UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

A Proposed Method for Optimizing Coal Pillar Design using Coalfield Specific Uniaxial Compressive Strength

F. Bruwer

29 July 2022

Content

- Introduction
- Thinking behind the suggested method
- Pillar Strength Formulae and their adjustment
- Research methodology
- Results obtained using the proposed method
- Questions

Acknowledgements

This research was made possible by the contributions of Mr. Trevor Rangasamy from Middindi Consulting who supplied UCS test results for use in the analysis; Professor Nielen van der Merwe who provided the South African coal pillar database, additional UCS data, as well as guidance and insight on the matter of coal pillar design. And finally Professor Thomas Stacey who supervised the research and provided feedback and support

Introduction

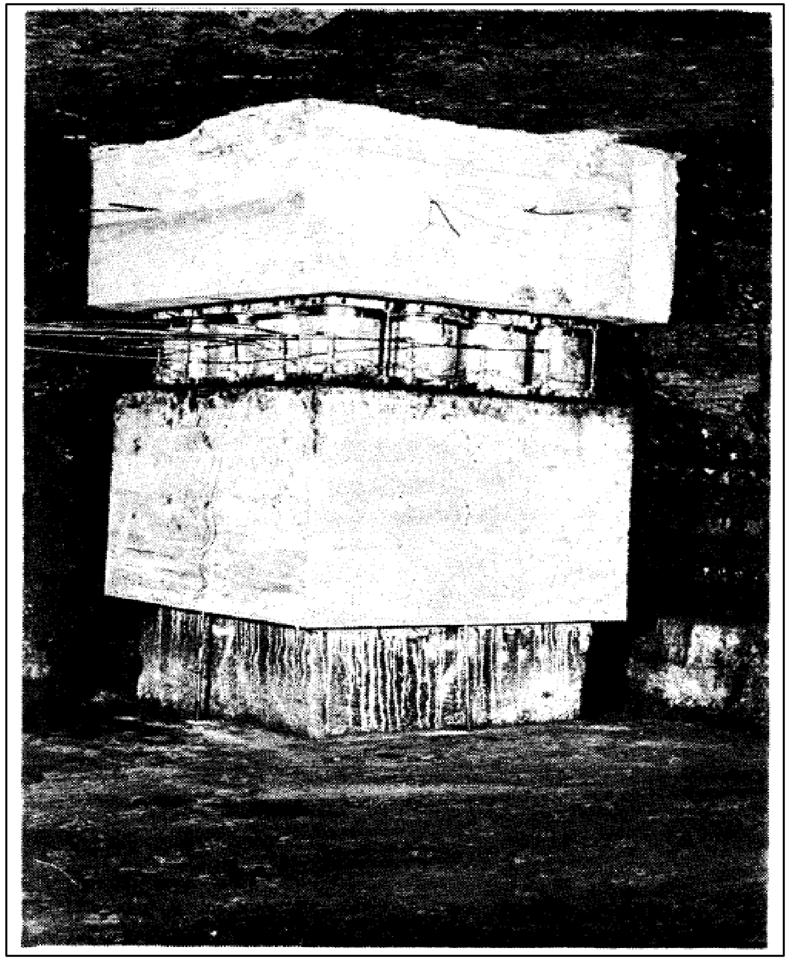
- Current empirical pillar design formulae make use of a fixed ‘bulk strength’ (k) – Therefore does not facilitate optimisation between different coalfields

- The fixed bulk strength is based on back analysis of historic pillar failures, intended for use predominantly in South African coalfields (with the exception of the Vaal Basin)

- The proposed method investigated whether UCS data could be used to optimise coalfields with relatively stronger material compared to the regional mean strength (Bulk Strength)

Introduction

- There have been many attempts to use the uniaxial compressive strength of coal to estimate pillar strength, none of which returned usable results. York and Canbulat (1998) provide a detailed summary of these attempts
- All attempts led to the conclusion that the extrapolation of pillar strength from a laboratory sample is significantly affected by the **'scaling' effect**. The 'scaling' effect refers to the estimated reduction in sample strength obtained when increasing the size of the sample
- Further attempts included full scale pillar testing. This however is not feasible on a continuous and repetitive basis and multiple tests would be required to provide sufficient understanding of the variability in pillar strength within a specific coalfield

