DYNAMIC SIMULATION OF CONVEYOR SYSTEMS IN UNDERGROUND HARD ROCK MINES

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TERMINOLOGY APPLIED IN THIS PAPER

Instantaneous Flow Rate (IFR) or instantaneous loading is a flow rate recorded in a specific moment of time, an example being a SCADA reading of a conveyor belt weightometer set to a minimum time resolution (typically, 0.2 second), expressed in metric tonne per hour.

$$IFR = \frac{dm}{dt}$$

1. Index time (IT) is the transport delay of a conveyor or time of a particle travelling from the tail of a conveyor to its head.
2. True loading (TL) is an average flow rate on a conveyor belt over an index time or, for all practical purposes, over an hour, expressed in metric tonne per hour.

$$TL = \frac{1}{IT}\int_0^{IT} IFR dt = \frac{1}{IT}\int_0^{IT} dm$$

3. Availability in this paper means inherent (as opposed to achieved) availability, i.e. it reflects corrective maintenance only and excludes planned maintenance downtime.

$$Availability = \frac{MTBF}{MTBF + MTTR}$$

4. MTBF is Mean Time between Failures and MTTR is Mean Time to Repair.

INTRODUCTION

A significant number of underground hard-rock mines in South Africa with reef planes declined at up to 12^o angle employ a so-called on-reef room-and-pillar mining method, where a conveyor system is installed in the reef plane itself, panels are blasted in such a way as they form “rooms” and the hanging wall is supported by pillars. Many underground Platinum Group Metal (PGM) and Chrome mines are operated like this. In the decline shaft a so-called decline conveyor system is installed (although the material actually flows up the incline, therefore from the conveyor viewpoint it makes more sense to call it an incline conveyor), with horizontal strike conveyors stretching sideways from the decline conveyor. Load-haul-dumpers (LHD’s) pick up blasted rock and load onto the strike belts, transferring the ore onto the decline conveyor, which will then take the ore up the surface. As the mine advances both deeper and wider, decline and strike conveyors are extended to maintain an economically viable LHD tramming distance (generally, no more than 100m one-way). A typical example of a plan over a conveyor system and the workings appear in Figure 1.

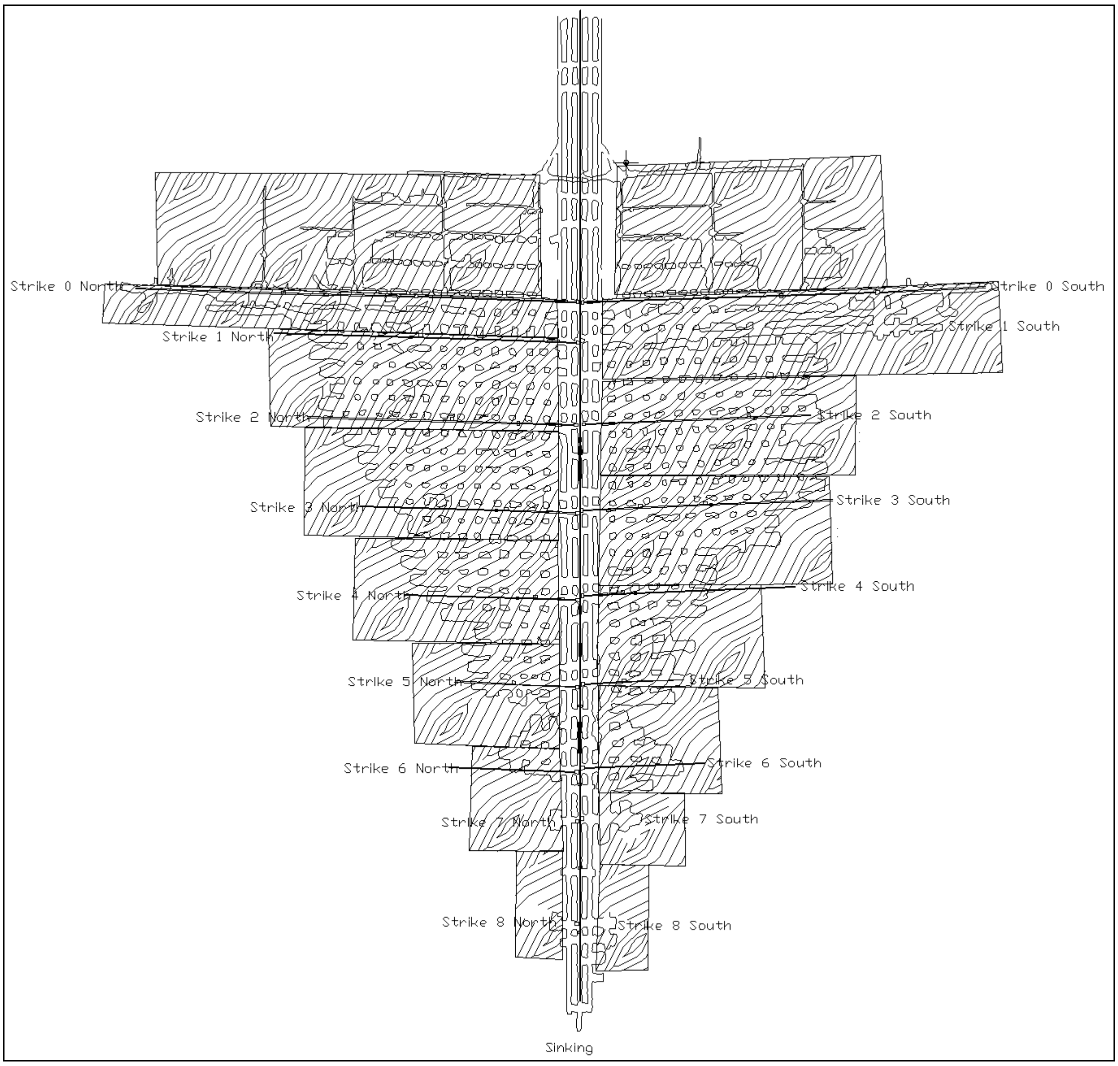


Fig 1: Plan over a conveyor system in an underground on-reef room-and-pillar mine

The operation of a conveyor system in a mine described above has distinct features, which should be taken into account both in the design phase, and in the operations, which will be discussed further in this paper.

