

# A Hybrid Statistical-analytical Technique for the Study of Rock Bursts in Sedimentary Rock Formations

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## Abstract

In an attempt to develop tools for assessing stress bump potential, the authors initiated a comprehensive study using site specific information from 25 case studies undertaken within the last four decades in U.S. mines. Data was painstakingly collected, integrated and analyzed initially in 1997 and reexamined, expanded and verified more recently. With the support of mining companies and NIOSH, the study was expanded recently adding two new case studies in burst-prone mines with geotechnical monitoring for verification of hybrid statistical-analytical models and for inclusion of additional variables. Multiple variable regression and numerical modeling analyses of geological and mining conditions were used to identify the most significant factors contributing to stress bumps in coal mines. Twenty-five factors were considered initially using site specific geologic and geometries in 27 case studies having experienced both violent and nonviolent failures.

This work identified the most important variables contributing to violent failure of near seam strata. These are (1) mechanical properties of strata, (2) gate pillar factors of safety, (3) stress gradients associated with the approach of mining to areas of higher stress concentrations such as abutment stresses from multiple seam mining or anomalous geologic conditions, and (4) roof beam thickness, joint spacing, and stiffness characteristics, which influence cave conditions and dynamic loading.

The latter variables, combined together to form a new variable called “strata rigidity-cavability”, reflect some of the most important aspects of violent failure, i.e. having massive and stiff near-seam stratigraphic units capable of absorbing high strain energy, forming high stress on mine structures and poor cave conditions, and thus the potential for dynamic loads. The two new case studies not only verified the significance of above factors but also reemphasized the significance of in-situ coal strength in increasing propensity for violent failure.

**Keywords;** Rock Burst, Multiple Variable Regression, Geotechnical Monitoring, Rigidity/Cavability

## 1. Introduction

Rock bursts are defined as sudden, violent failures of rock mass that are of such a magnitude that they expel large amounts of coal and rock into the face area during longwall or pillar extraction in sedimentary rocks. Typical ejected material varies from 5-100 tons filling up the pan at the longwall face. Rock bursts and coal bumps are an important safety concern in U.S. coal mines. However, U.S. experiences reflect just one part of what is really an international problem; Safety and resource recovery have been affected in many other countries, including Germany, England, Poland, France, Mexico, China, India and South Africa. Gradual or progressive failure, which is commonly experienced in coal mines, has less effect on mining continuity and safety and is generally controlled by timely scaling, cleaning, and bolting.

The occurrence and mechanism of these failures have been studied for decades in both hard rocks and coal mines (Crouch 1973, Salamon 1994, Babcock 1984, Iannachione 1994, and Maleki 1995). While unstable slip along geologic discontinuities is known to be associated with many large seismic events in hard rock mines (Maleki and White 1997), many coal bump events in the U.S. coal fields are related to the failure of marginally stable structures under high stress conditions (stress bumps) triggered by dynamic energy resulting from failure of stiff enclosing stratigraphic units in the overburden and underburden (Maleki 2015, Maleki 2006). These stress bumps (the focus of these

investigations) are influenced by geologic conditions, the geometric design of coal mine excavations, and the sequence of extraction.

In spite of significant progress in understanding the mechanics of violent failure within the last fifty years, there is still an urgent need to develop practical, predictive techniques for assessing coal bump potential. Cook (1965) suggested comparing the stiffness of the testing frame to post-failure modulus of coal samples to determine whether a test sample will fail violently or nonviolently. Salamon (1994) proposed a criterion for assessing mine stability (not coal bump potential) using the concept of mine stiffness. For a discussion of other criterion including Energy Release Rate, the interested reader is referred to Maleki and Wopat (1995). Many practitioners have suggested simple indices for assessing coal bump potential using either near seam mechanical properties or energy concepts. For instance, Maleki (1995) proposed a strata stiffness index, the ratio of strata stiffness-strength to that of the coal seam, for identifying bump-prone conditions. However because coal bumps are influenced by a number of geologic and mining factors, these indices have limited usefulness in a preliminary evaluation of burst-prone nature of mining properties.

