Root Causes of Tailings Dam Overtopping: The Economics of Risk & Consequence

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ABSTRACT

This paper examines overtopping failures of embankments at tailings impoundments from 1915-2015 and compares the severity of consequence for overtopping failures to that of other causes of failure. We find that the distribution by severity of consequence for overtopping at active mines is not significantly different from any of the other established "causes of failure." Further we find that the distribution by severity within and across all active TSF recorded failure causes (N=125) is also reflected in the mean distribution of severity for all of our recorded TSF failures (N=267) suggesting that a common root cause, rather than the individual causes of failure, may determine the severity of failure. We look here at the demonstrated link between severity of consequence of failure and the economic dynamics of the "Mining Metric" over 100 years (Bowker and Chambers 2015) as it applies to overtopping. We offer what is available from authoritative sources on the economics backstory of known overtopping failures and crises. We conclude that the deviations from best available technology and best applicable practices at the mine level are conscious choices driven by economics and that without a reframing of the professional, regulatory, and legal frameworks for mining these choices will continue to be made even where proven technology and new promising technology are available and better suited to a given mining asset. Solutions that will prevent mine failure require not only the work of evolving consensus on best available technology/best applicable practices, but also the recognition of root causes which build to catastrophic failure. A complete solution cannot be attained without accountability to best knowledge, best practice, best effective technology in mining law and regulation, as permit standards, as standards for oversight for life-of-mine and of life-of-tailings storage facilities.

Keywords: *overtopping failures, embankments, tailings impoundments, severity of consequence of failure*

1. INTRODUCTION

Overtopping (OT) is one of 8 codes developed by ICOLD for their survey reported in Bulletin 121 (UNEP/DTIE 2001). The original framing of data elements developed by ICOLD continued with WISE (2014) who are the official global record keepers of significant unplanned incidents at above ground tailings impoundments (Tailings Storage Facilities – TSFs). Previous research (Bowker and Chambers 2015) utilized the only direct measures of severity in WISE (2014), run out and release volume, supplemented as necessary by other authoritative narratives and compilations containing direct information on consequence, to develop severity of failure classes. In our data base 267 failures of tailings storage facilities could be divided into three major classes: Very Serious Failures; Serious Failures; and, Other Failures. As is shown in Figure 1, outside of foundation failures (FN) and erosion (ER) - both high severity low frequency causes of loss - no one cause of failure is any more correlated with high severity losses than any other. All others are very close to the mean of the 125 TSF failures at active mines which had complete cause-of-failure codes (i.e. all codes are similar to one another in severity profile). The 125 events which are failures at active mines only, mirror the distribution of severity in the 267 database events of 1915-2015.

This suggests that there is a common root cause that shapes severity of consequence. The data suggests that all customarily used causes of failure, including overtopping, are only a final event in a cluster of other factors that