INSTANTANEOUS VERSUS TRUE LOADING OF A CONVEYOR

Typically, loading points in the mines concerned are equipped with static of vibrating grizzlies, with strike belts positioned beneath the grizzly and LHD's tipping directly onto the grizzly as shown in Figure 2. The aperture of the grizzly is usually 350 mm x 350 mm, which is perceived to ensure that a – 300 mm feed, is passed onto the belt with the oversize rock being pushed to the back. The oversize material should be predominantly waste, however due to an almost unpredictable rock fragmentation ore particles can be oversized as well, obtaining a shape similar to a rugby ball with a diameter close to the desired 300 mm and length up to 600 mm. Since it is almost impossible for a tip attendant to distinguish between ore and waste, a large number of oversize particles are forced through the grizzly, either by LHD hitting the oversize material with an empty bucket, or manually with hammers by tip attendants. This practice can actually become a normal modus operandi, specifically in the mines where contract mining is employed, with the contractor compensated on a Rand per tonne toll basis. It is therefore not unusual to observe oversized material on conveyors in such mines.

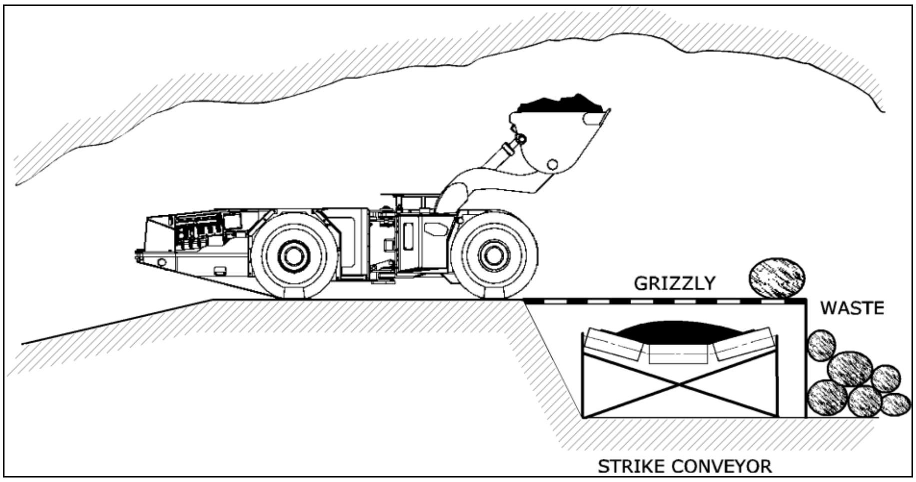


Fig 2: LHD tipping onto the grizzly

Assuming a more or less correct rock fragmentation, the loading of conveyors is determined by the LHD tipping process, which is a function of the scoop load and the tipping time. Observations taken in one of the platinum mines allowed a distribution to be defined that described an instantaneous flow rate of ore from the LHD bucket onto the strike conveyor, shown in Figure 3.

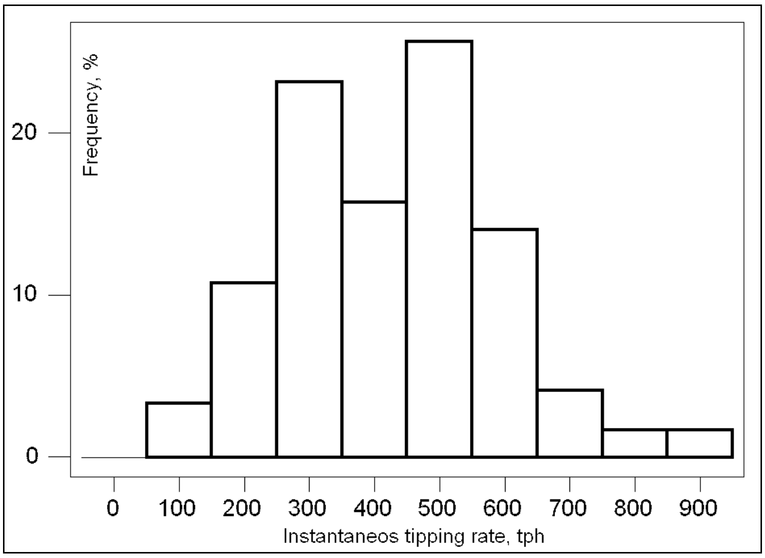


Fig 3: Example of an instantaneous loading rate of a strike conveyor

As can be seen, the instantaneous strike conveyor-loading rate can reach 900 tph volumetrically while most of the strike belts are designed to 400 tph. This however does not present a risk of the conveyor overload; instead, it creates a spillage risk due to the fact that the geometry and the speed of the belt rated at 400 tph cannot accommodate the volume of material arriving at an instantaneous 900 tph flow rate as illustrated in Figure 4. Matching instantaneous volumetric tipping rate of an LHD and volumetric capacity of a conveyor is therefore important in the conveyor design.

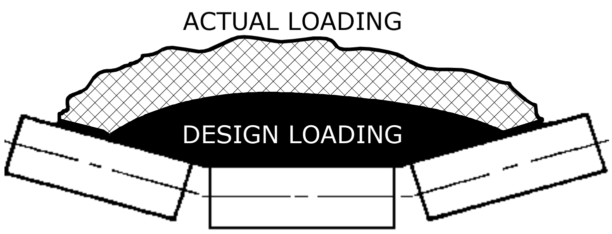


Fig 4: Actual versus design volumetric loading

From the author's observations, 900 mm-wide strike belts always have spillage all the way along the conveyors, mainly oversize material that simply roll down off the heaps.

From a conveyor-loading viewpoint, instantaneous flow rate is not that critical due a discrete nature of introducing material onto the belt in the given circumstances. With LHD's arriving to a tip point with a variable interval, a strike conveyor will actually move heaps of material with gaps in between generally far exceeding space occupied by the heaps themselves as indicated in Figure 5, where black segments on the belts indicate heaps of material. In this operating scenario, conveyors actually move discrete parcels of bulk material as opposed to a evenly spread material over the entire belt length under continuous loading conditions, observed, for example, on large coal overland conveyors feeding power stations. Since the conveyor drives are designed for a full belt lading, it is virtually impossible to overload strike conveyors in the applications concerned.