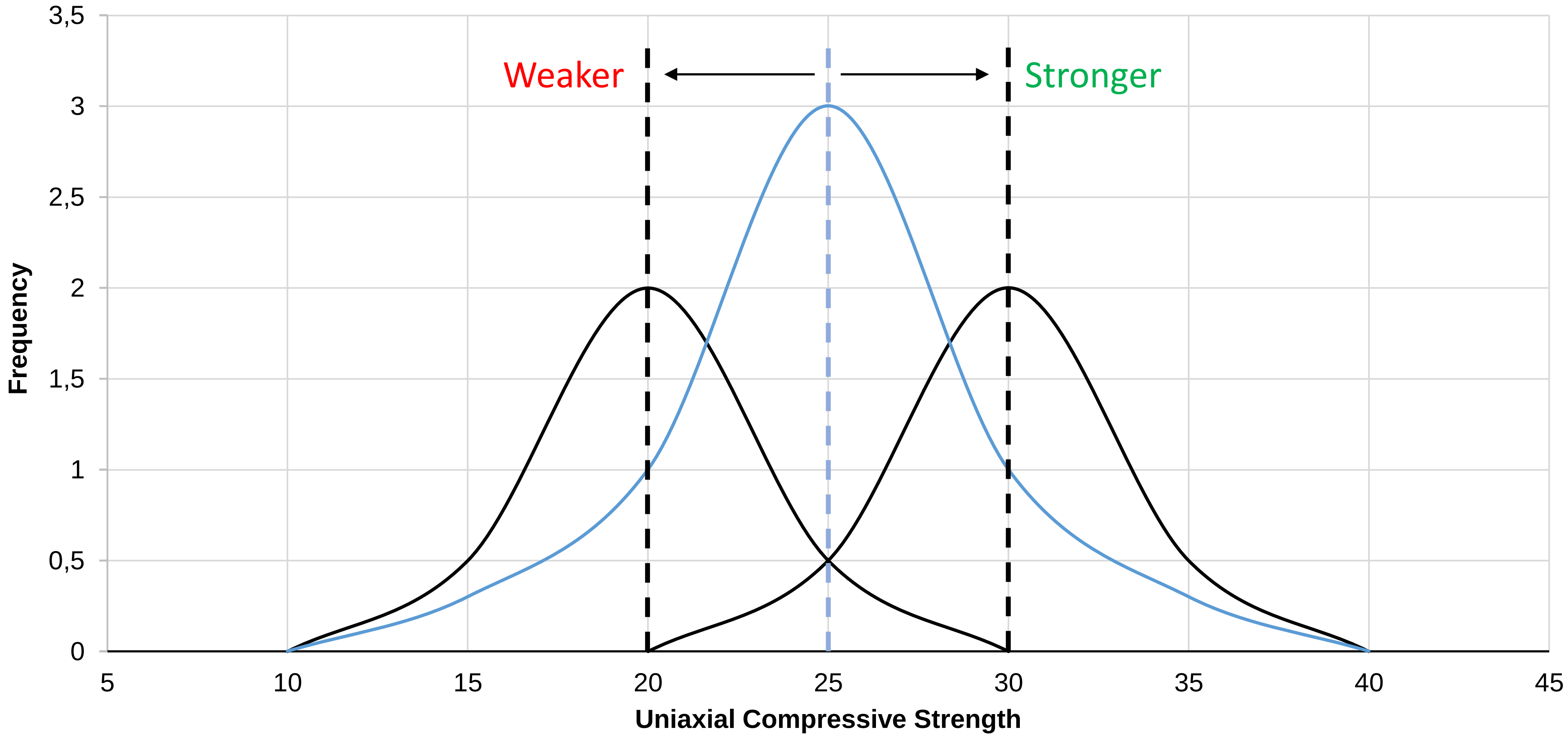


(Van Heerden, 1975)

Introduction

- Rather than extrapolating pillar strength from UCS data, this research investigated whether the **variability in coal material strength** could be used to estimate the **variability in coal pillar strength**
- The proposed method suggests expressing a pillar design as a distribution of strength values rather than a single bulk strength (k)
- Subsequently, the design can be expressed as a **Probability of Failure** rather than the conventional **Safety Factor** (not a single value but a distribution of values)

Introduction



Assumptions applied to the analysis

- Pillar loading is accurately expressed by the application of the Tributary Area Theory (TAT), where every similar sized pillar carries an equal overburden load; and

- The set of UCS results used in the study, obtained from various South African collieries within the Mpumalanga province, provides a realistic indication of the strength of, and variability in, the coal material in Mpumalanga coalfields

Datasets

- Two sets of data were used in the study:
  - UCS dataset

Source	Number of datapoints	Mean	Min	Max	Std. Dev
Mine A	9	**22.4**	12.3	40.5	8.9
Mine B	21	**21.9**	9.3	40.5	7.9
Mine C	20	**29.4**	22.0	38.5	5.3
Multiple sources	33	24.1	7.6	48.8	9.7
Total Dataset	83	**24.6**	7.6	48.8	8.7

  - South African Coal Pillar Failure database – Latest iteration covers 424 pillar cases

Pillar Strength Formulae used in the study

Salamon and Munro (1967)	Van der Merwe (2003)
$Strength = 7.17\left(\frac{w^{0.46}}{h^{0.66}}\right)$	$Strength = 3.5\left(\frac{w}{h}\right)$
Maximum Likelihood	**Overlap Reduction**
$Strength = 6.61\left(\frac{w^{0.5}}{h^{0.7}}\right)$	$Strength = 5.47\left(\frac{w^{0.8}}{h}\right)$

Research Methodology

- The approach adopted for this study, to keep to the bulk strength values determined for each of the formulae by the original authors, introducing UCS results only as a means of expressing variability

Research Methodology – Adjustment to pillar formulae

$$Bulk\ Strength\ (k) = \frac{UCS}{Factor\ (f)}$$

- This factor is constant regardless of the coalfield being designed for
- The formulae were adjusted to using the total *'regional'* probability density functions – Each formulae had to produce the same bulk strength as the original formula

Research Methodology – Adjustment to pillar formulae

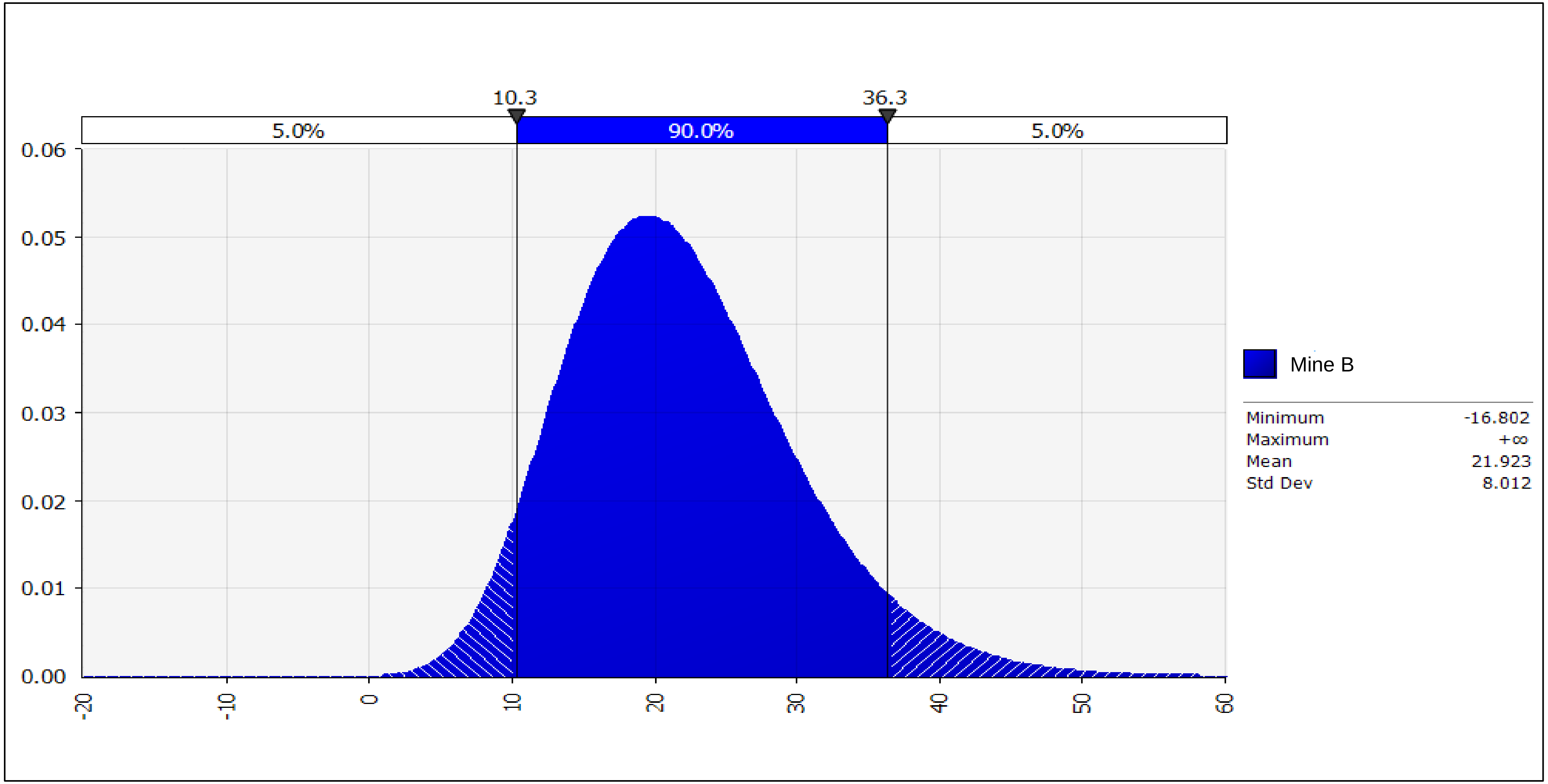
Adjusted Salamon and Munro (1967)	Adjusted Van der Merwe (2003)
$Strength = \left(\frac{UCS}{3.43}\right) \times \left(\frac{w^{0.46}}{h^{0.66}}\right)$	$Strength = \left(\frac{UCS}{7.05}\right) \times \left(\frac{w}{h}\right)$
Adjusted Maximum Likelihood	**Adjusted Overlap Reduction**
$Strength = \left(\frac{UCS}{3.73}\right) \times \left(\frac{w^{0.5}}{h^{0.7}}\right)$	$Strength = \left(\frac{UCS}{4.51}\right) \times \left(\frac{w^{0.8}}{h}\right)$