determine severity of failure. In addition to the essential continuing collaborative push to identify and develop best practice and best technology to prevent catastrophic public loss, the law and regulation of mining must look to these root causes beyond available or potentially workable technology.
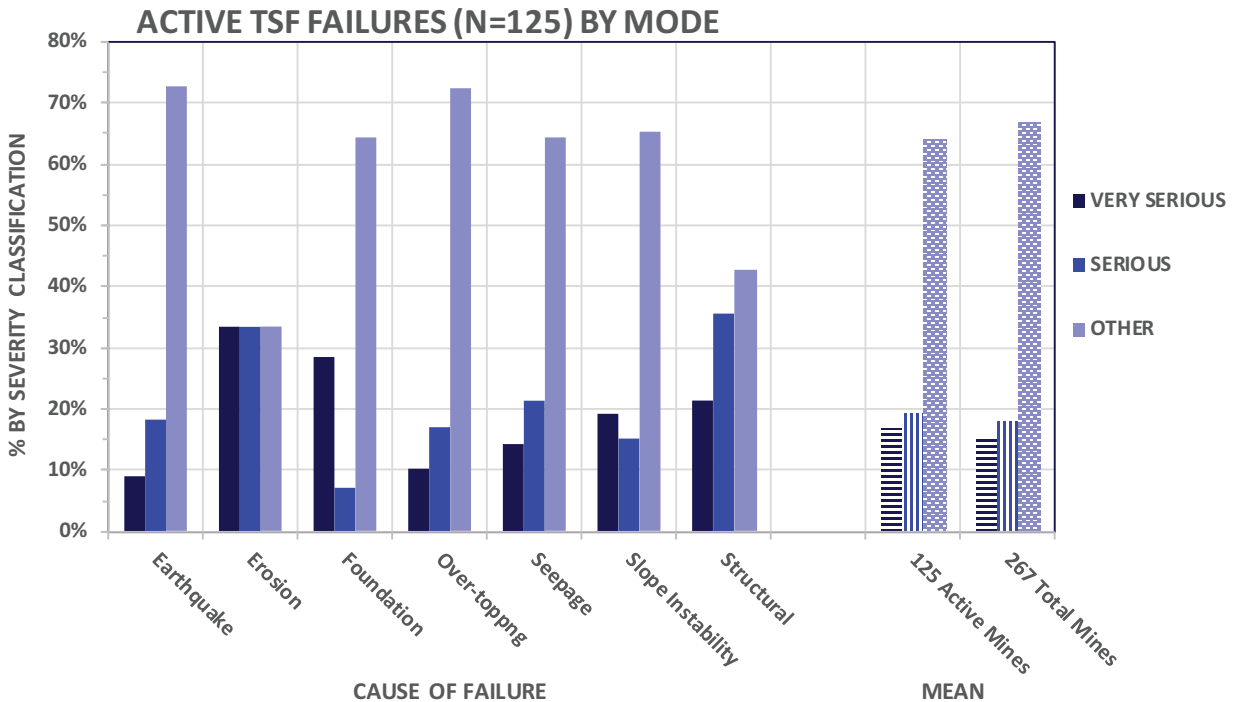
ACTIVE TSF FAILURES (N=125) BY MODE

Figure 1. Failure Modes by Severity Classification for Active TSF Failures

We know from experience, from historical narrative, and from the research of Rico et.al. (2007) that key risk indicators reside in the characteristics of the tailings storage facility itself: type of construction; construction materials; height; length; total storage volume; and, adequacy of drainage. However, there is insufficient data on many of these elements in the official compilation for analysis of correlation with severity of consequence in the event of failure, and it is difficult to fill in the blanks from publicly available reports and records. Obviously, even though the larger the facility, the larger the possible failure, it is an oversimplification to think about reducing risk by not allowing large dams. The key issue in effective loss prevention strategy is recognizing and incorporating technologies and practices that will reduce the long-term rate of dam failures to a level that is acceptable to society.

It is widely recognized as well that regulatory and legal gaps are a common root cause shaping severity of failure. The June 9, 2016, police investigation in Brazil supporting the indictment of a Vale senior engineer (in addition to the 6 already indicted, including Samarco's former President) put it very well, correctly observing that behind the failure was a conscious choice to allocate all resources to higher throughput volumes with no corresponding investment in additional waste management technology (Kiernan 2016a). Vale's own independent evaluation of the last planned expansion in 2010 endorsed proceeding with no identified possibility of managing tailings waste (Amira et. al. 2010). Nothing in Brazilian law or regulatory requirements, or Minas Gerais permitting requirements, reviewed or objected to that.

In British Columbia, at Mt. Polley, Imperial Metals was grandfathered from new law and regulation on hazard rating and stricter inspection. As is common practice in most regulatory regimes, existing permitted facilities are seldom held accountable to new and higher standards. Even though Imperial Metals deviated from best available technology (BAT) and best applicable practices (BAP) as recommended by the original designer of the dam, the official finding was that Imperial broke no laws and was in violation of no regulations (McCrae 2015). The Mt Polley Expert Panel found that if the original design had been followed, the failure would not have occurred (Mt Polley Expert Panel 2015).

The BC Ministry of Energy and Mines, like most regulatory agencies, allows the dual use of the facility for storage of water. In May, 2014, prior to the dam failure, there had been an overtopping of the dam, but quick action by mine personnel prevented failure of the dam (Mt Polley Expert Panel 2015). Overtopping at Mt Polley could also have led to a dam failure, with similar damage as eventually occurred in the foundation failure in August in 2014.

Throughout Canada and all over the world new mines and new dams are approved within regulatory and legal structures that do not hold miners to best available technology and best applicable practices.   Until this changes, it is clear that the industry will not consistently choose best available technology and best applicable practices unless required to do so. Geoffrey Blight emphasizes this in his authoritative and informed re-visitation of several notorious failures, among his very last works and summing a life time of excellence and insight on design and management of tailings storage facilities (Blight 2010).

