Rock Fracture Extension from Blasting

Kentucky Professional Engineers in Mining Seminar

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Project sponsored by: UKERT

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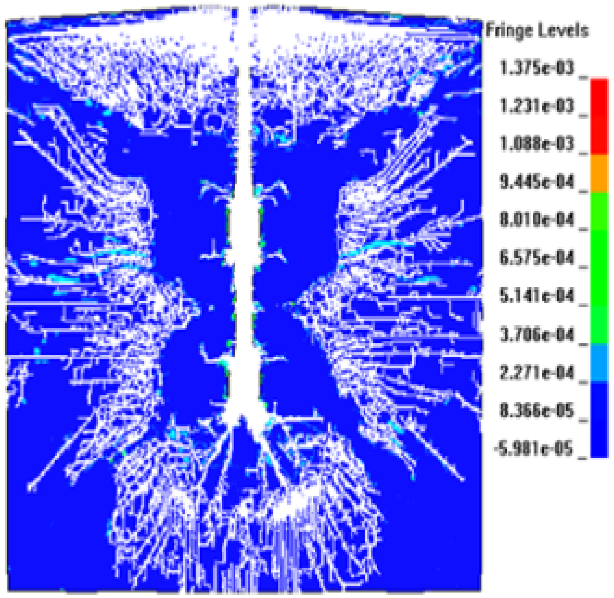
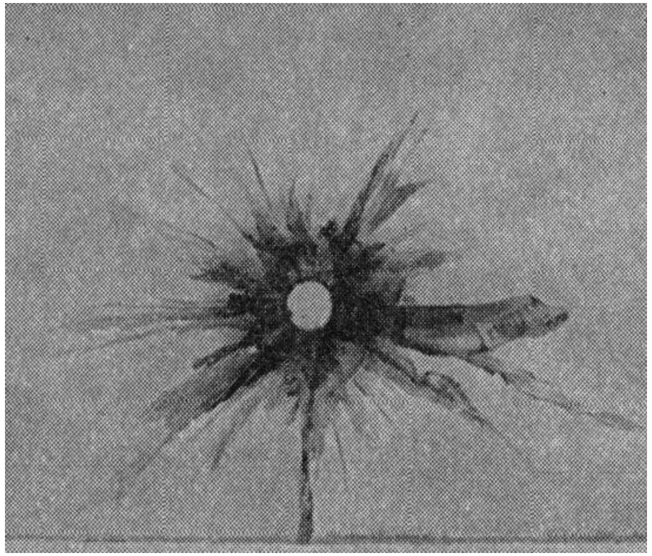
University of Kentucky