Advancements in numerical modeling has made it possible to back analyze both static and dynamic (i.e., excess shear stress (Maleki 2014a) conditions leading to violent failure. However, most applications are challenged by poor availability of complete data sets regarding geologic, geometric and geotechnical data which include post-failure behavior of coal pillars and cave conditions (Maleki 2015, Maleki 1981, Maleki 1992). Statistical techniques, on the other hand, are powerful tools for studying failure mechanisms where there is good data but poor understanding of the contributing factors.

By combing the strength of computational and statistical techniques, it is possible to advance the understanding of violent failure mechanisms through identification of the significant factors affecting the failure. This is the approach undertaken in this research. This research utilizes the first author's observations and back analyses of violent failure in twenty seven US operations including both single- and multiple-seam operations in flat lying and dipping seams. Although not all data could be collected at the exact location of failures, the existing data base is the closest to the source of the event as feasible. Where possible, field activities included coring and mechanical property testing of rocks with stress measurements within 50-ft of coal bump events. Back analyses of stress conditions from case studies provided additional insights regarding poor, cyclic cave conditions (Maleki 2015, Maleki 2006) influenced by poorly jointed, stiff strata. Data was painstakingly collected, integrated and analyzed over the last forty years forming one of the most comprehensive geomechanical data base for US mines.

## 2. Data Analysis

Twenty-five geologic, geometric, and geomechanical factors were first identified as having the potential to contribute to coal bump occurrence. Table 1 lists these variables excluding averages, ranges, and standard deviations due to limitations in this publication size; these case studies provided good coverage of the variables (Maleki and Lawson 2017). Several meaningful attributes of violent failure are difficult to measure quantitatively. By assigning numerical values, it is possible to integrate these important aspect of violent failure.

These variables include:

- Thickness of the roof beam: Roof beam thickness varied between 1.5-12 m and was chosen to be the strongest member of the near-seam strata, located between 1 and 4 times seam thickness in the mine roof. Although there is strong evidence (Maleki 2015), that massive upper strata have contributed to seismicity and possibly coal bumps in some mines (Maleki 2006), their influence was not directly evaluated in this study because of a consideration of reduced impacts because of attenuation of energy with distance.
- Near-seam strata and seam properties: Mechanical properties of roof, floor, and coal seams were obtained through laboratory tests of samples of near-seam strata. In situ strength of coal seams was estimated using the procedures suggested by Maleki (1992) including both confinement-controlled and structurally controlled coal seams.

- Horizontal stress: Both maximum and minimum secondary horizontal stresses were obtained using overcoring stress measurements from one to three boreholes (Bickel 1993).
- Local yield characteristics: Local yield characteristics of the immediate roof and floor strata influence coal pillar failure and the severity of coal bumps. This factor varied from 0 to 2, where 0 indicates insignificant yielding in the roof and floor and 2 indicates favorable, gradual yielding in both roof and floor.
- Mining method: Both violent (bump-prone) and nonviolent conditions in six room-and-pillar mines and 21 longwall mines were studied.
- Stress gradients: Stress gradients near the rock burst varied from 0 to 2, depending on whether or not mining proceeded toward an area of high stress (resulting from previous mining or approaching topographic highs) and/or abnormal geologic conditions, such as occasionally found near faults or grabens. Stress gradient of zero reflected mining in virgin stress conditions and two reflected mining toward most severe multiple-seam solid-gob crossings (Maleki 2014a)
- Factors of safety: Pillar and face factors of safety (strength to stress ratio) were calculated for individual cases studies using both two- and three-dimensional, boundary-element techniques (Maleki et. al 2003). Results were compared with field data when such data were available.
- Energy release: Energy release from a potential seismic event was calculated using both boundary-element modeling and analytical formulations suggested by Wu and Karafakis (1994) for estimating energy accumulation in both roof and coal and energy release (McGarr 1984) in terms of Richter magnitude ( $M_1$ ) using the following formula:

$$1.5 M_1 = A \times \log (E) - 11.8, \text{ Where}$$

E = total accumulated energy in roof and seam, erg, and

A = coefficient depending on joint density and expected cave conditions (Maleki 2015)

- Damage (severity): A damage rating was developed based on authors' observations of physical damage and citations by other researchers (Maleki and White 1997). Damage levels varied between 0 and 3, depending on whether or not the result was significant damage to equipment and miners. Level 1 signifies interruptions in mining operations while level 3 signifies damage to both face equipment and injuries to mine personnel. The latter is considered significant because injuries often result where there is frequent damage to face equipment requiring presence of maintenance personnel for fixing the problem.