Research Methodology – Probability density functions

- In order to calculate a probability of failure from the UCS data, the UCS data were expressed as probability density functions
- To assist with analysis, the function curves were produced using the software program @Risk
- Best fit statistical functions were selected for the data - **Lognormal**

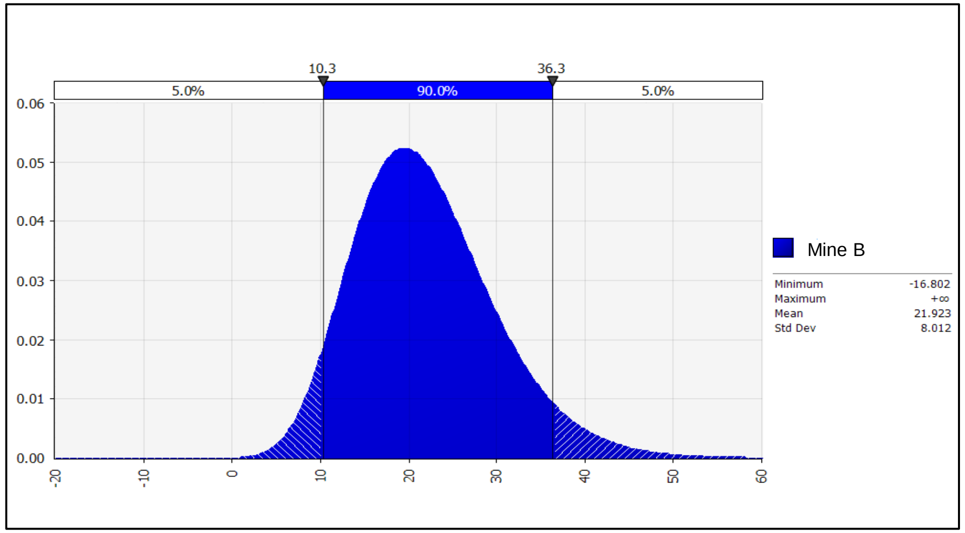
Dataset	Mean		Standard Deviation	
	Original	Lognormal curve	Original	Lognormal curve
Mine A	22.4	22.8	8.9	12.3
Mine B	21.9	21.9	7.9	8.0
Mine C	29.4	29.5	5.3	5.8
Total Dataset	24.6	24.7	8.7	8.8

Research Methodology – Probability density functions



Research Methodology – Calculation of Probability of Failure

- Using @Risk, the probability density functions obtained from the UCS data set, were used as the input parameter into the 'UCS' parameter of the adjusted formulae



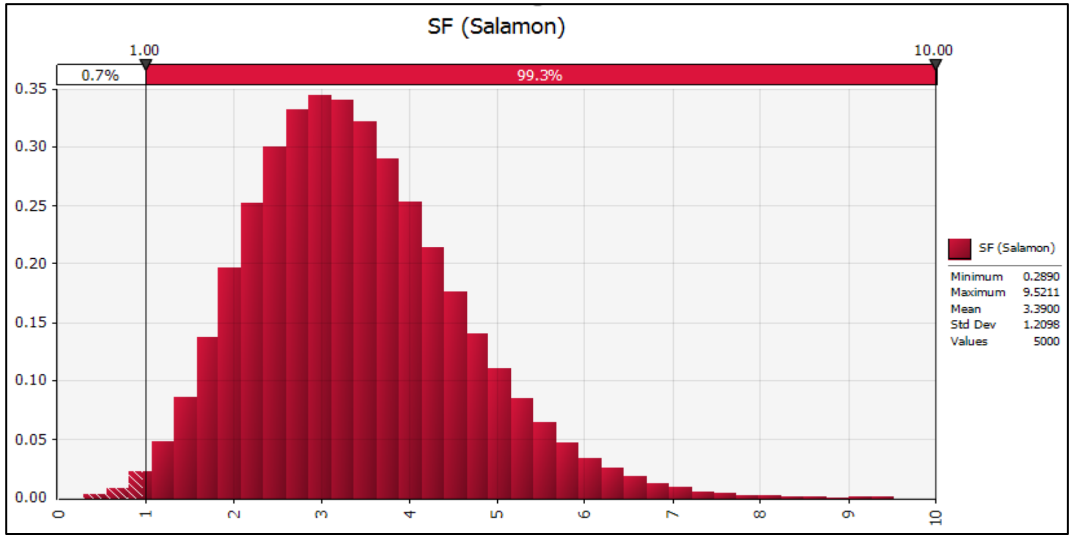
$$Strength = \left(\frac{UCS}{3.43}\right) \times \left(\frac{w^{0.46}}{h^{0.66}}\right)$$