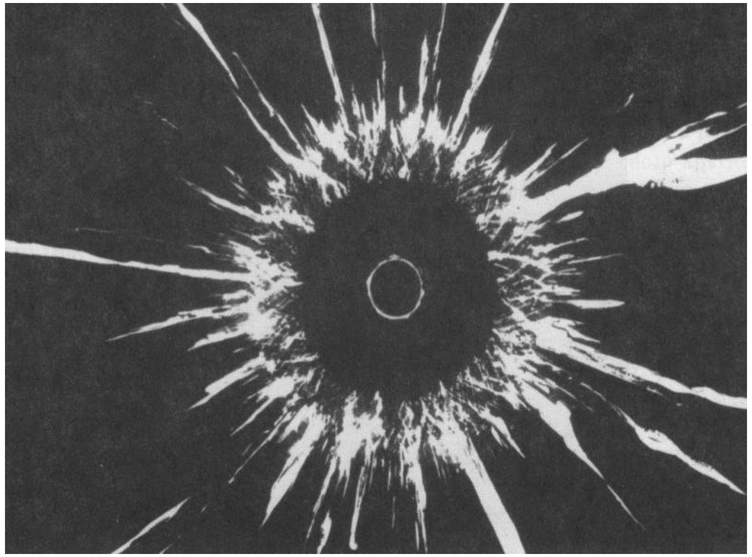
Fracture Extension

Fracture extension – Fracture Propagation



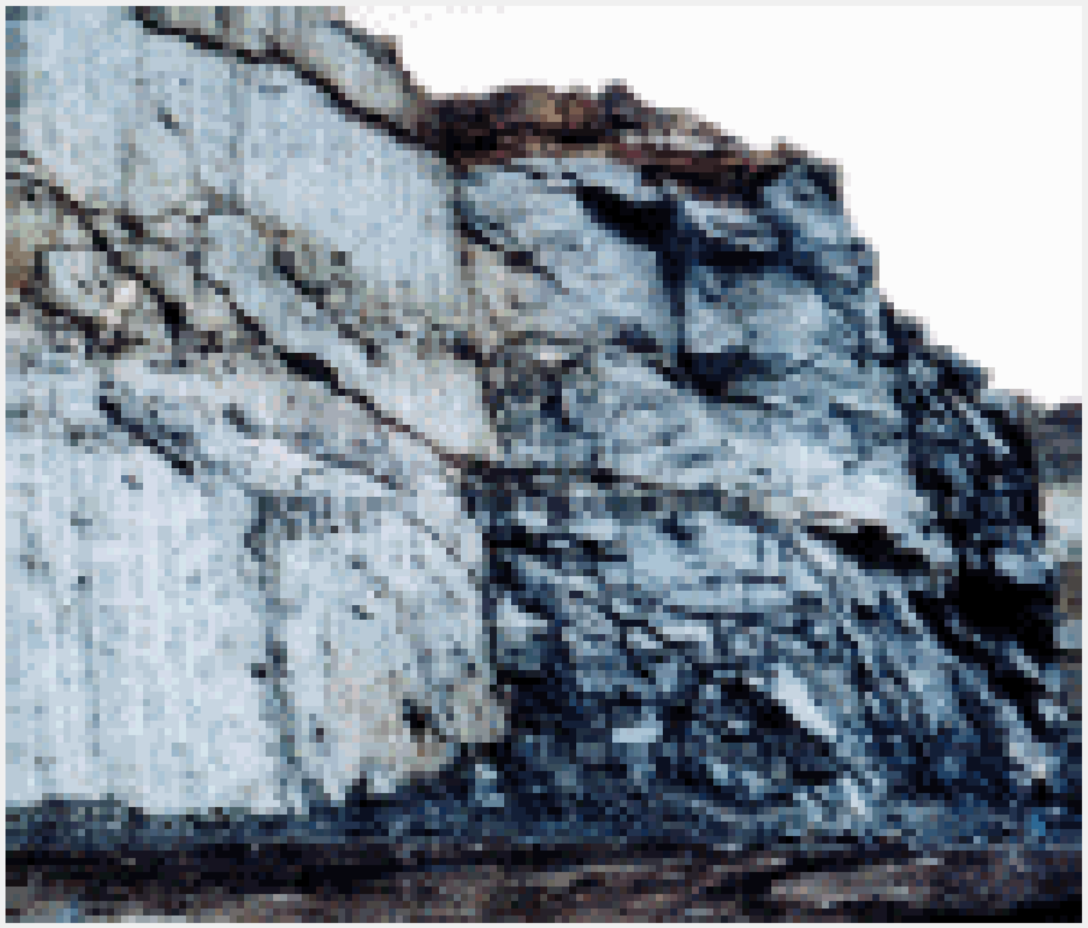
2100μs

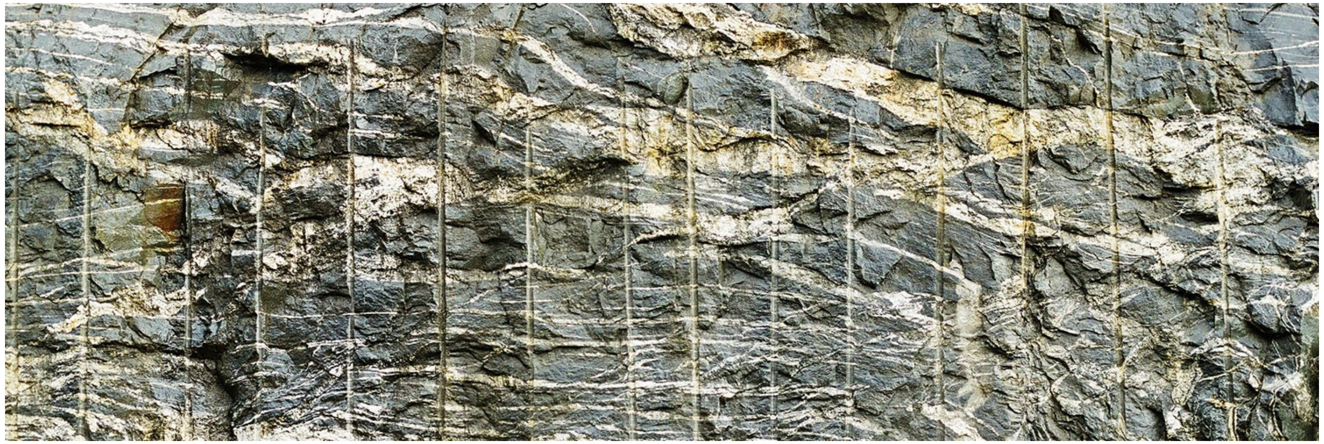