Table 1. Listing of geologic, geometric and geomechanical variables.

Geologic	Geometric	Geomechanical
Joint sets, number of	Pillar width, m	Pillar factor of safety
Cleat sets	Pillar height, m	Face factor of safety
Inseam partings	Entry span, m	Energy ( $M_1$ )
Joint spacing in strata, m	Barrier pillar width, m	Damage
Rock Quality Designation of roof/floor	Face width, m	
Depth, m	Mining method	
Roof beam thickness, m	Stress gradient	
Young's modulus coal, Gpa		
Young's modulus of roof and floor, Gpa		
Uniaxial strength of roof and floor, Mpa		
Uniaxial strength of coal, Mpa		
Max. horizontal stress, Mpa		
Interacting seams, number of		
Local yield characteristics of roof/floor		

### 3. Bivariate Correlations and Data Reduction

The statistical analyses were first completed on the entire data set followed by data reduction and the introduction of new variables using both linear and nonlinear (weighted) parameters (Maleki and White 1997). The linear bivariate correlation of the entire data matrix, for instance, identified the following significant variables. Correlation was found to be significant at 0.05 level (2-tail) between the following variables and “damage”, Yield (localized yielding of the roof and floor), Stress gradient, Joint spacing, Barrier pillar width, Face stability, Energy, Uniaxial strength of roof, Roof beam thickness. These findings are all logical, pointing to the significance of strong near-seam stratigraphic members in accumulating energy, joint spacing affecting regular cave conditions and load transference to the face, and the importance of barrier pillars in reducing inter-panel cantilevering as identified in case studies (Maleki 2015, Maleki 2006). Additional paired comparison of high damage (risk) and low damage (risk) events confirmed the significance of above factors.

An accurate reconstruction of high-risk versus low-risk cases was achieved pointing to significant differences in several geomechanical parameters at burst prone mines. Based on paired comparisons of high-risk versus low-risk events, significant geologic differences included (1) the thickness (Figure 1)/strength of the immediate roof beam, (2) coal seam stiffness, (3) joint spacing (Figure 2)/ no of joint sets, (4) stress gradient, (5) yielding characteristics of immediate floor, (6) number of coal seams, and (7) the far-field horizontal stress. Mining geometric design factors of significance included barrier pillar/chain pillar widths, and mining method (i.e., room-and-pillar vs. longwall).

Following these preliminary bivariate correlations and paired comparisons among all geologic, geometric, and geomechanical variables, the number of variables was reduced by combining some variables into new ones. In addition, the cause-and-effect (SPSS 1995) structure in the data was identified, helping to tailor the procedures for multiple regression analysis using forward stepwise inclusion of dependent variables, as described later in this paper.

The new variables were as follows.

P_Q ratio	The ratio of maximum principal horizontal stress (P) to minimum stress (Q).
UR_UC	The ratio of uniaxial compressive strength of the roof to the coal.
DEP_INSI	The ratio of depth to in-situ coal strength using Maleki’s upper bound formulas
JS_TH_H_NJ	Joint spacing* roof beam thickness/ mining height* number of joints.
GR-YIELD	Ratio of roof and floor yield characteristics to stress gradient.
PANW_D	Ratio of panel width to depth.
ER_EC	Ratio of Young’s modulus of the roof to the seam.
Rigidity	Beam thickness*Young’s modulus
Rigidity-JS	Rigidity* Joint spacing

Table 2 presents the bivariate correlation coefficients among select geologic, geometric and geomechanical variables. Energy ( $M_1$ ), Face stability, Stress gradient and Yield characteristics, Rigidity-JS, and Rigidity were the most significant correlating with Damage.