- This provided a distribution of pillar strengths

Research Methodology – Calculation of Probability of Failure

- The resulting pillar strength distribution is subsequently used as the input into the capacity parameter for calculating a distribution of safety factors

$$Safety\ Factor = \frac{Capacity}{Demand}$$



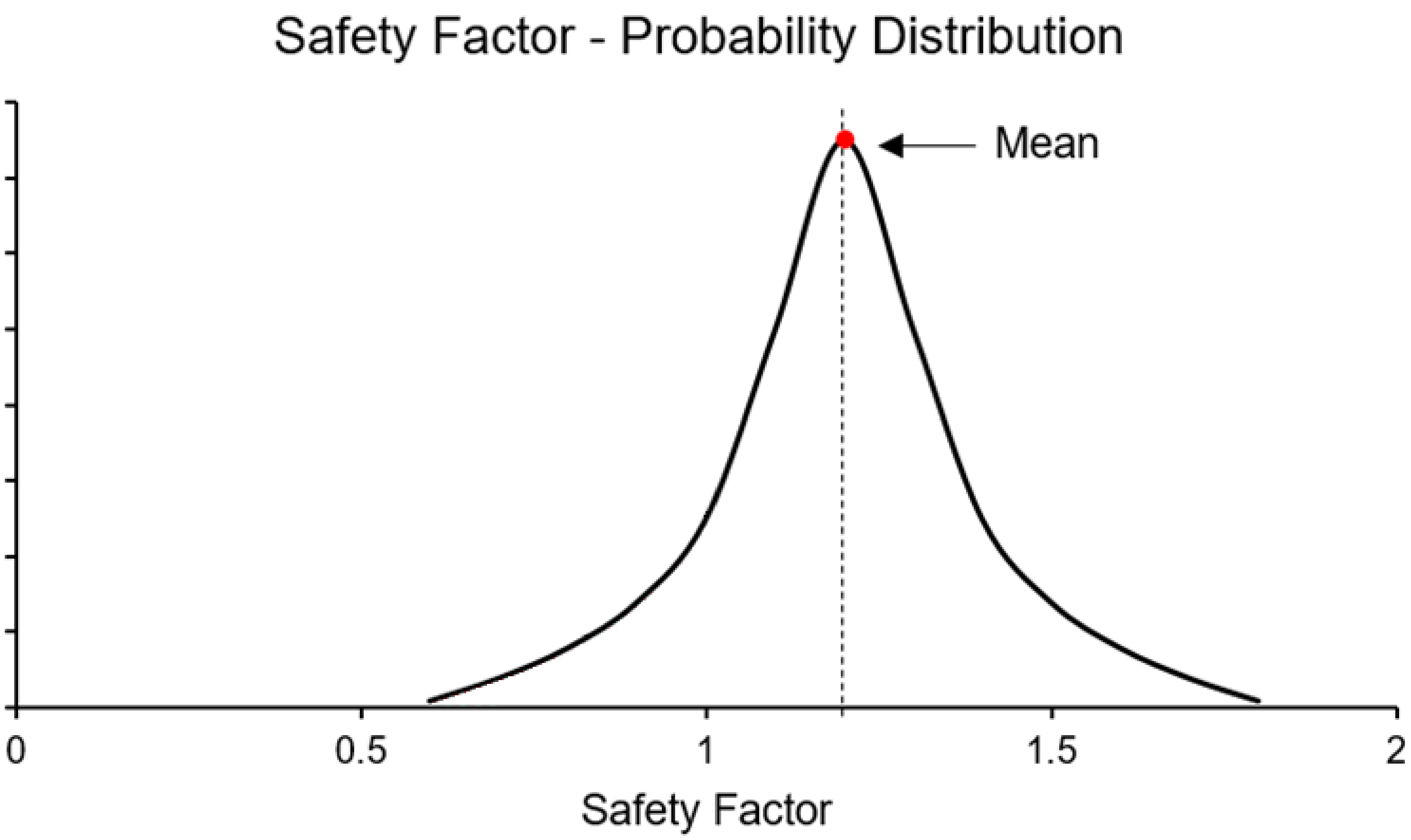
- This process is repeated for each of the datasets available using each of the adjusted formulae

Research Methodology – Validation of adjusted formulae

- To validate whether the adjusted formulae still provided similar results to the original pillar strength formulae, 10 randomly selected pillar scenarios were selected from the pillar failure database (5 from the unfailed and 5 from the failed datasets)

- For each scenario the **mean safety factor** from each **distribution** was selected (being the value which occurs the most frequent in the distribution)