While we cannot examine these other root causes systematically through any official or recognized recorded history, we can and did examine the global historical relationship between the primary economic parameters of the Mining Metric (the main strategy for mining continually falling grades of ore over a century of falling prices across all metals) against changes in the level of consequence in mine failures over the 100-year period ending 12/31/2009 (Bowker and Chambers 2015). That work demonstrated the strong correlation between the Mining Metric and the emergence of a pattern of higher severity of failure over a sustained 100-year trend of falling prices.

2.   THE EMERGENCE OF INCREASING SEVERITY AND ITS RELATIONSHIP WITH THE MINING METRIC OVER 100 YEARS

2.1.   The Emerging Trend of Increased Severity
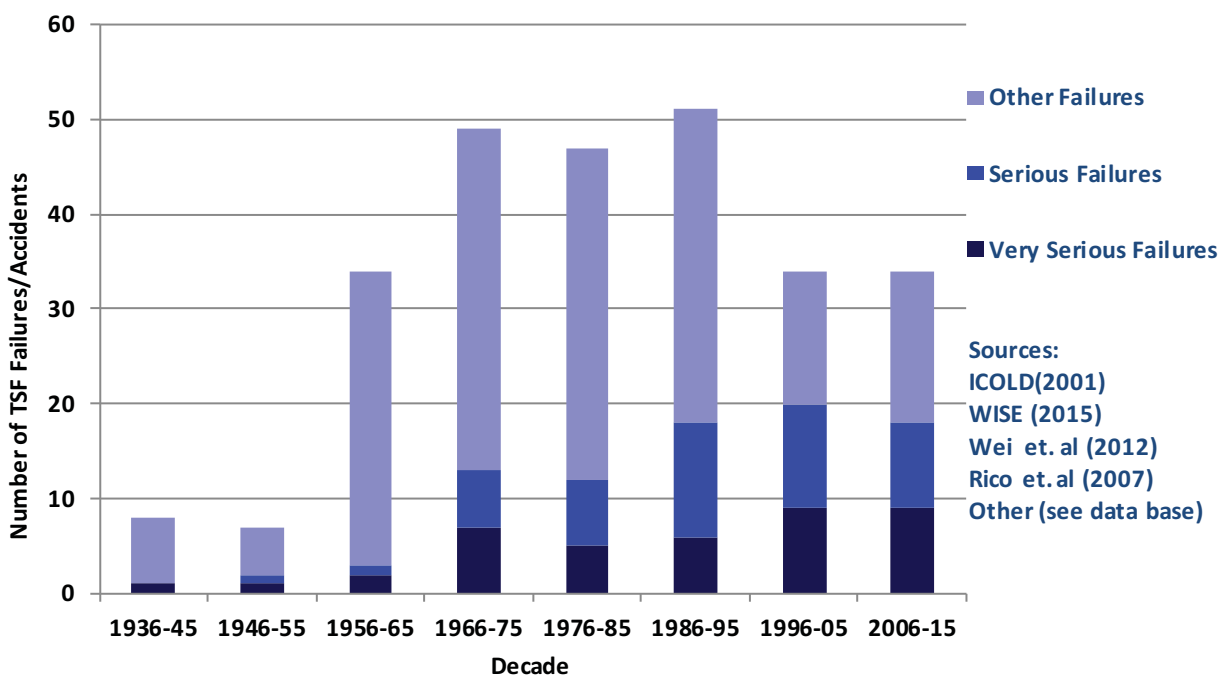

Figure 2. Increasing Severity of TSF Failures Globally by Decade 1936-2015

The overall distribution by severity over time is shown in Figure 2 for the period 1936 through 2015 by decade. The increasing severity of consequence in the recent three decades is apparent. Over the 80 years 1936-2015 the expected rate of very serious failures is 5 per decade (40/8). In the last three decades the rate has been 8.0 (24/3), a 60% elevation above the 100-year average. These data as of 12/31/2015 trend to an expected count of 10 for the decade 2010-2020,

as predicted in Bowker Chambers 2015. Important to note that since completing Bowker Chambers (2015) we discovered 7 additional Very Serious Failures as of 12/31/2009, indicating the degree of underreporting in the ICOLD and WISE compilations even for the most significant TSF failures. It was reported by Kiernan (2016b) that ICOLD spokesman Emmanuel Grenier said "ICOLD doesn't include the structures in its 58,000-entry World Register of Dams due to internal concern that their high failure rates would tarnish the reputation of all dams." Meanwhile slurry depositions at upstream earthen dams as at Samarco, continue to be planned, built and used. It is our hope that this paper will help bring large tailings dams into a common practical understanding and advocacy for the engineering and stewardship it takes for very large dams to avoid accrual of public liability at a level beyond funding or recovery.