Variables	GR_YIELD	DEP_INSI	face_st	Pil_sta	method	damage	energy	RigidJS	Rigidity
N	27	27	24	26	27	27	25	27	27
GR_YIELD PC	1	-.032	.442*	.083	.064	<b>-.593**</b>	-.349	-.438*	-.287
Sig		.874	.030	.688	.751	<b>.001</b>	.087	.022	.147
N	27	27	24	26	27	27	25	27	27
DEP_INSI PC	-.032	1	-.593**	-.442*	-.161	.104	.419*	-.170	-.042
Sig	.874		.002	.024	.422	.605	.037	.397	.834
N	27	27	24	26	27	27	25	27	27
face_st PC	.442*	-.593**	1	.264	-.056	<b>-.447*</b>	-.734**	-.059	-.244

	Sig	.030	.002		.224	.796	.028	.000	.784	.251
	N	24	24	24	23	24	24	24	24	24
Pil_sta	PC	.083	-.442*	.264	1	.190	-.322	-.124	-.294	-.152
	Sig	.688	.024	.224		.351	.109	.565	.145	.460
	N	26	26	23	26	26	26	24	26	26
method	PC	.064	-.161	-.056	.190	1	.183	.287	-.037	.053
	Sig	.751	.422	.796	.351		.360	.164	.856	.792
	N	27	27	24	26	27	27	25	27	27
damage	PC	-.593**	.104	-.447*	-.322	.183	1	.693**	.524**	.420*
	Sig	.001	.605	.028	.109	.360		.000	.005	.029
	N	27	27	24	26	27	27	25	27	27
energy	PC	-.349	.419*	-.734**	-.124	.287	.693**	1	.248	.405*
	Sig	.087	.037	.000	.565	.164	.000		.232	.045
	N	25	25	24	24	25	25	25	25	25
Rigid-S	PC	-.438*	-.170	-.059	-.294	-.037	.524**	.248	1	.747**
	Sig	.022	.397	.784	.145	.856	.005	.232		.000
	N	27	27	24	26	27	27	25	27	27
Rigidity	PC	-.287	-.042	-.244	-.152	.053	.420*	.405*	.747**	1
	Sig	.147	.834	.251	.460	.792	.029	.045	.000	
	N	27	27	24	26	27	27	25	27	27

N Number of Data, PC Pearson Correlation Coefficient, Sig Significance level  
\*Correlation is significant at .05 level (two-tailed) \*\* Correlation is significant at 0.01 level (two-tailed)

#### 4. Primary Multiple Linear Regression Analysis

There are two methods used by engineers and researchers as tools to help predict conditions in the future: statistical and computational. Starfield and Cundall (1988) identify rock mechanics problems as “data-limited,” that is, one seldom knows enough about a rock mass to use computational models unambiguously. Statistical methods, on the other hand, are uniquely capable of being applied where there are good data but a limited understanding of certain natural phenomena, such as rock bursts.

In this study, the authors combined the strength of both methods to identify important variables and to develop predictive capabilities. Computational methods have been used to assess the influence of a combination of geometric variables into single variables, such as pillar factor of safety and released energy. This was very useful for increasing goodness-of-fit and enhancing multiple regression coefficients. Statistical methods were used to identify significant variables, to build confidence intervals, and so forth.

The multilinear regression procedure consisted of entering the independent variables one at a time into the equation using a forward selection methodology (SPSS 1995). In this method, the variable having the largest correlation with the dependent variable is entered into the equation. If a variable fails to meet entry requirements, it is not included in the equation. If it does meet the criteria, the second variable with the highest partial correlation will be selected and tested for entering into the equation. This procedure is very desirable when there is a cause-and-effect structure among the variables. An example of the cause-and-effect relationship is shown when a greater depth reduces pillar factor of safety, contributes to an accumulation of energy, and ultimately results in greater damage. Using the above procedures, any hidden relationship between depth, pillar factor of safety, energy and damage is evaluated and taken into account during every step of the analysis.

The regression analyses were completed in two steps using the same procedures developed during the initial (Phase 1) investigations (Maleki and Lawson 2017). First, using the rigidity variables and including energy calculations and second, excluding energy calculations while still explaining the variability in the outcome with lower multiple correlation coefficient. The original data base was also updated using the latest data from the cooperating mines.

Several geomechanical variables were initially used as dependent variables. The damage variable, however, resulted in the highest multiple correlation coefficient. The multiple correlation coefficient (R), which is a measure of goodness-of-fit, for the last step was 0.82.

The assumptions of linear regression analysis were tested and found to be valid by an analysis of variance, F-statistics, and a plot of standardized residuals (SPSS 1995). The residual plot did not indicate the need for inclusion of nonlinear terms because there was no special pattern in the residuals (Maleki and White 1997).

Based on an examination of standardized correlation coefficients (table 3), the following variables best explain the variations in damage and thus statistically have the most significant influence on coal bump potential.