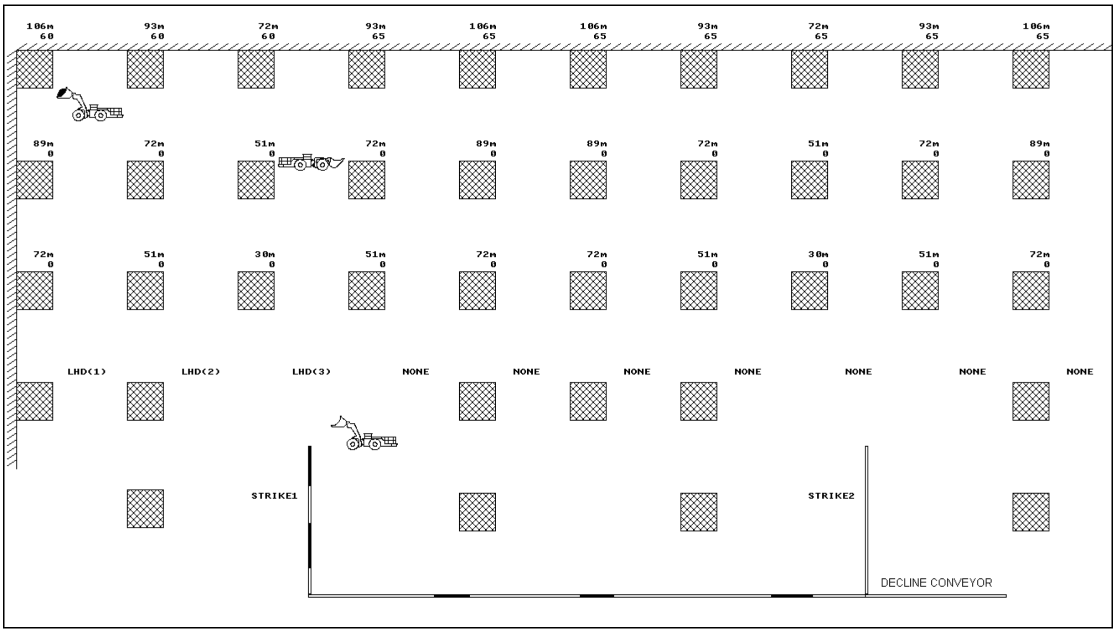


Fig 5: Discrete flow of material on conveyors loaded with LHD direct tipping

In other words, since the conveyors are designed for the true loading conditions, i.e. for full loading of the belt over its entire length, the excess of the instantaneous flow rate with direct LHD tipping over the rated capacity is not critical.

However, once several strike belts transfer to the decline conveyor, the latter will be loaded reasonably full with only limited gaps (vacant spaces) on the belt. It does not automatically imply though that the variation of the instantaneous flow rate on the decline belt will be much smoother than on the strike belts; however, zero flow rate values will be observed with lower frequency.

Dynamic simulation was found to be a useful tool to analyse the actual loading of the decline conveyors. Figure 6 displays an animation screenshot of a dynamic simulation model of a PGM mine with four decline conveyors underground and up to eight strike conveyors loading concurrently.

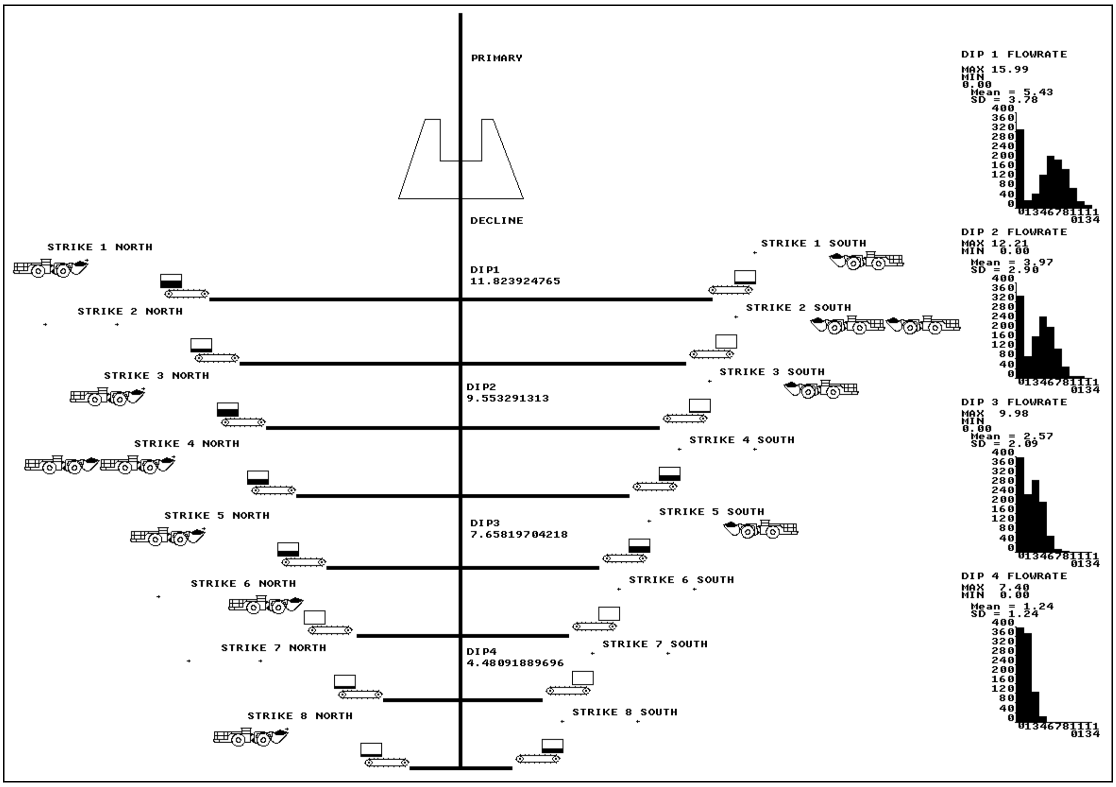
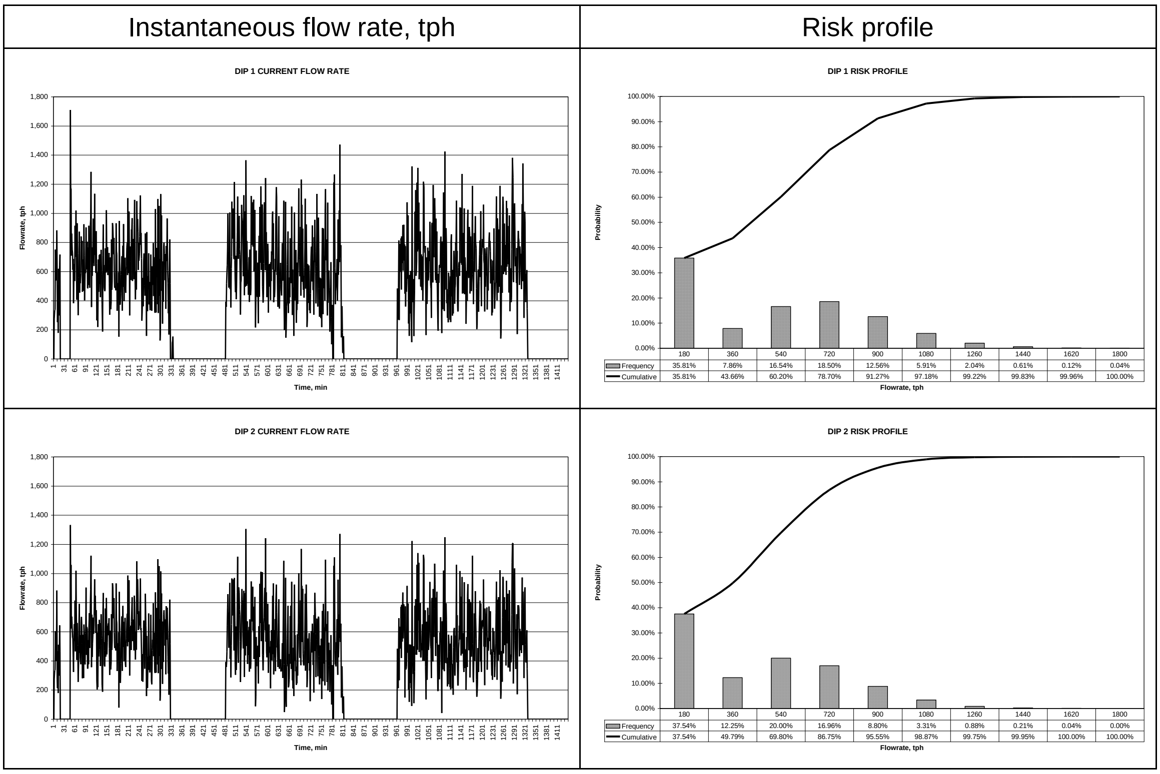