Research Methodology – Validation of adjusted formulae

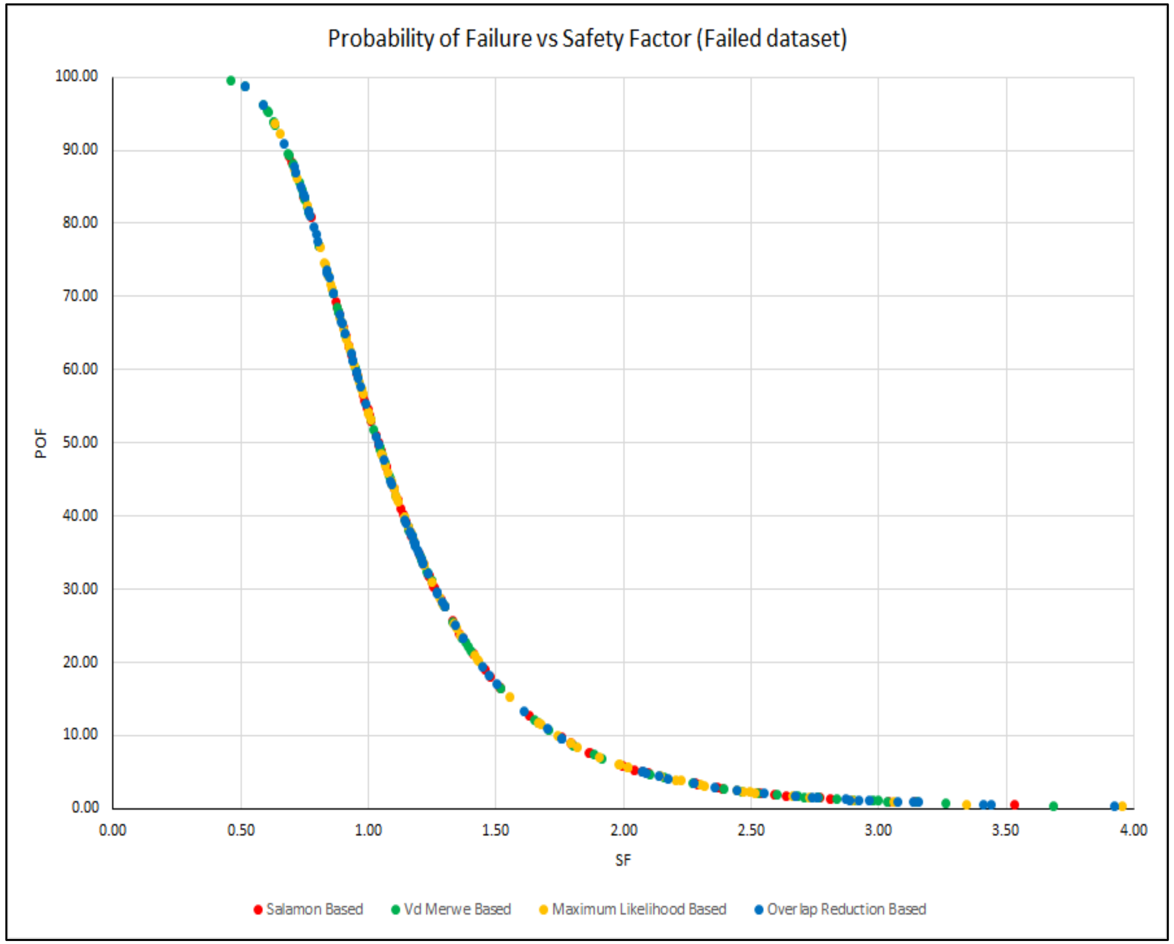


UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

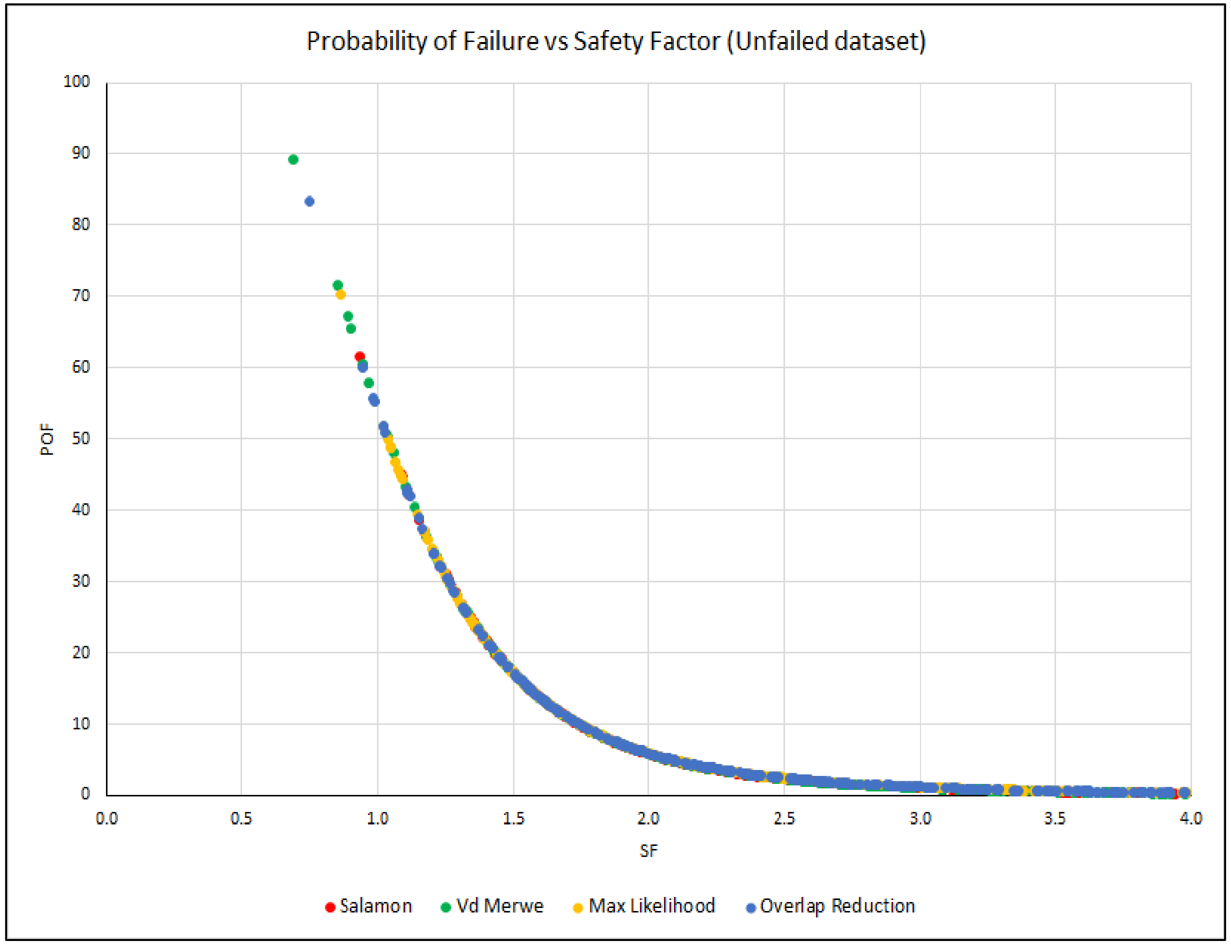
Research Methodology – Validation of adjusted formulae

Database	Pillar case number	SF - Salamon		SF - Van der Merwe		SF - Maximum Likelihood		SF - Overlap Reduction	
		Original formula	Adjusted formula	Original formula	Adjusted formula	Original formula	Adjusted formula	Original formula	Adjusted formula
Failed	5	4.85	4.84	4.45	4.45	4.58	4.59	4.75	4.75
	29	1.26	1.25	0.95	0.94	1.16	1.16	1.03	1.03
	51	0.92	0.92	0.63	0.63	0.85	0.85	0.76	0.76
	66	1.01	1.01	0.71	0.71	0.94	0.94	0.88	0.88
	83	0.77	0.77	0.63	0.63	0.72	0.72	0.67	0.67
Unfailed	71	2.48	2.47	3.82	3.82	2.47	2.47	3.85	3.84
	140	2.29	2.29	3.21	3.21	2.25	2.25	3.05	3.05
	228	2.35	2.35	3.82	3.82	2.34	2.34	3.50	3.50
	284	4.02	4.02	6.69	6.68	3.98	3.98	5.77	5.77
	328	4.01	4.01	5.18	5.17	3.92	3.92	5.10	5.10