2.2. Severity Distribution by Cause of Failure Code

Table 1, based on all recorded/known failures through 12/31/2015, shows Overtopping Failures at active mines in the context of all other cause of failure codes developed by ICOLD. This table is for the 125 incidents with listed causes of failure at operating mines recorded out of 267 Very Serious, Serious, and Other Failures recorded in our data base. The data in this table is also presented graphically in Figure 1. With the exception of Erosion (ER) and Foundation Failures (FN) which are low-frequency high-severity, the distributions by severity across the other 5 codes are very similar. Also the pattern by cause of TSF failure code at active mines (N= 125, excluding inactive failures) is the same as the severity distribution for the 267 records in Table 1 (N=267, inclusive of inactive mines), again pointing to a common root cause of severity of consequence beyond the coded cause of failure or the operating status of a mine at failure.

Table 1. Failure Modes by Severity Classification for Active TSF Failures

TSF FAILURE MODE BY SEVERITY CLASS (N=125)

ICOLD Classification	Active-EQ	Active-ER	Active-FN	Active-OT	Active-SE	Active-SI	Active-ST	Total Active (N=125)	Total All (N=267)
Cause → Failure ↓ Severity ↓	Earthquake	Erosion	Foundation	Over-toppng	Seepage	Slope Instability	Structural	TSF Failures by Severity	TSF Failures by Severity
Very Serious	2 (9%)	2 (33%)	4 (29%)	3 (10%)	2 (14%)	5 (19%)	3 (21%)	21 (17%)	41 (15%)
Serious	4 (18%)	2 (33%)	1 (7%)	5 (17%)	3 (21%)	4 (15%)	5 (36%)	24 (19%)	48 (18%)
Other	16 (73%)	2 (33%)	9 (64%)	21 (72%)	9 (64%)	17 (65%)	6 (43%)	80 (64%)	178 (67%)
TOTAL	22 (100%)	6 (100%)	14 (100%)	29 (100%)	14 (100%)	26 (100%)	14 (100%)	125 (100%)	267 (100%)

2.3. The Economics of Best "Waste Care" Practices in Ever Decreasing Global Grades

The economics of the Mining Metric 1910 to 2010, the basis of Bowker Chambers 2015, are shown in Figure 3. The term Mining Metric refers to a hypothesis often attributed to Edgar A. Scholz that production volume and scale of extraction would enable profitable mining of the globally depleted quantity of quality reserves even against a trend of falling prices. At the aggregate global level, that worked until about 1990. As is clear from Figure 3, which uses copper to show the same pattern present in all metals, falling prices were offset by falling ore production costs which absorbed the extra costs of increased ore production needed to attain the same level of finished metal output as grades fell steadily. Mining economist Richard Schodde's analysis showed that ore production costs declined 4-fold while milling costs declined 2-fold over the century (Schodde 2010). The decline in ore production costs was the key to threading the needle of profitability in an overall trend of falling prices, and falling grades which necessitated ever higher volumes of ore production and mill throughput to generate a given desired output of final product.

Larger higher grade mines had an easier run up until 1990 compared with the many smaller, inexperienced, less well financed miners who came into production after 1950. Those mines and miners were not as able to attain a satisfactory margin because of lower grades and generally higher production costs due to their more limited ability to achieve Scholz's economies of scale. They showed their vulnerability through more frequent periods of standby. None of the