Fig 6: Animation screenshot of a dynamic simulation model

The model was used to evaluate the performance of the mine in the future when all production sections would be brought on line. It was monitoring instantaneous flow rate on all the decline belts every minute and also tonnes actually conveyed over an hour period for the top decline conveyor, referenced as Dip 1 in Figure 6.

Results are summarised in Figure 7



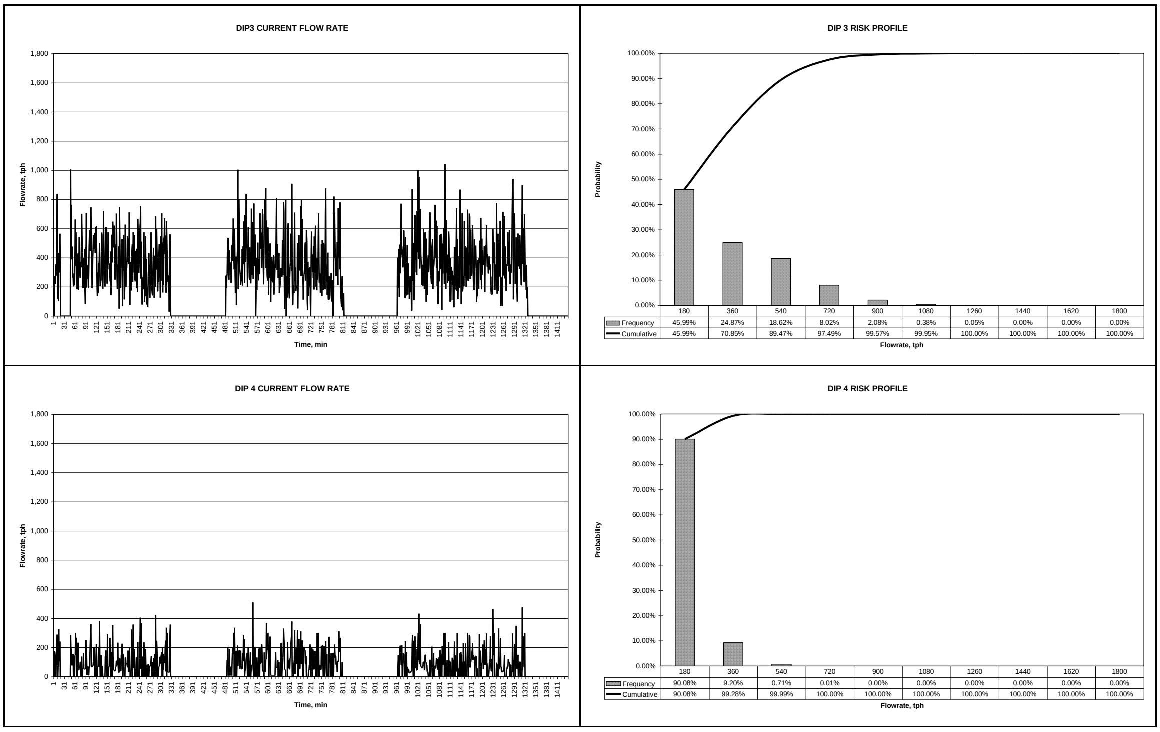


Fig 7: Instantaneous loading of decline conveyors

The interpretation of the risk profile follows:

- Vertical bars indicate a fraction of time the conveyor was flowing in a specific range of flow rates. For example, the first bar in all histograms is responsible for any flow rate in [0;120) tph range, i.e. {>=0 and <120} and indicates a fraction of time when the conveyor was actually receiving feed from one or two strikes or was idling. In other words, the total capacity of the conveyor was divided into virtual "pockets", each responsible for a specific range of flows, and the model was monitoring the current (i.e. instantaneous) flow rate every minute and placed and observation into the appropriate "pocket". The second bar is responsible for [120;240) tph flow rate and so on.
- The solid black line shows the cumulative probability of the flow rate, ending at 100% since the histogram covered a full range of the conveyor flow capacity. For example, the probability of Dip 1 flowing under 1,080 tph was 99.99%.

While instantaneous flow rate is an important design consideration from the spillage viewpoint, true loading remains the key driver for the belt class and drive selection (drive being an assembly of a motor, a gearbox and a coupling). With Dip 1 instantaneous flow rate peaking at 1,800 tph the true loading (tonnes moved per hour) has never exceeded 800 tph as can be seen in Figure 8.