Research Methodology – Validation of adjusted formulae

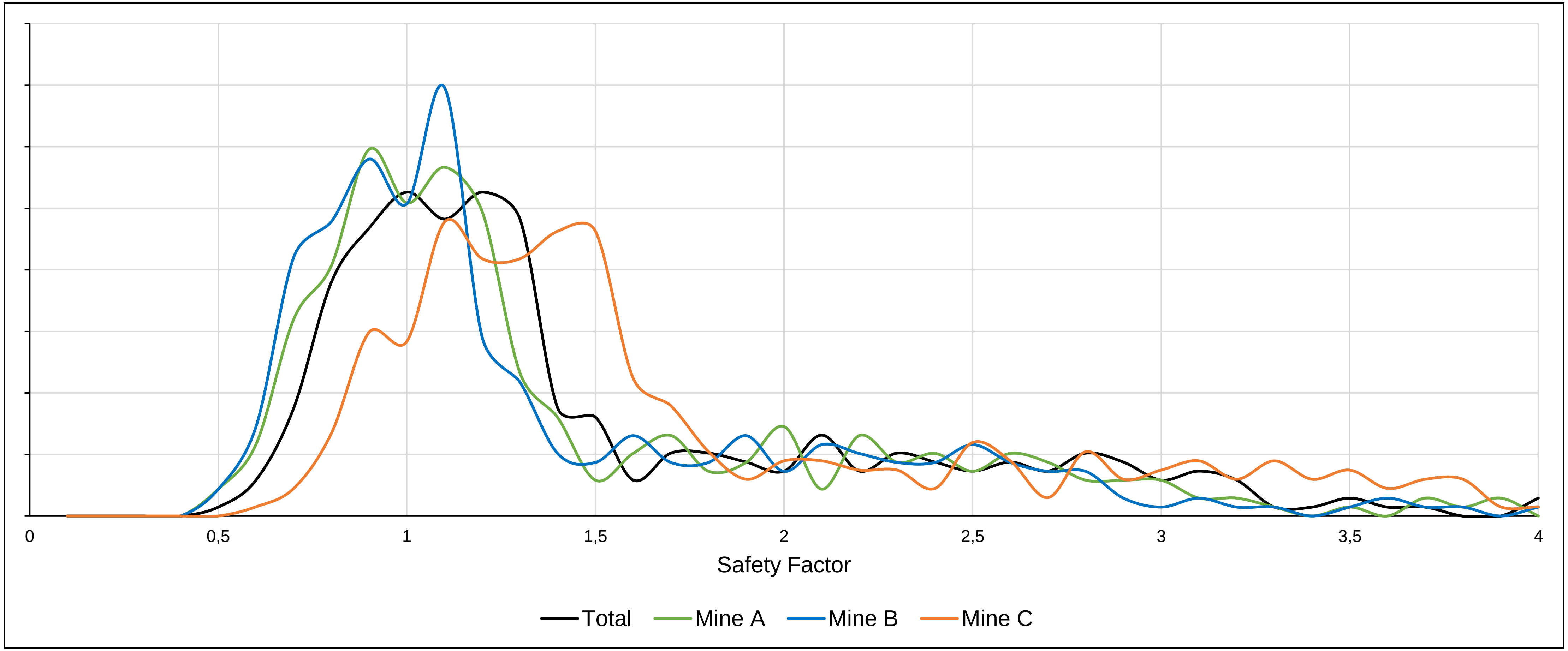


Probability of failure 50 % = Safety factor 1.04



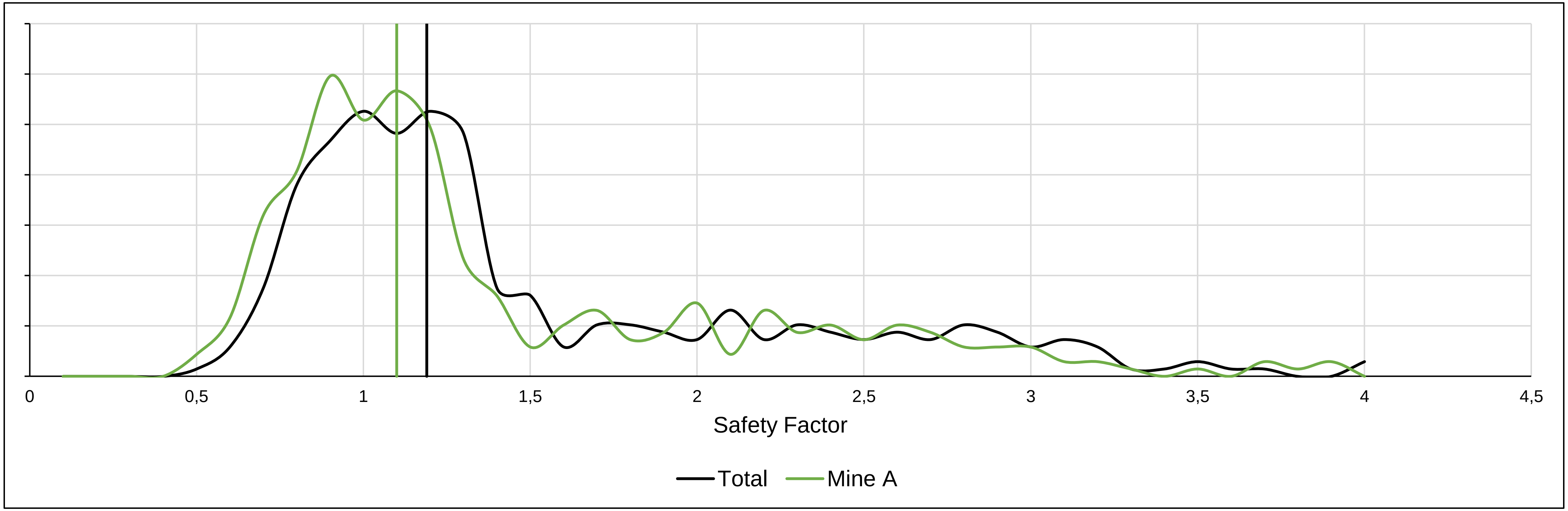
Safety factor 1.6 = Probability of failure 13.8 %