mines Scholz himself developed according to his hypothesis ever actually attained profitability. Taseko and its sole asset in development, Gibraltar being the latest example. Gibraltar was one of the original Scholz mines.
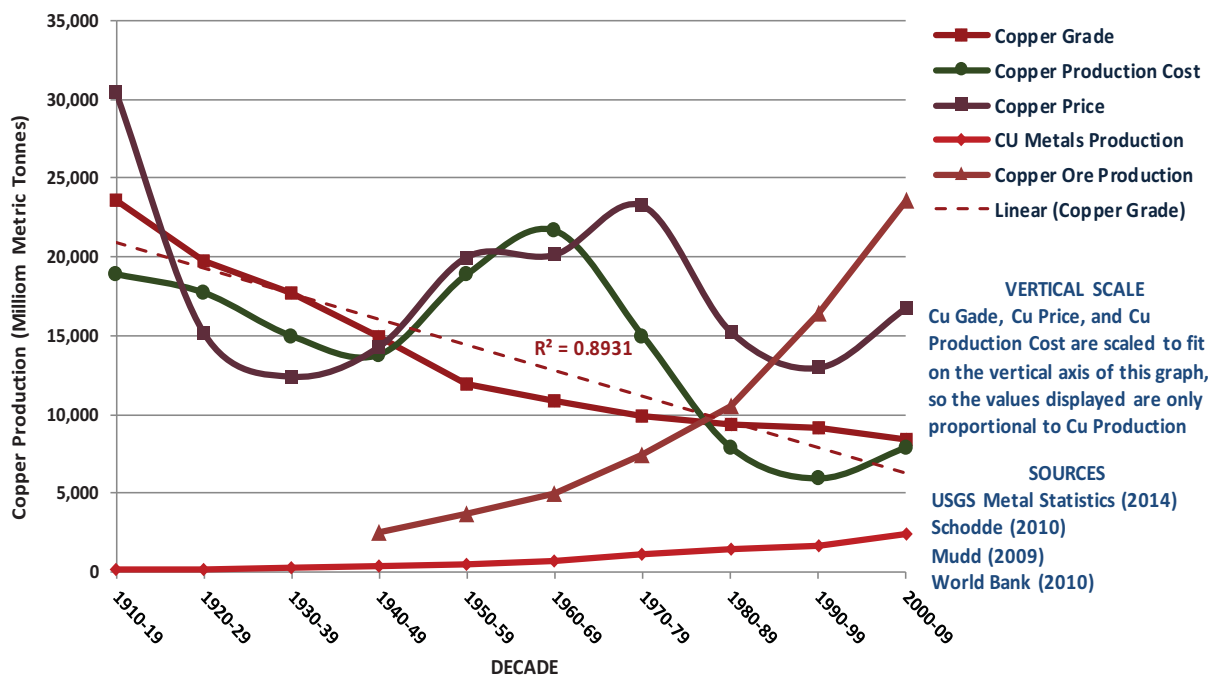

Figure 3. Mining Metric 1910-2010 Declining Prices Offset by Lower Production Costs

In 1990 the sustaining relationship between falling prices and concurrently falling ore production costs changed, both heading upward but with continued declines in grade and a very significant upward swing in ore production volumes needed to offset those lower grades. Some overproduction also occurred in this "super cycle" so the huge upward swing in ore production is not 100% attributable to continuing decline in grade. It is in this period of change in the relationship between as-milled grade and ore production volume that the trend to increasing severity of failures emerged. It is important to note that while there was an upswing in copper price, prices in real dollars ($2009) during the super cycle never reached their previous cycle-high in 1970. This limited recovery in price viz. historic prices, in combination with upward swing in ore production costs, set up the economic squeeze manifesting as an emerging trend of higher severity failures. As at Samarco, the largest tailings storage facility failure in recorded history, the manifestation of the economic squeeze is no longer limited to small mines and junior and mid-sized miners.

Obviously the high volume/lower cost ore production possible through open pit mining and the need that created for bigger and higher tailings facilities dramatically increased the risk profile of the global tailings inventory as noted by Dr. A. Mac G. Robertson in his key note address at the 2011 tailings conference (Robertson 2011). However, what we can see from examining reports on existing mines is that increased tailings capacity is being created at older tailings storage facilities with smaller footprints, not by the design and development of new TSFs specifically engineered to handle the higher volumes, longer lives, and higher throughputs. Major throughput expansions rarely include a systematic reevaluation of existing TSF capacity, or a reevaluation of tailings management needs inherent in the planned expansion. This is the Samarco failure story. There was no capacity and no plan or space to create capacity. They knew as a result of much lower grades the level of fines in the tailings generated for the two years prior to failure precluded use of dry stack and/or paste, as a way to get more and safer life out of the existing modern era facility which went on line in 2009 (Amira et. al. 2010). Vale vigorously denounced Brazil's plan to ban large upstream dams like the Fundao acknowledging that mining ore in Minas Gerais was not possible economically with such a ban (Eisenhammer and Nogueira 2016). Brazil backed down.