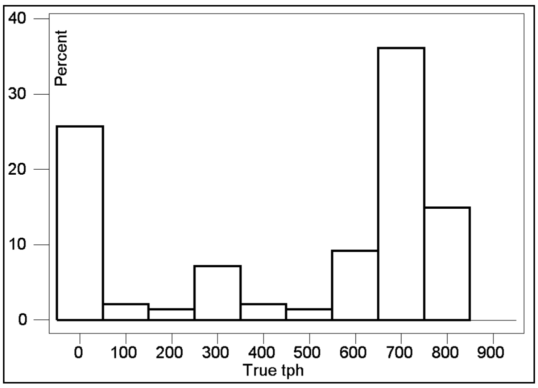


Fig 8: True loading of Dip 1

Conveyor true loading is an intricate value to calculate, although true loading is nothing else but a mere floating average, and an hour may not necessarily be the correct time basis. For example, the shorter the time basis, the closer the true loading will be to the instantaneous flow rate. The benefit of calculating the true loading is that it may be used as a design criterion of a conveyor and as a measure to assess the performance of a conveyor already in operation.

Strictly speaking, the true loading magnitude (i.e. the average flow rate over the time basis) and the time basis itself are interlinked, i.e. there should be an operating envelope with true loading that can be sustained infinitely, L_∞, on one side and true loading that will trip the conveyor immediately (called killer loading L_k in Figure 9), on the other side. A conveyor index time, i.e. a transport delay from tail to head, is probably the most appropriate time basis for calculating the belt true loading. It will therefore imply, that should the true loading of the belt exceed the rated capacity continuously over a period of time equivalent to the index time of the belt, the conveyor will trip.

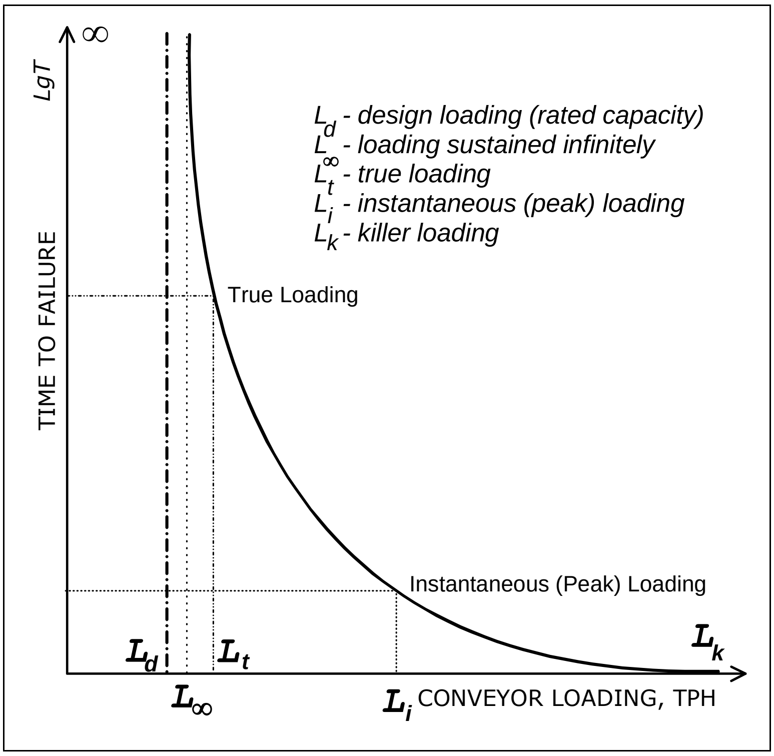


Fig 9: Illustrative correlation between conveyor loading and time it can be sustained (time to failure)

This section attempted to highlight a simple observation that conveyors operated in hard-rock mines as described above are typically loaded in excess of their design (rated) capacity, and the only reason why they still perform the duty is that the duration of true loading is shorter than time to failure.

On the contrary, a conveyor whose true loading duration exceeds the time to failure, will obviously trip. There are basically four solutions to correct the problem:

1. If practically possible, spread the load, i.e. reduce the flow rate and increase the load duration (effectively it means climbing up the curve in Fig 9). In practical terms it implies a longer LHD tipping time on a static grizzly or reducing the flow rate of vibrating grizzly feeders. Optimised allocation of LHD's to strikes also contributes to smoothing the decline conveyor loading, but this is a separate subject of discussion.

2. Allow for controlled transfer of ore from strikes to decline, for example by installation of hoppers and vibrating feeders at transfer points. This is very much the same solution as the one above, but with smoothing effect applied at the transfer points rather than at loading points.

3. Increase the rated capacity of the conveyor system, which can be easily achieved in the design phase, or upgrade the conveyors if these have been already built.

4. Reduce the production target, if nothing of the above can be done.

Problems with the conveyors loaded in discrete mode are almost always associated with both operating philosophy and mistakes in design criteria, some of which will be discussed later on. This raises a need to carefully plan and, even more importantly, control the operations as well as review the design principles.

SPILLAGE AND MULTI-LAYERING

Apart from the instantaneous volumetric loading rate exceeding the design volumetric rated capacity, multi-layering may also cause spillage. The effect of multi-layering occurs when a number of strike conveyors transfer material onto the decline conveyor, and a few parcels land on top of each other. It may not necessarily cause spillage, but with poorly fragmented rock, most definitely it will. Through dynamic simulation, the following diagram was obtained for a decline conveyor receiving feed from up to eight strikes operating in parallel (refer to Figure 9)

