaim calculations are based upon an assumed pressure dip following the form of that presented by Smid and Novosad then the optimization results for conical stockpiles changes dramatically. Figure 7 (previous pages), shows reclaim capacity for a 30 meter high stockpile made from a fine gold ore with both the reduced hydrostatic pressure and a possible M distribution with a center depression of 50% of hydrostatic. The peak in the pressure graph is assumed to be at 0.4 radius from the center as shown below in figure 10.

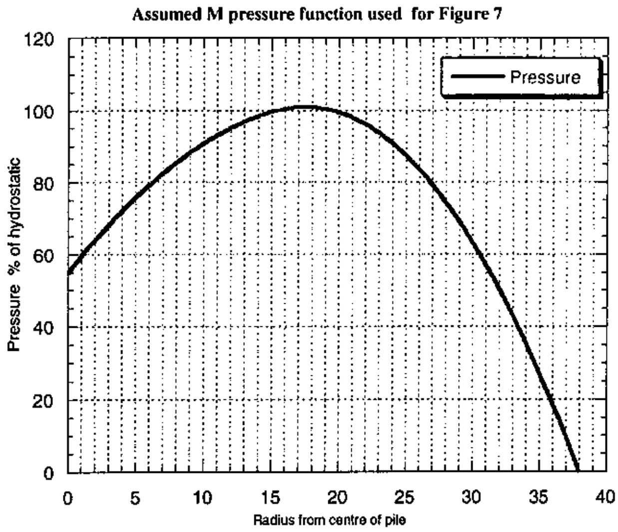

Figure 10 – Assumed distribution of the M pressure used in the generation of figure 7's data.

Other ramifications of the M pressure distribution

If the M pressure distribution is evident in full size conical stockpiles then the placement of hoppers for future stockpile installations will need to be reviewed. Also requiring review will be the tunnel designs. Many stockpiles reclaim system consists of an ARMCO type entry tunnel leading into the concrete vault. This concrete vault represents a significant capital cost and at this time there is no definitive method for the determination of the loads acting upon the structure. This lack of detailed knowledge invariable leads to a general over-design of the tunnel structure itself. Of greater concern is the potential failure of the ARMCO section due to higher than expected loads, if the M pressure is evident.

All of these reasons indicate a general need for more work to be undertaken both at model and full scale stockpiles to determine to what effect the pressure is distributed under a range of stockpile forms. The effect that the bulk material properties have on the pressure, as well as the effects of emptying and filling on the pressures at work on the tunnel structure need to be measured on full size installations where the full effects of compressibility can be assessed.

It is difficult to believe that the pressures obtained by Smid and Novosad in their experiments (9.5kPa hydrostatic) can be scaled to hydrostatic pressures experienced in say a 30 meter stockpile of gold ore (500kPa).

CONCLUSIONS

Even though the use of gravity reclaim stockpiles in industry is widespread, there is little field data available on the geometry of ratholes. This is principally due to the difficulties in measuring the shape of ratholes with any degree of safety. By their very nature, a rathole is unstable so that any item that is lowered into a rathole needs to be expendable. It is also seldom that the feed conveyor stops over the center of the feeder. This fact makes dropping some form of laser measuring device into the rathole extremely difficult.

The crater section has been approximated on field stockpiles and measured in physical model stockpiles. The use of the effective angle of internal friction, δ, for the surface angle appears to be correct. The repose angle of a stockpile, although an important parameter, has not yet been satisfactorily linked to the fundamental bulk material properties. The determination of the repose angle can be conducted on a reduced particle size sample in a laboratory or more preferably on site using a larger sample size.

The computer modelling work completed to date indicates some important relationships. First it indicates that the optimal separation of hoppers is mostly independent of the hopper opening size for the cases studied. Secondly it is indicated that a linear relationship may be present linking the stockpile height to the optimal hopper separation.

The modelling work has shown that the inclusion of a third central feeder into a two feeder system requires an increase in the outer hopper separation in order to maximise the reclaim potential.

The experimental work on stockpile pressures has shown that for small stockpiles that the M distribution may exist. However with increasing pile height the pressure dip at the centre of the pile appeared to reduce until the stress distribution appeared hydrostatic in form. If, however the pressure remains in the dip form, the significance is far ranging as illustrated by the reclaim capacity shown in Figure 7.

The basic concept of using close coupled hoppers to maximize the reclaim from a stockpile is valid whether or not the M pressure exists, as such the use of close coupled feeder should be promoted where appropriate.

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