2.4. The Link Between Severity of Failure, Grade of Ore and Production Costs

The methods used to establish the relationship between the Mining Metric and the emergence of a trend of increasing severity of failures is shown in Bowker and Chambers (2015) and its technical appendices.

Our final input data set for this analysis is shown in Table 2, and is also available in machine readable form at the CSP2 website along with more comprehensive technical documentation.

Table 2. Input Data Set

Decade	Very Serious Failures	Serious Failures	Other Failures	Other Accidents	Non-Dam Failures	All Failures	Cu Prod (K tonnes)	Cu Grade (%)	Cu Prod Cost $/tonne	Cu Price $/tonne
1940 – 49	0	0	5	0	0	6	2545	1.52	$35	$3,633
1950 – 59	1	0	7	0	0	7	3680	1.21	$48	$5,076
1960 – 69	3	4	25	17	2	51	5004	1.1	$55	$5,112
1970 – 79	4	8	23	15	3	53	7445	1.01	$38	$5,895
1980 – 89	5	9	22	14	4	54	10575	0.95	$20	$3,871
1990 – 99	9	9	10	3	1	32	16437	0.93	$15	$3,292
2000 – 09	7	8	5	1	0	21	23658	0.85	$20	$4,256
	======	======	======	======	======	======	======	====	======	======
Total/Ave	29	38	97	50	10	224	69,344	1.54	$33	$4,448

Sources: USGS Metal Statistics (2014), Schodde (2012), ICOLD (2001), WISE & additional

Abbreviations:
Very Serious Failures = Very Serious tailings dam failures
Serious Failures = Serious tailings dam failures
Other Failures = tailings dam failures and incidents other than Serious or Very Serious Failures
Cu Prod = copper ore production (thousand metric tonnes)
Cu Grade = grade of copper in the ore (%)
Cu Prod Cost = Cost to produce copper concentrate from copper ore, including waste disposal ($/tonne)
Cu Price = Copper price ($/tonne)

The key relationships between severity and Mining Metric elements were identified in an analysis of univariate correlations as shown in Table 3. In analysis leading up to 1990, costs of production canceled out price (as Schodde had correctly concluded in his analysis) and had stronger relationships with severity.

Table 3. Univariate Correlation Between Mining Metric Variables and Severity Variables

Variables	Cu Ore Production	Cu Grade	Cu Prod Cost
Very Serious Failures	0.860	-0.794	-0.788
Serious Failures	0.720	-0.884	-0.682

Abbreviations:
Very Serious Failures = Very Serious tailings dam failures
Serious Failures = Serious tailings dam failures
Cu Prod Cost = Cost to produce copper concentrate from copper ore, including waste disposal
Cu Grade = grade of copper in the ore
Cu Prod = copper ore production
Sources: USGS Metal Statistics (2014), Schodde (2010), ICOLD (2001), WISE (2015) & additional

While all three mining metric variables: ore grade; ore production volume; and, unit costs for ore production, correlated highly with both Very Serious and Serious Failures, in univariate analysis it is interesting and important to

note the different patterns of correlation between the two severity classes. Very Serious Failures have a much stronger relationship with ore production volume and costs of production as compared with Serious Failures which have a stronger relation with as-milled grade. These are exceptional correlations with the economic descriptors of the Mining Metric.

Exploring these relationships further to see how much of the variation in severity was accounted for by each of the key Mining Metric variables, we used canonical correlation analysis (Bowker and Chambers 2015). Canonical Correlation Analysis (CCA) is almost universally defined as "the problem of finding two sets of basis vectors, one for data set Y1 (the two high severity classes) and the other for data set Y2, (the Mining Metric variables) such that the correlations between the projections of the variables onto these basis vectors are mutually maximized."

CCA seeks a pair of linear transformations, one for each of the sets of variables such that when the set of variables are transformed the corresponding co-ordinates are maximally correlated. The linear transformations are synthetic variables. One "synthetic variable" or canonical variate is created for each data set (F1, F2 for our two sets), as shown in Table 4.

Table 4. Correlations between Input Variables and Canonical Variables

Y1 Data Set of Severity by Decade			Y2 Data Set of Mining Metric Values by Decade		
	F1	F2		F1	F2
Very Serious Failures	-0.922	-0.388	Ore Production	-0.802	-0.558
Serious Failures	-0.995	0.096	Copper Grade	0.929	-0.072
			Copper Cost	0.755	0.45

The principal output of a canonical correlation analysis are the canonical functions (variates) which seek to maximize explained variability between the two arrays (Y1 and Y2). Each function produced is an equation (similar to the equations created in regression analysis) but instead of explaining the relationships in terms of causality, it seeks to define the dimension (strength) of the relationship between (or in larger data sets among) the arrays. Essentially it asks are these arrays independent of one another, or does there appear to be an influence of the two arrays on one another. As many canonical functions are produced as there are variable sets (in our case 2).