Relevance - Use

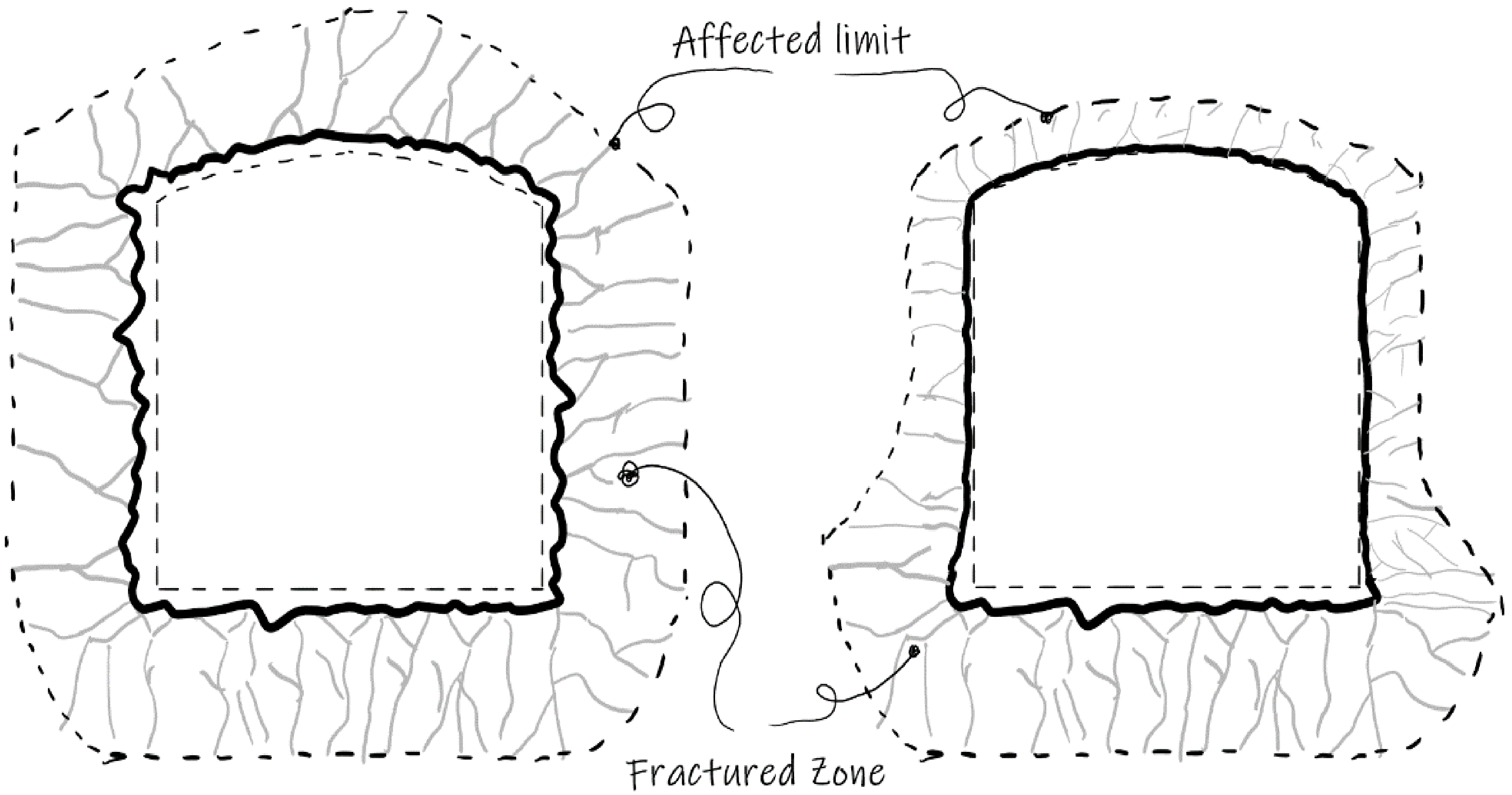
Surface Mining





Relevance - Use

Underground



Assessment methodologies

Rock damage extend models.