Research Methodology – Results obtained from method

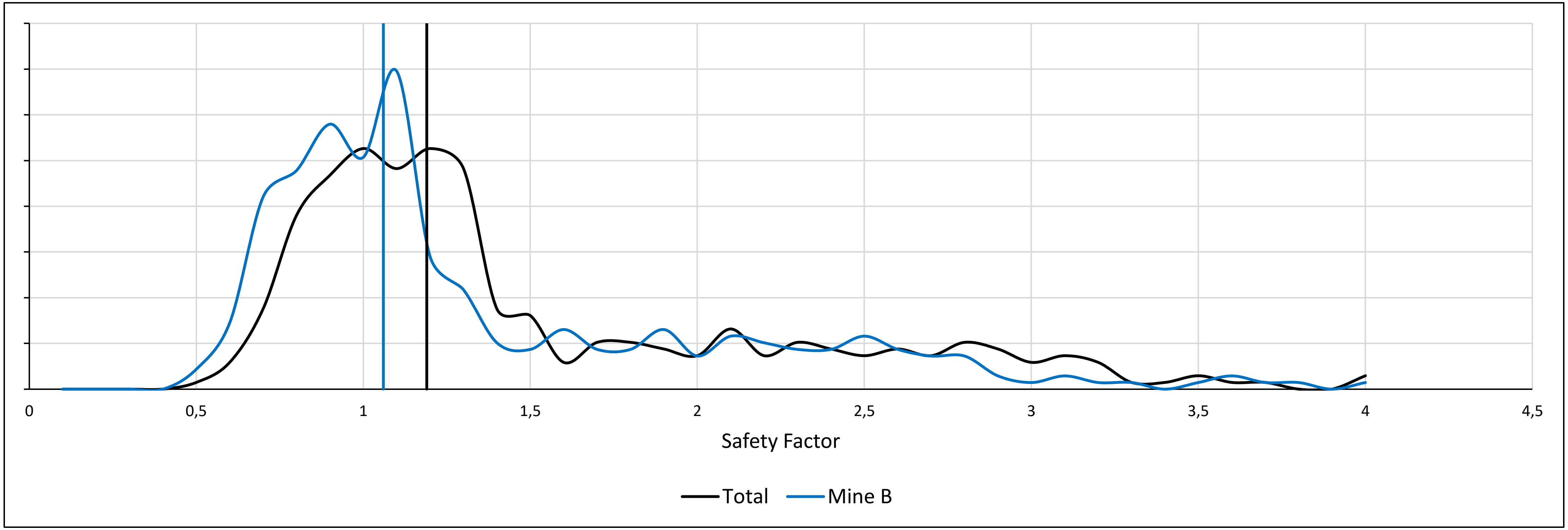


Research Methodology – Results obtained from method

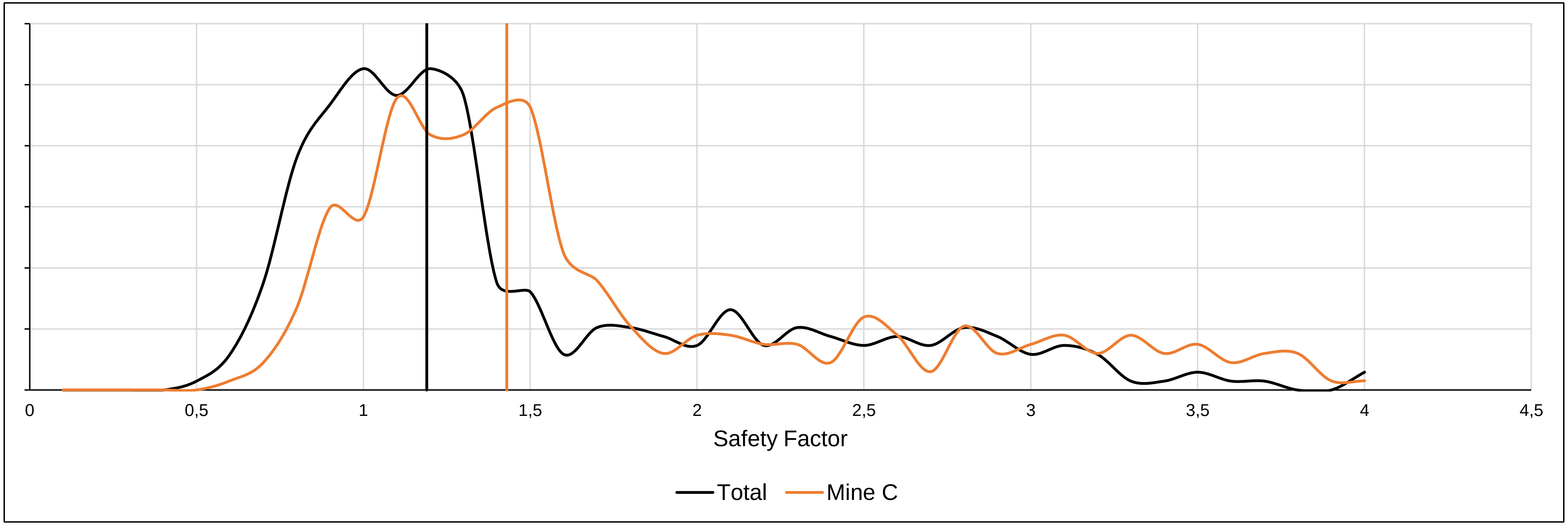
- Due to the datasets returning bi-modal distributions, the harmonic mean was used for comparisons



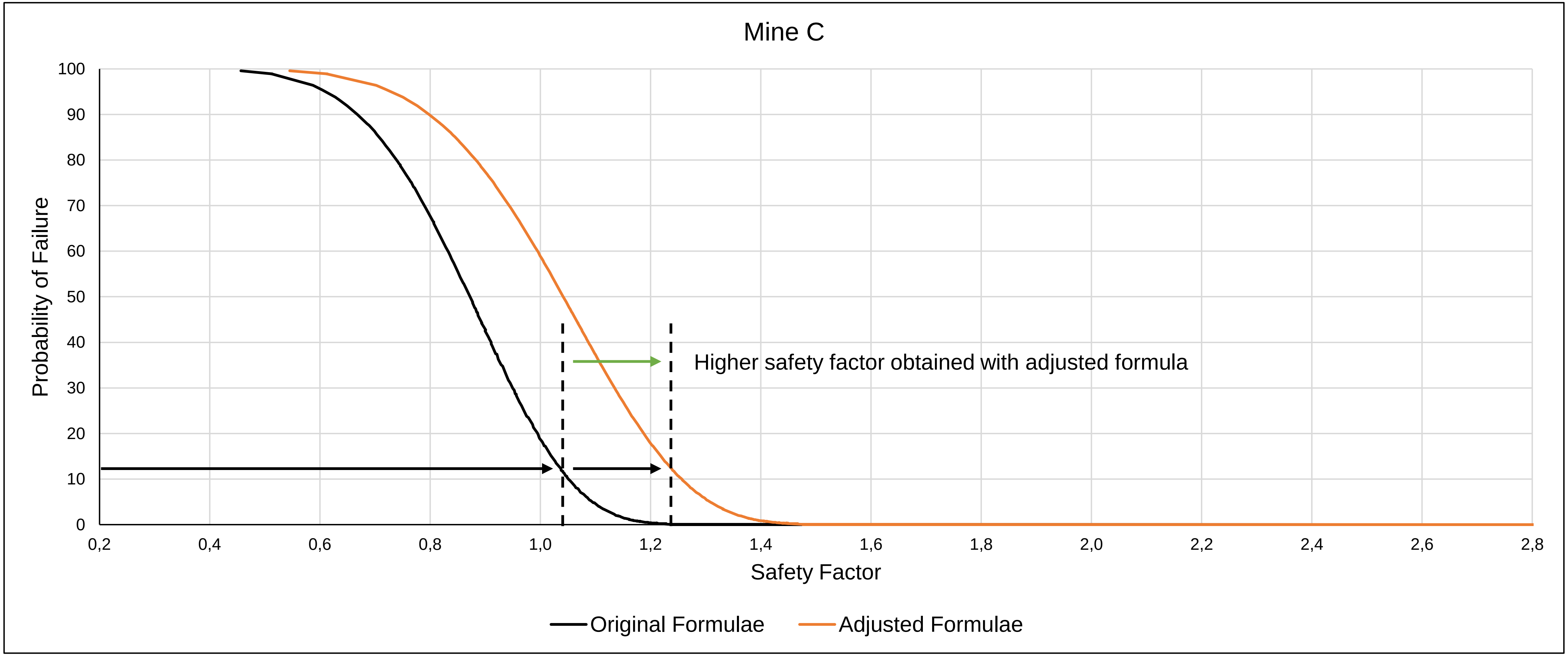
Research Methodology – Results obtained from method