- Energy release. This variable includes the effects of the mechanical properties of the roof and coal, depth, stress field, panel width, and joint density/cave conditions, and thus directly relates to damage.
- Stress gradient and yield characteristics. Mining toward areas of high stress creates a potential for coal bumps, while localized yielding roof and floor conditions encourage gradual failure, reducing the severity of damage particularly in properly designed mining systems using narrow “yield” pillars with limited confined core (Maleki 2014b).
- Pillar stability. Gate pillar geometry contributes directly to the severity of damage.
- DEP\_INSI. This variable is significant with negative coefficient. The higher the in-situ strength of the coal, the higher the potential for violent failure. Implications are that confinement controlled coal seams (Maleki 1992) with higher load bearing capacity can store higher strain energy and upon failure release it more violently, resulting in damage.

Table 3. Standardized regression coefficients and statistical significance, primary analysis, all variables.			
Model	Variable	Standardized Coefficients, Beta	Significance
1	Constant		0.024
	Energy	0.686	0.000
2	Constant		0.098
	Energy Depth/In-situ strength (DEP_INSI)	0.837 -0.387	0.000 0.021
3	Constant		0.709
	Energy	0.691	0.000
	Depth/In-situ strength (DEP_INSI) Stress gradient-Yield (GR_YIELD)	-0.311 -0.304	0.049 0.053
4	Constant		0.389
	Energy	0.687	0.000
	Depth/In-situ strength (DEP_INSI)	-0.393	0.013
	Stress gradient-Yield (GR_YIELD) Pillar Stability (Pil sta)	-0.306 -0.206	0.038 0.059

### 5. Secondary Multiple Regression Analysis

The intent of secondary analysis was to exclude the energy calculations while still explaining variability in the outcome with lower but still acceptable regression coefficient (R=.69).

Based on an examination of standardized regression coefficients (table 4), the following variables best explain the variations in damage and thus statistically have the most significant influence on violent failure potential. The multiple correlation coefficient (R), which is a measure of goodness-of-fit, for the last step was slightly reduced to 0.69 as the “energy” variable was

intentionally excluded from the analyses. Thus, these additional analyses did not improve the goodness-of-fit. However, they were helpful in confirming the significance of “rigidity/cavability” index that is simpler to calculate and is correlated with the “damage”. The correlation coefficient is reduced because the Rigidity-JS variable does not include the effect of panel geometries and depth; on the contrary, the latter are explicitly included in the Energy calculations.

- Rigidity-JS: This variable includes the effects of the stiffness of the roof beam, and the resistance of near seam strata to gradual caving and release of energy depending on joint spacing, and thus directly relates to damage.
- Stress gradient and yield characteristics. Mining toward areas of high stress creates a potential for coal bumps, while localized yielding roof and floor conditions encourage gradual failure, reducing the severity of damage particularly in properly designed mining systems using narrow “yield” pillars with limited confined core (Maleki 2014b).
- Method: Mining method has a bearing on coal bump potential. The room-and-pillar method is associated with a higher degree of risk than is longwall mining.

Model	Variable	Standardized Coefficients, Beta	Significance
1	Constant	N/A	.000
	Stress gradient-Yield (GR_YIELD)	-.587	.003
2	(Constant)		.000
	Stress gradient-Yield (GR_YIELD)	-.442	.022
	Rigid-JS	.370	.052
3	(Constant)		.325
	Stress gradient-Yield (GR_YIELD)	-.352	.058
	Rigid-JS	.371	.040
	Method	.308	.072

## 6. Conclusions

A hybrid statistical-analytical approach was used to identify the most significant factors contributing to violent failure of near seam strata. By combining the strength of both computational and statistical methods, this study achieved new capabilities for predicting coal bump potential and for building confidence intervals. Since the method relies on an extensive amount of geotechnical data from 27 case studies in U.S. coal mines, it should be helpful to mine planners in identifying bump-prone conditions and in improving health and safety standards. This final phase of the study, seeks to improve on a preliminary statistical-analytical technique developed earlier (Maleki and Lawson 2017). This final research has expanded the data base by including two additional case studies where detailed geotechnical data is collected for characterization of geologic and mining conditions which have contributed to violent failure of near seam strata.