Model	Year	Procedure	Advantage	Disadvantage
Holmberg-Persson	1978	Calculate PPV to compare against PPV damage ranges	-Developed for cylindrical charges -Easy to use when all parameters are known	-Properties of explosive are not considered -Not strong theoretical support for its derivation -Parameters of the equation are established after several tests
Swedish Rock Engineering Research Organization (SevBeFo)	1996	Fractures mechanics theories. Calculates extent of damage zone around a borehole	-Uses gas pressures generated in the borehole -Explosive properties included Velocity of Detonation (VOD) and isentropic properties of the explosive	-Difficult to follow because the complexity of the formulation and the number of variables Fracture toughness parameter from the rock needs lab testing -Too many "correction" factors in the final formulation
Colorado School of Mines (CSM)	1969	Calculate PPV to compare against PPV damage ranges	-Uses gas pressures generated in the borehole -Uses Poisson ratio, density of the rock and longitudinal wave speed of the rock	-Cylindrical charges divided into a chain of spherical charges -Number of field tests needed to be conducted to find inelastic coefficient
Hustrulid-Lu	2002	Calculate PPV to compare against PPV damage ranges. Improved from CSM approach	-Uses gas pressures generated in the borehole -Introduces attenuation formulations for the PPV	-Number of field tests needed to be conducted to find constant parameters (attenuation) in the equation
Modified ash	2010	Calculates extent of damage zone around a borehole using the explosive energy	-Uses basic properties of explosives -Uses ANFO as reference -Easy to use	-Only density of the rock is accounted as a rock variable
Rock constant approach	2010	Based on Holmber's approach for tunnels. Calculate extent of damage zone around a borehole	-Uses basic properties of explosives -Uses ANFO as reference -Easy to use	-No rock properties are included -Degree of hole confinement difficult to assess
Neiman hydrodynamic Approach		Based on hydrodynamic studies by Hustrulid. Calculate PPV to compare against PPV damage ranges	-Uses basic properties of explosives -Includes compressive strength of the rock as a variable -Easy to use	-Explosive energy parameter difficult to assess
Jang and Topal–artificial Neural Network Approach	2013	Based on Artificial neural network (ANN) and multiple regression	-Considers rock and rock mass parameters (UCS, RQD, RMR)	-Blasting parameters are not involved in the problem.
Mohammadi et al.–fuzzy Logic Approach	2015	Based on Fuzzy Logic techniques and linear multiple regressions	-Considers rock mass parameters (RMR), -Considers blasting parameters (powder factor, ratio of contour holes to total holes)	-A large data set of blasting parameters (202 data sets) are required to obtain a reliable model. -Applied in a site specific project (Alborz tunnel)