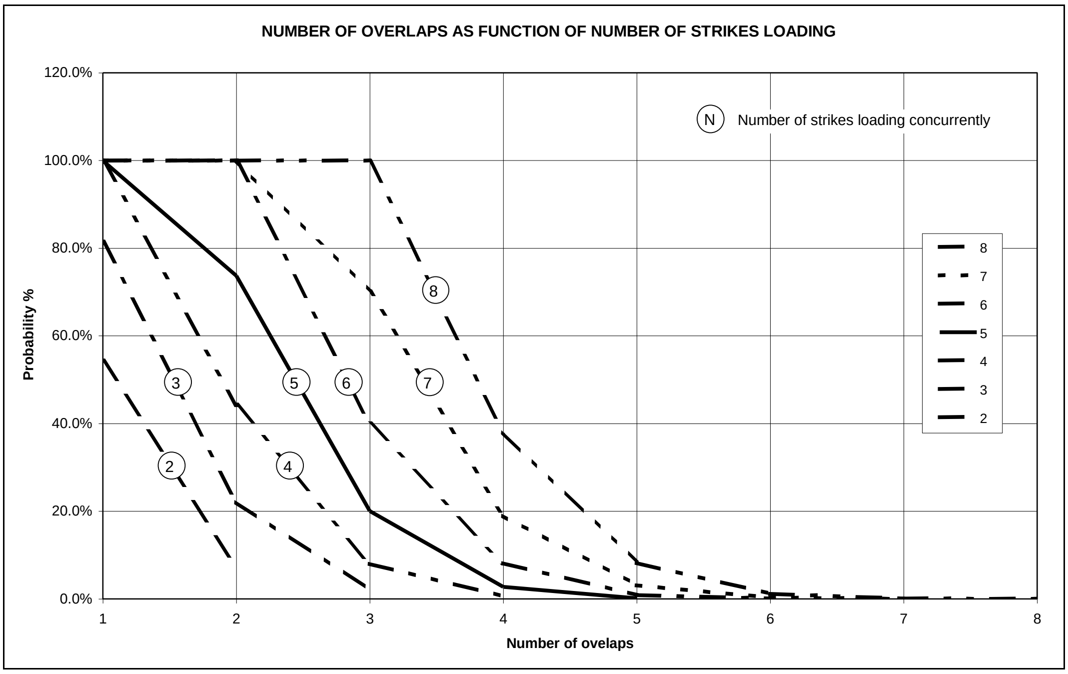


Fig 9: Multi-layering effect on decline belt

With eight strikes loading concurrently, three parcels will definitely land on top of each other, four – with a probability of 38%, five – 8%, six – 1%. With seven strikes loading concurrently, two parcels will definitely overlay, three parcels – with a probability of 70%, four – 19%, five – 3%, and so on.

This type of analysis is both important at the design phase and also for the operation planning in an existing mine as it will help minimise spillage specifically in the mines with poor rock fragmentation. For example, 1050 mm-wide decline conveyors, which are still a commonplace in the underground mines, as a rule has spillage believed to be the result of multi-layering.

CONVEYOR UTILISATION

With discrete conveyor loading as described above, it is difficult to achieve high utilisation of conveyor systems. Figure 10 shows an example of decline conveyor utilisation

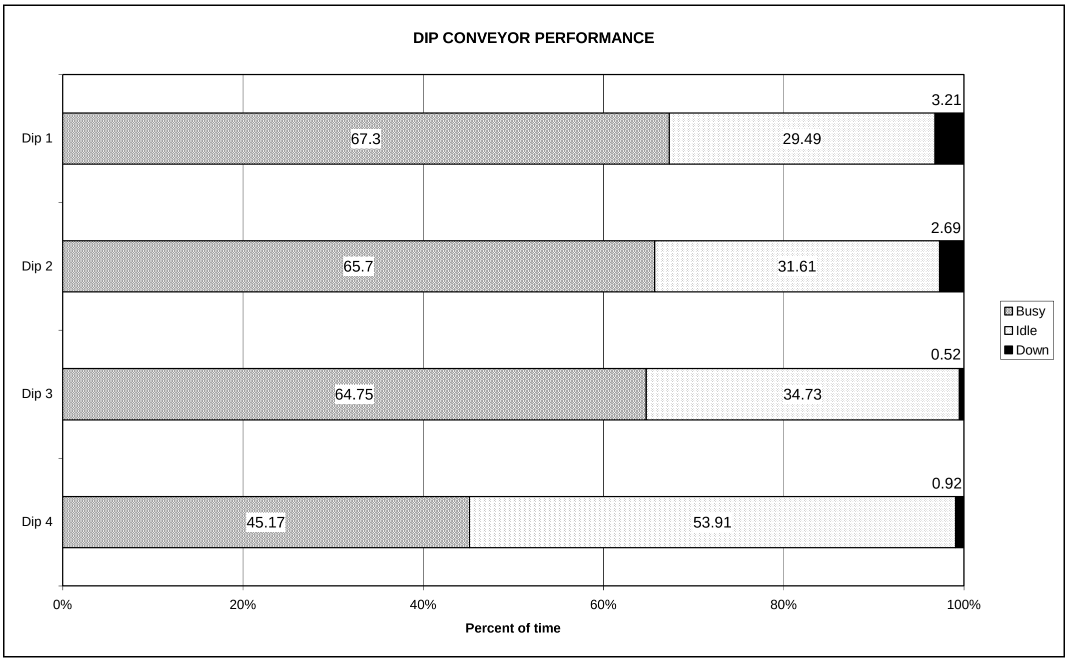


Fig 10: Example of decline conveyor utilisation

The following interpretation applies to the time components in the bar chart:

- All time fractions are related to operating (i.e. manned) time.
- “Busy” time a fraction of operating time when a conveyor was actually moving material.
- Idle time is the time when conveyors were available, i.e. not broken down and not on planned maintenance or off-shift, but were not performing the duty, i.e. an empty conveyor belt running.
- Downtime is the time when conveyors could not perform the duty due to incidental equipment breakdowns (failures).

Since Dip 1 received feed from all the sections, it has the highest utilization. Going down, the number of strikes transferring to the dip conveyor chain reduces and hence the utilization, i.e. time ore was flowing on the belt, is shrinking.

An important observation from the performance bar chart is that the highest utilisation observed was 67%, which is a frequently observed order of magnitude of the decline conveyor utilisation in discrete feed scenario. There are various factors contributing to that, LHD net effective loading time being the one that cannot be neglected. Out of an eight hour shift, 6 hours net effective loading time is a representative benchmark observed in some of the better-operated underground mines, however 5.0 to 5.5 hours net effective LHD loading time is not unusual with the decline belt utilised at 60% or even lower.

With decline conveyor utilisation standing generally below 70%, the average required flow rate will be most probably higher that the design rated capacity, frequently based on 80% assumed utilisation, which is one of typical design criteria mistakes mentioned above.

THE EFFECT OF CONVEYOR AVAILABILITY AND MITIGATION MEASURES

If correctly designed, operated and maintained, conveyors are relatively reliable equipment with availability ranging between 95% and 98%. From the authors experience in the underground mines concerned, strike belts can show up to 98% availability while decline conveyors – up to 97% (both figures quoted are best observations). However if conveyors are under-rated or abused in operations, or if maintenance is neglected, their availability can easy drop to 90% and even lower. With a number of decline conveyors connected in series, a cumulative effect of breakdowns occurs specifically with upper belt failures, when the entire chain has to be stopped.

Figure 11 illustrates the cumulative effect of conveyor availability on mine production and more notably, performance, as by degrading conveyor availability by 8% (all other factors being equal) the mine loses 29% of production.