Research Methodology – Results obtained from method



Research Methodology – Results obtained from method



UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Research Methodology – Results obtained from method

- To quantify the potential optimization using the data from the various mines, a single mining scenario was selected

Depth (m)	Pillar width (m)	Bord width (m)	Mining height (m)	Load (MPa)
100	11	6.5	3	6.33

Formula	Salamon	Van der Merwe	Maximum Likelihood	Overlap Reduction
Safety Factor	1.65	2.03	1.61	1.96

Research Methodology – Results obtained from method

Dataset	Harmonic mean	Difference in SF
Mine A	1.10	0.09
Mine B	1.06	0.13
Mine C	1.43	-0.24
Harmonic mean of total dataset – 1.19		

Dataset	Formula	Original width (m)	Updated width (m)	Difference (m)	Practical difference (m)
Mine C	Salamon	11	9.7	- 1.3	- 1.0
	VdM	11	10.2	- 0.8	- 0.5
	ML	11	9.7	- 1.3	- 1.0
	OR	11	10.1	- 0.9	- 0.5

Research Methodology – Results obtained from method

Formula	Salamon	VdM	ML	OR
Pillar width original (m)	11.0	11.0	11.0	11.0
Pillar width new (m)	10.0	10.5	10.0	10.5
Difference in width (m)	- 1.0	- 0.5	- 1.0	- 0.5
Gain in tonnes per pillar	157.50	80.63	157.50	80.63

Formula	Salamon	VdM	ML	OR
Original extraction %	60.49 %	60.49 %	60.49 %	60.49 %
Updated extraction %	63.27 %	61.85 %	63.27 %	61.85 %
Gain in extraction %	+ 2.78 %	+ 1.36 %	+ 2.78 %	+ 1.36 %

Discussion points

- Can the behaviour of a pillar be effectively estimated using only the UCS of a material without considering the effect that jointing?
- The results of the research confirm on a theoretical basis the applicability of the proposed optimisation method. The results however, do not confirm the proposed method as one that can be implemented without due consideration
- It is recommended that the optimised pillar sizes obtained from this approach, be trialed in a controlled environment where abnormal pillar behaviour will not affect the rest of the mine

References

Bertuzzi, R., Douglas, K. and Mostyn G. (2016). An Approach to Model the Strength of Coal Pillars. International Journal of Rock Mechanics and Mining Sciences, 89: 165-175.

Bieniawski, Z.T. (1968). The effect of specimen size on compressive strength of coal. International Journal of Rock Mechanics and Mining Sciences, 5: 325-335.

Esterhuizen, G. (2000). Jointing Effects on Pillar Strength, 19th Conference on Ground Control in Mining. Morgantown, WV (USA).

Gaddy, F. L. (1956). A study of the ultimate strength of coal as related to the absolute size of the cubical specimens tested. Engineering Experiment Station, Bulletin 112, Virginia Polytechnic Institute.

Hoek, E. (2007). Practical Rock Engineering. Retrieved from https://www.rocscience.com/assets/resources/learning/hoek/Practical-Rock-Engineering-Full-Text.pdf [Accessed 12 May 2020].

Lunder, P. J. and Pakalnis, R. (1997). Determination of the Strength of Hard-Rock Mine Pillars. Bulletin of the Canadian Institute of Mining and Metallurgy, 90: 5125.

Madden, B. J., Canbulat, I., Jack, B. W., and I'Rohaska, G. D. (1995). A reassessment of coal pillar design procedures, SIMRAC Final Project Report - COL021. Pretoria: CSIR Division of Mining Technology.

Madden, B. J., Hardman, D. R. (1992). Long-term stability of bord-and-pillar workings. Proceedings of the Symposium on Construction Over Mined Areas, May 1992, South African Institution of Civil Engineers.

Mark, C. and Barton, T. M. (1996). The Uniaxial Compressive Strength of Coal: Should it be used to Design Pillars? 15th International Conference on Ground Control in Mining, Golden, CO (USA).

Mark, C., F. E. Chase, and A. A. Campoli. (1995). Analysis of Retreat Mining Pillar Stability. 14th Conference on Ground Control in Mining, Morgantown, WV (USA):

Ozbay, M. U., Ryder, J. A. and Jager, A. J. (1995). The design of pillar systems as practiced in shallow hard-rock tabular mines in South Africa. Journal of the South African Institute of Mining and Metallurgy, Vol 95, Jan/Feb 1995: 7–18.

Potvin, Y., Hudyma, M. R. and Miller H. D. S. (1989). Design Guidelines for Open Stope Support. Bulletin of the Canadian Institute of Mining and Metallurgy; 82: 53262.

Salamon, M. D. G. and Munro, A. H. (1967). A study of the strength of coal pillars. Journal of the South African Institute of Mining and Metallurgy, Vol 67, September 1967: 55-67.

Salamon, M. D. G., Canbulat, I., and Ryder, J. A. (2006). Development of seam-specific strength formulae for South African collieries. Final Report: Task 2.16, Coaltech, Johannesburg.

Van der Merwe, J.N. (2003). New pillar strength formula for South African coal. Journal of the South African Institute of Mining and Metallurgy, 103: 281-292.

Van der Merwe, J. N. (2016). A three-tier method of stability evaluation for coal mines in the Witbank and Highveld coalfields. Journal of the Southern African Institute of Mining and Metallurgy, 116: 1189-1194.

Van der Merwe, J.N., (2021). Coal Pillar Database. [email].

Van der Merwe, J.N. and Mathey, M. (2013a). Update of Coal Pillar Strength Formulae for South African Coal using two Methods of Analysis. Journal of the Southern African Institute of Mining and Metallurgy, 113: 841-847.

Van der Merwe, J.N. and Mathey, M. (2013b). Probability of Failure of South African Coal Pillars. Journal of the Southern African Institute of Mining and Metallurgy, 113: 849-857.

Van Heerden, W. L. (1975). In situ complete stress-strain characteristics of large coal specimens. Journal of the South African Institute of Mining and Metallurgy, Vol 75, March 1975: 207-217.

Wagner, H. (1974). The determination of the complete load deformation characteristics of coal pillars. Proceedings of the 3rd International Congress of the International Society for Rock Mechanics, Denver, December 1974: 1076-1081.

York, G. and Canbulat, I. (1998). The scale effect, critical rock mass strength and pillar system design. Journal of the South African Institute of Mining and Metallurgy, Vol 98, January/February 1998: 23-37.