The proper use of canonical correlation analysis for descriptive analysis requires no assumptions of distribution. To test the significance of the relationships between canonical variates, however, the data should meet the requirements of multivariate normality. We were not able to conduct a full multivariate normality as it was not an option in XLSTAT©. The normality of each variable within the data set is not a proof of multivariate normality, but all elements of a data set that does meet the requirements of multivariate normality must meet univariate tests of normality. All variables met Jarques-Bera normality test, a test most frequently applied in economics.

The first exploration of these canonical functions is the eigenvalue which measures how much variability is explained by each of the canonical functions. The closer the eigenvalue is to zero the less likely the two arrays form a diagonal matrix, i.e. have a linear correlation to one another which might therefore be suitable for linear modeling (regression analysis).

As can be seen in Table 5, the canonical correlation itself, 0.950 accounted for 95% of the variability between the two data sets. In this case the Eigenvalue for the first canonical function, F1 = 0.903, strongly indicates a diagonal matrix.

Table 5. Canonical Correlation Values

	F1	F2
Canonical Correlation	0.950	0.727
Eigenvalue	0.903	0.528
Wilks' Lambda	0.046	0.472

Wilks' Lambda is a test of the null hypothesis that the data sets are independent of one another as measured via the canonical coefficients. The lower the Wilk's Lambda, the less likely that the data sets Y1 and Y2 are independent. The results, a Lambda of 0.046, significant at a 92% confidence level means it is unlikely that the two data sets are independent of one another. That is, if accepted the null hypothesis that the two data sets are independent of one another there is a 92% chance we'd be wrong. A further explanation of canonical correlation analysis and its interpretation may be found in Appendix II of Bowker and Chambers (2015). As evident in Table 5, which includes the correlations for the second factor as well (F2), it added little to the overall understanding of the mutual dependence between severity and Mining Metric.

It is reasonable to infer that the influences of declining grades, production cost, and ore volume produced (virtually same as tailings volume) on severity of consequence exist also at the level of "cause of failure" for overtopping and all other coded causes of failure. The Mining Metric has a strong linear relation with each of the two high severity classes for all such recorded significant failures and incidents. Therefore, the Mining Metric must also have this same linear relationship with severity at the level of cause of failure code. How this works at the mine level is illustrated in the discussion below, which places some well-known overtopping events in the context of the global economics of the Mining Metric.

2.5. Economic Root Causes of Well Known Overtopping Failures: Grade as a Key Root Determinant

The fundamentals of how this plays at the mine level is simply and succinctly expressed by Andrey Dashkov, Senior Analyst, Casey Research: "As a project moves to the development stage, the higher the grade, the more robust the projected economics of a project. And for a mine in production, the higher the grade, the more technical sins and price fluctuations it can survive." (Dashkov 2013). Continuing in this analysis Dashkov goes on to declare that volume and throughput (the Scholz foundation for profitability of low grade mines) is "no longer king," and that grade is "now king" in determining which mines will be successful and which will fail. This was essentially validated by Bowker and Chambers (2015) as the context and main driver of the emerging prevalence of catastrophic failure. This applies equally to failure by any of the 8 causes of failure, including overtopping.

Dashkov's analysis that a grade advantage is a critical determinant of ability to survive serious technical flubs and dramatic unpredictable price fluctuations, a norm for all metals, means that smaller, lower grade mines will suffer more and have more physical manifestations of their economic stress than larger, higher grade mines. Very simply, smaller, lower grade mines operated by junior and midsize miners have no cushion. They have to ride too close to the edge of financial viability viz. global metals markets and major producers to stay in production. They also have less access to high quality capital markets, paying more and operating under more onerous terms of credit than the top producers at higher grade mines, a factor that George Ireland has frequently cited as creating financial instability and uncertainty when the due dates of credit don't match up with cash flows needs, expected revenue generation, and production capacities of the mine. This mismatch can actually lead to failure or involuntary investor takeover elevating uncertainty and instability (Sylvester 2012).