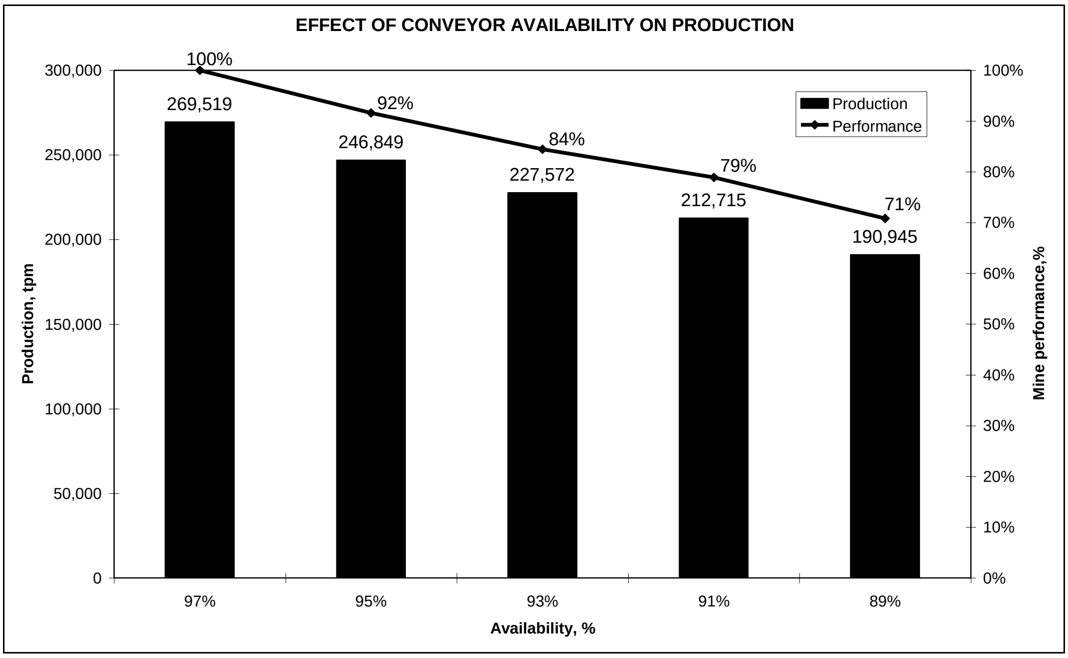


Fig 11: Effect of conveyor availability on mine performance

This effect aggravates with the mine going deeper as more conveyors are added to the decline chain.

One of the known remedy measures to improve a conveyor chain system availability and utilisation is to disconnect the chain by installing a surge capacity in a form of a bunker in between. Correctly sized, the bunker absorbs the feed if the downstream conveyors are down and, on the contrary, allows running the downstream plant if the one of the upstream conveyors breaks. Another benefit of having the bunker is a controlled loading rate of the downstream conveyors and also protection from impact at transfer points should strikes be also loading onto the downstream decline belts.

The question however is: Where to install a bunker and how large should it be?

The best place(s) for the bunker installation should be the one(s) splitting the chain in two (or more) sub-chains with equal system availability. It is however not that straightforward to estimate a system availability of the sub-chains as while each sub-chain will have a single discharge point, they may, and some of them definitely will, have multiple feed points so as the number of links between loading points to the discharge point will be different for the same sub-chain. Dynamic simulation can simplify the task, as by moving a bunker along the decline chain the best position can be determined by maximising the total production.

A case study below illustrates the advantage of having such a bunker, refer to Figure 12. Two scenarios were run, namely with the bunker in line and bypassing, i.e. with direct transfer from Dip 4 to the Trunk conveyor. The results indicated that by using the bunker, production could be increased by 10,057 tpm or 7.5% with all other operating factors being equal. While the numbers do not seem impressive enough, if we assume that PGM ore is mined with an average effective recovery of 2.6 gram per tonne at a reduced Platinum price of US$1,000 per ounce (at the time of writing the spot price was $1,275 per troy ounce), an additional revenue of US$9.8 million per annum will be gained. The bunker will be therefore paid back within the first month of operation and further generating clean profit.

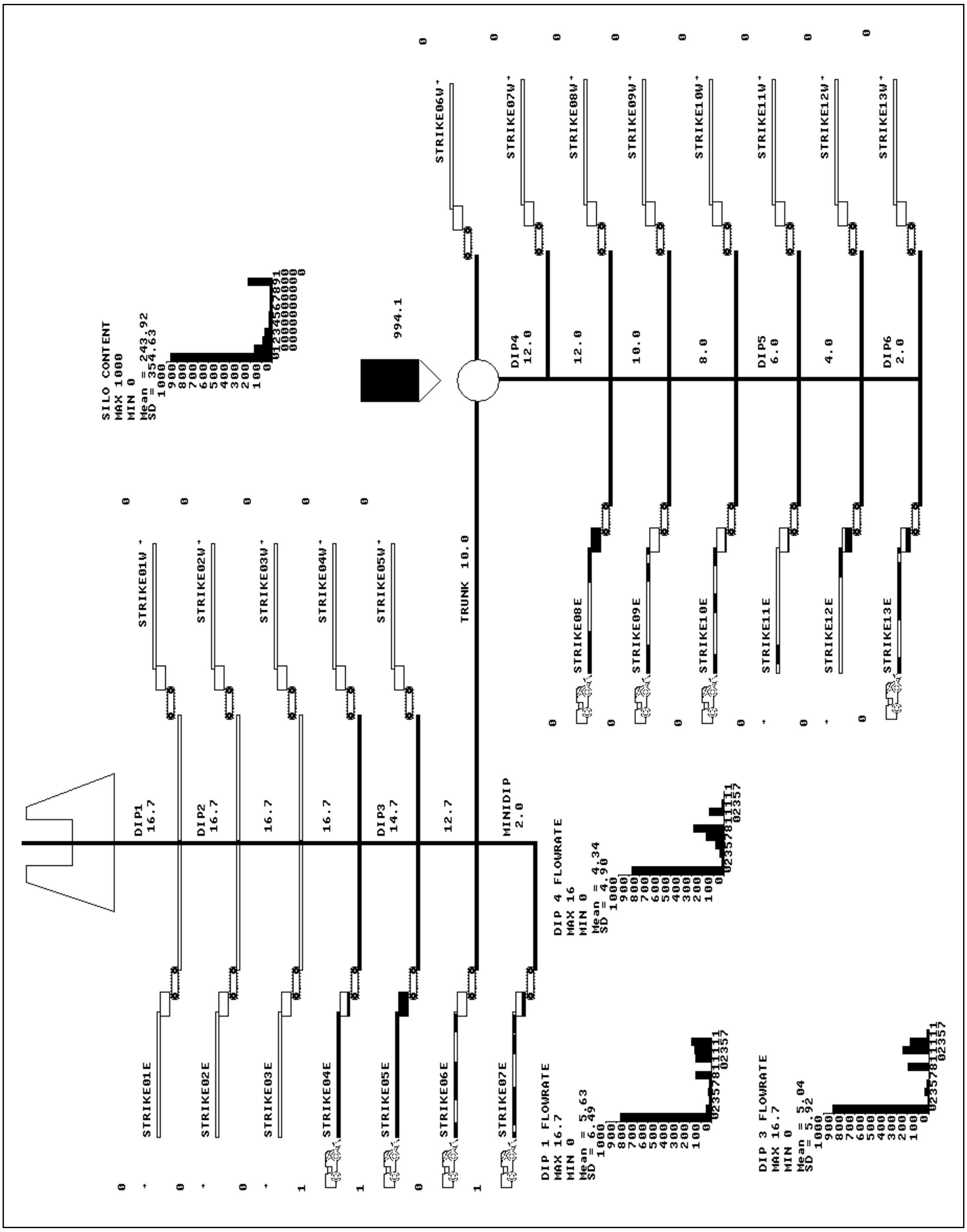
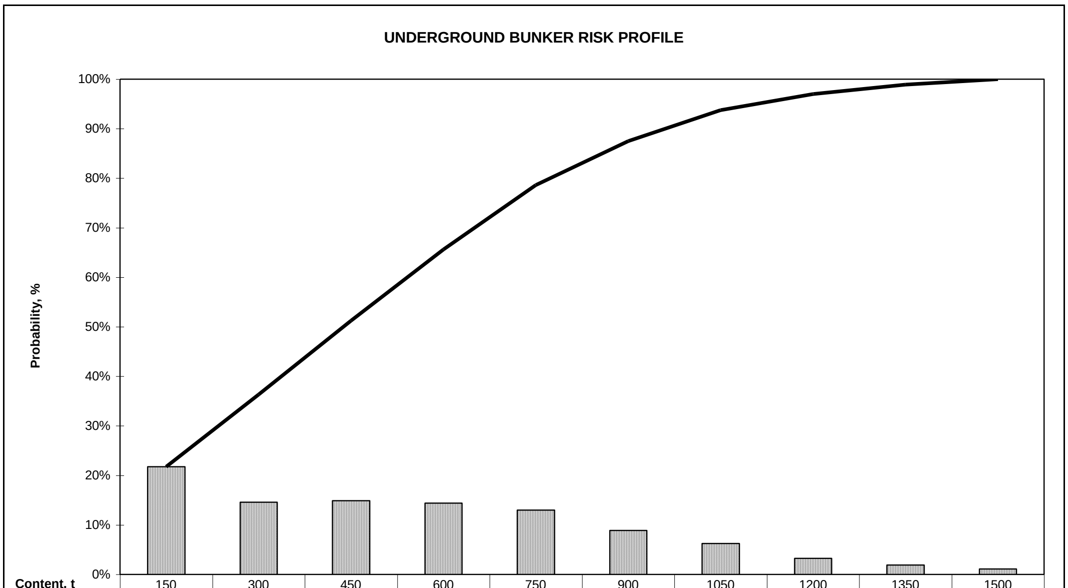