Important variables include Energy release, Pillar stability, Mining method, Stress gradient and Yielding characteristics of immediate roof and floor. Other analyses reinforce the significance of beam rigidity and lack of jointing on promoting a poor cave, facilitating the sudden release of energy; this creates a potential for dynamic loading, forcing any marginally stable structures toward violent failure. The newly identified “rigidity-cavability” index reflects these conditions and effectively correlates with damage. In view of difficulties in assessing both the potential for violent failure and cavability of rocks (Maleki 2015), this is considered practically important. The rigidity-cavability index, however, is no replacement for the Energy term because the latter incorporates depth and mining geometries in the calculations.

This final research has included two additional case studies, verifying previous analyses results (Maleki and Lawson 2017) and identifying another significant variable. The in-situ coal strength is

shown to be significant pointing to higher capacity of confinement-controlled coal seams (Maleki 1992) in accumulating higher strain energy and releasing it in a violent fashion where other conditions are met, namely improper mine layout designs and having non-yielding layers in the immediate roof and floor.

### Acknowledgements

This research was partially supported by a grant from the United States National Institute of Occupational Safety (NIOSH). It benefitted from numerous investigations implemented by the USBM, Maleki Technologies Inc. and mining companies. Contributions of Heather Lawson, Denise Rains, and Dr. David Hanson are acknowledged.

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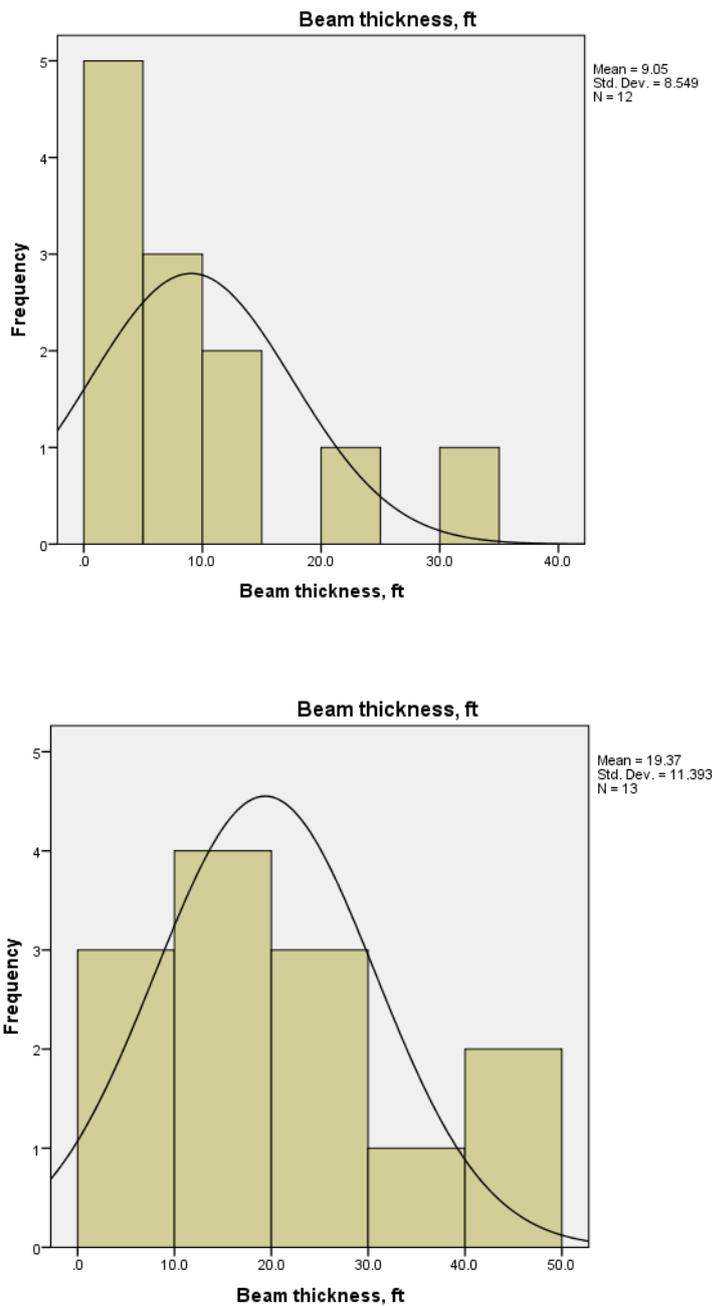


Figure 1. Comparison of histogram frequency diagram of Beam Thickness for low-risk (top) and high-risk (bottom) events. On average, Beam Thickness, is 110 percent higher in high-risk event sites.