In gold, as a respected analyst Mark Fellows explains, a 10% fall in global average ore grade gives rise to a $50/oz rise in average global production costs (Fellows 2010). At the mine level, a difference between a gold mine with 1.72g/t and 2.2 g/t translates to a likely cost difference of $100/oz in total production costs. These are the actual differences at the Gold Ridge mine, Guadalcanal, in 2009. This mine never achieved profitability, not because of political unrest, but because the low quality of the deposit compared to the quality of ores shaping world markets. Gold Ridge, with a 20 million cubic meter capacity tailings storage facility with a long history of many owners, frequent interruptions, and continually falling recovery rates (another emerging consequence of mining very low grade ores), under ownership of landowners with no technical competence, has hovered on the brink of complete failure by overtopping for two years. Blight and Fourie (2004), George Ireland (Sylvester 2012) and Irwin Wislesky (Moore 2016), among others, all cite technical competence, technical mistakes, and caliber of mine operators as an unexamined and significant back drop to mine failures.

Merriespruit, South Africa, is one of the most famous and examined cases of overtopping failure (1994) in history. The mine's long demise and its many manifestations of economic stress over the entire course of Harmony Gold's ownership illustrates another aspect of how an economic squeeze shaped by global markets and major global producers affects the viability of a given mine. The dam that failed began construction in 1978 (Fourie 2011), at the end of a

period of South Africa's global dominance in gold. "As a proportion of world production (excluding that of the U.S.S.R.), South Africa's production peaked in 1971 at 79.1 per cent. [it fell] consistently, to a 1985 level of 55.8 per cent, under the combined influence of declining total South African production and increasing output from elsewhere, particularly North America, Australia, and Brazil. As a percentage of new world supply, which includes imports from the Communist sector, South Africa's contribution decreased from 78.7 per cent in 1970 to 47.3 per cent in 1985" (Janisch 1986). South African gold mines still had exceptional grade compared to emerging producers, but Merriespruit and most others were all costly underground mines whilst the emerging major markets were all open pit mines. The economic advantage of much higher grade wasn't enough to overcome the disadvantage of much higher costs to extract and process it compared to other emerging markets and top producers, placing further economic stress on Merriespruit and all South African mines.

3. CONCLUSIONS

As we see most stunningly at Samarco's largest failure ever in recorded history, without clear standards in law and regulation viz. best available technology and best applicable practices, and adequate competent independent life of facility oversight, efforts to attain profitability will continue to lead to choices at the mine level that can eventually lead to catastrophic loss. As we see at Mt Polley, that eventual catastrophe could emerge as any one of several causes of loss. Mt Polley could have been an overtopping failure of the same magnitude as the foundation failure. Samarco's Fundao dam, it is important to note, was only put in service in 2009, had an Independent Tailings Review Board, and highly regarded expert advisers. In British Columbia, Imperial Metals was found not to be in violation of any law and regulation, even though its economically driven deviations from best available technology and best applicable practices culminated as one of the 10 largest failures ever in recorded history. Similar economic forces and economically driven decision making that maximize throughput have shaped the wrong choices that have led to very serious failures throughout recorded history.

Preventing overtopping is an essential and key part of global overall loss prevention. Identifying best technology and best practice for achieving overtopping prevention is essential to preventing accruals of public liability, protecting investors, local communities, and non-replaceable natural resources. Most importantly a better understanding of causes of loss establishes a basis for intervention in time to prevent tailings dam failures. If we can recognize the early warning signs that could evolve to catastrophic loss, we will be able to address actions and changes to prevent loss. We can expect future losses to routinely exceed the severity of Mt. Polley. With so many very large upstream tailings dams in use and continuing to be authorized, we can also expect others to fail at the scale of Samarco, a very small impoundment compared to others standing and in operation.

Law and the use of truly independent expert panels speaking for the public interest cannot operate effectively without this continual collaborative work. In this paper we are suggesting that best available technology and best applicable practices must be partnered with reforms in law and regulation, and an awareness of the role of economics to build solutions that will save investors, communities, and natural resources from the unfundable damages of catastrophic failure at super-sized tailings storage facilities. If permits continue to be given to mines that are not economically competitive in the present and emerging global markets, even with apparent or agreed compliance with best available technology and best applicable practices, there will be economic pressure on mine operators to bend the rules. Only truly independent life of mine review and oversight, extending the technical knowledge, and developing the understanding and capacity of regulators can prevent further dam failures.

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