Fig 12: Evaluation of the effect of a bunker in the decline conveyor system

Risk profiles similar to the ones discussed above for conveyor loading can also be applied for right sizing the underground bunkers. In this case study, a risk profile appearing in Figure 13 was obtained for the bunker.



Content, t	150	300	450	600	750	900	1050	1200	1350	1500
Frequency	21.77%	14.58%	14.88%	14.42%	12.97%	8.91%	6.26%	3.22%	1.88%	1.12%
Cumulative	21.77%	36.34%	51.23%	65.64%	78.61%	87.52%	93.78%	97.00%	98.88%	100.00%

Fig 13: Underground bunker risk profile

If 100% of overflow risk should be covered, the bunker must be sized at 1,500 tonne live capacity, however if 3% overflow risk can be tolerated, the size can be reduced to 1,200 t.

In practical terms, underground bunkers were found particularly helpful if the number of links in the decline conveyor chain (from the bottom of the shaft to the discharge point into a surface silo or onto a stockpile) exceeds six as was in the case study above (six dip belts and one trunk conveyor).

CONCLUSION

Conveyors in underground hard-rock mines with on-reef room-and-pillar mining and LHD's directly tipping ore on strike belts perform as predominantly discrete conveyors as opposed to continuously loaded. Direct LHD tipping is a process that is difficult to control in real operations, resulting in instantaneous loading rates exceeding the design volumetric capacity of the strike conveyors. The result is spillage and increased belt wear.

Parcels flowing down the strikes and eventually being transferred to the decline conveyor may overlap, depending on the number of concurrently loading strikes, which also creates a spillage risk.

Instantaneous and true loading of the decline conveyors is an important analysis that should be done in the design phase to ensure that the rated capacity is correctly defined as in most of the mines observed; the true loading rate exceeded the design capacity necessitating drive upgrades when the mine is already in operation.

While –300 mm rock fragmentation is considered the target for blasting, in reality it is larger, and from observations of real operating mines, the following minimum belt width can be recommended:

- Strike conveyors = 1050 mm wide
- Decline conveyors = 1200 mm wide

Wider belts will obviously perform even better, however a trade-off study needs to be done between the costs of production loss due to spillage and of a larger conveyor installation.

Due to the discrete nature of conveyor loading in the mines concerned, it is almost impossible to achieve conveyor utilisation in excess of 70%, with 65% being a more practical benchmark suggested or the design purposes.

In order to mitigate the downtime risk in the long decline conveyor chains, underground bunkering is recommended, specifically if the number of links in the chain exceeds six. Ultimately, one bunker must be allowed for each four or maximum five decline conveyors in series. The position(s) of the bunker(s) must be selected in such a way as to split the chain in segments with more or less equal system availability. Live capacity is difficult to determine by static (Excel-type) calculations, but a rough guideline of a 1,000 t live underground surge capacity per bunker for each 100,000 tpm ROM ore production can be suggested.

This paper is not intended to produce final answers but rather induce a discussion and establish industry-accepted best practice to ensure that the conveyors help the miners improve their bottom line. Conveyors, being not the most expensive equipment in the underground hard-rock room-and-pillar mines are the arteries, which may dictate the overall mine performance regardless of other installed capacity.

AURTHOR'S CV

Alex Lebedev was born and educated in Russia (MSc Eng 1982 and PhD 1987 from Moscow Institute of Steel and Alloys). He is presently a South Africa-based independent consultant to the mining and mineral processing industry, specialising in logistics and production optimisation. His consulting clients include both large mining houses such as Anglo Platinum, Impala Platinum, Lonmin, De Beers, and mid-tier producers operating in a wide range of commodities. He also consults South African Port Operations on bulk terminal expansions.

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