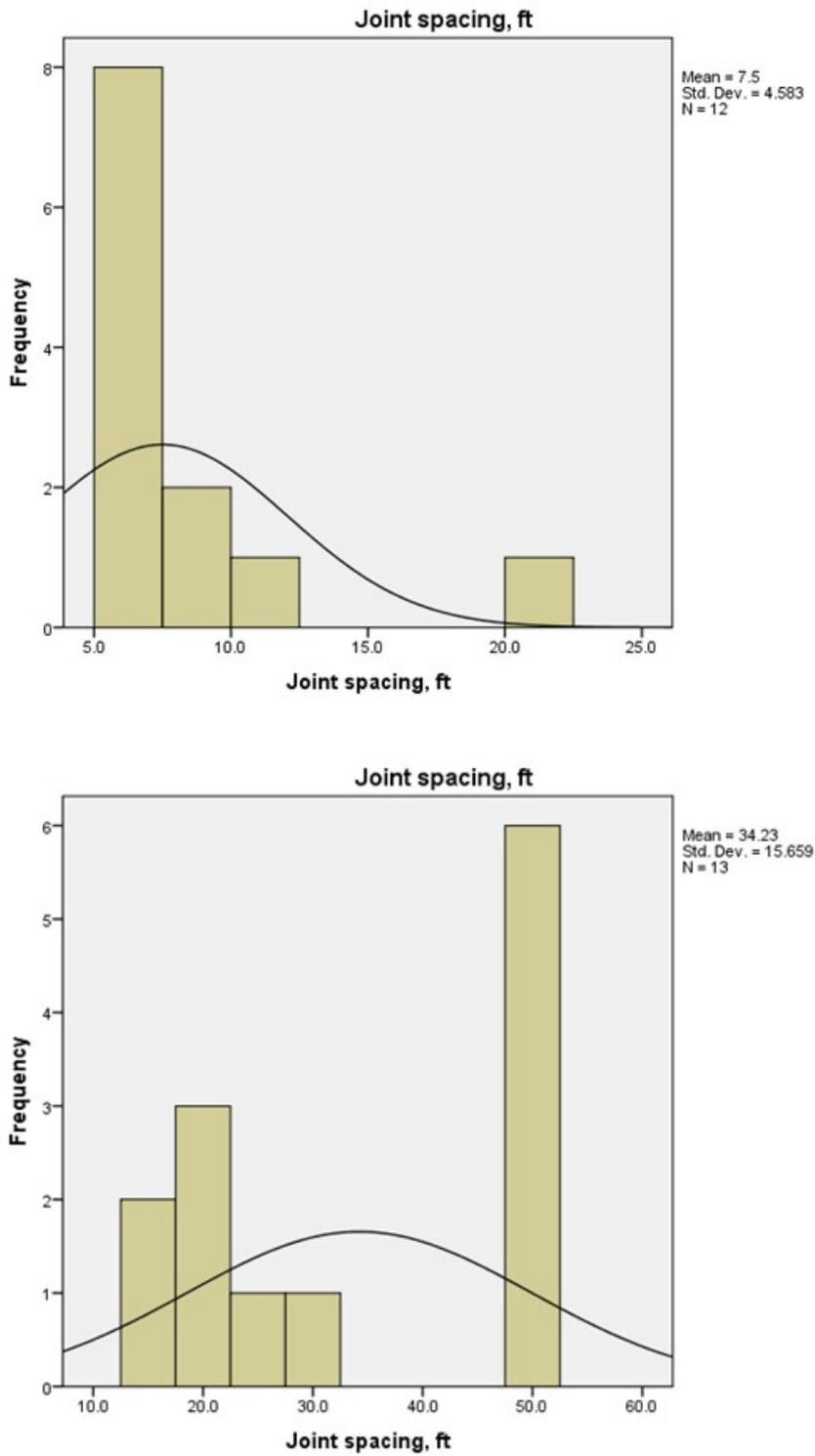


Figure 2. Comparison of histogram frequency diagram of Joint Spacing for low-risk (top) and high-risk (bottom) events. On average, Joint Spacing, is 350 percent higher in high-risk event sites.