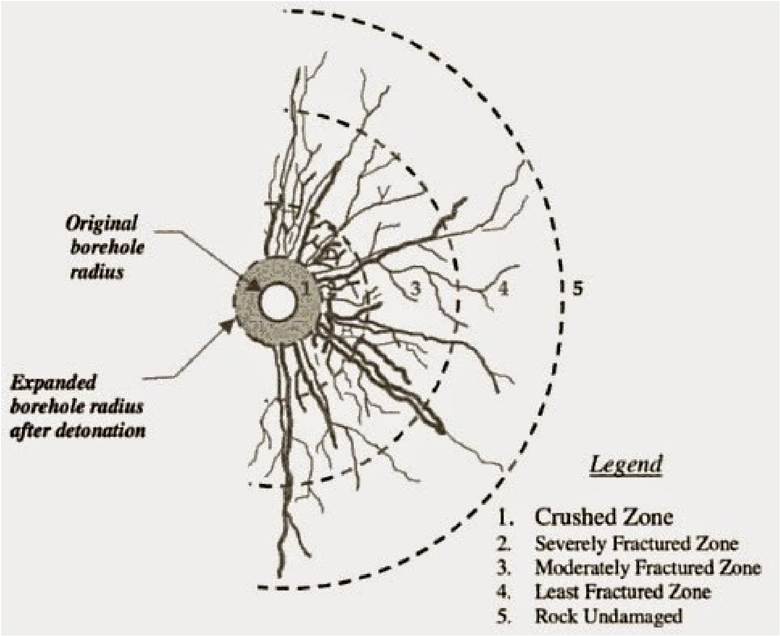
More than 18 methods

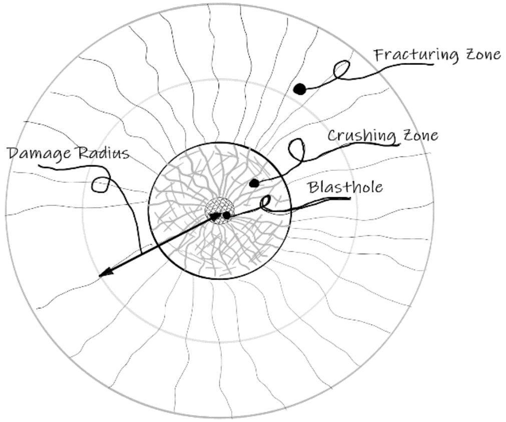
PPV criterion for blast-induced damaged, modified from Zadeh [15].

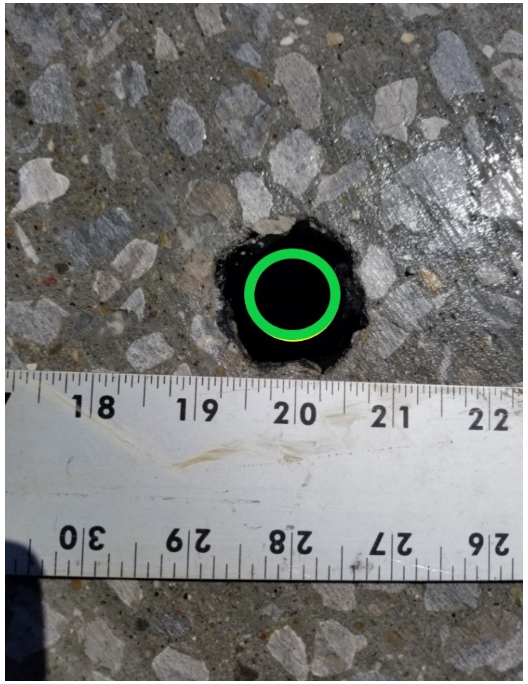
PPV (mm/s)	Effect
<250	No fracturing of intact rock
250–635	Minor tensile slabbing will occur
635–2540	Strong tensile and some radial cracking
>2540	Complete break-up of rock mass

"Practical assessment of rock damage due to blasting"
https://doi.org/10.1016/j.ijmst.2018.11.003

Assessment methodologies







Assessment methodologies

Most Popular:

- Modified Ash Energy-based equation,

$$R_d = 12.5 D_e \sqrt{RBS_e \frac{2.65}{SG_r} * \frac{D_e}{D_h}}$$

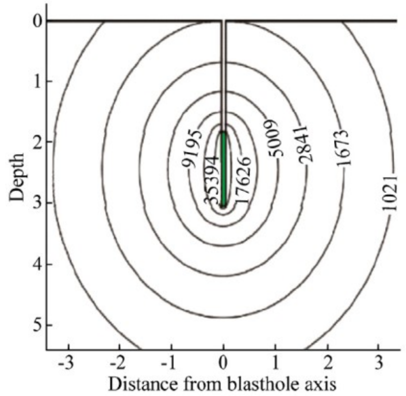
$$R_d = 0.9 * 12.5 * D_e \sqrt{0.4 * \pi \frac{2.65}{SG_r} \frac{SG_e * RWS_e}{c_b * f * K_s}}$$

R_d: damage radius (m),
D_e: charge diameter (m),
D_h: blasthole diameter (m),
RBS_e: explosive relative bulk strength,
SG_r: rock specific gravity,
2.65: rock specific gravity conversion factor.

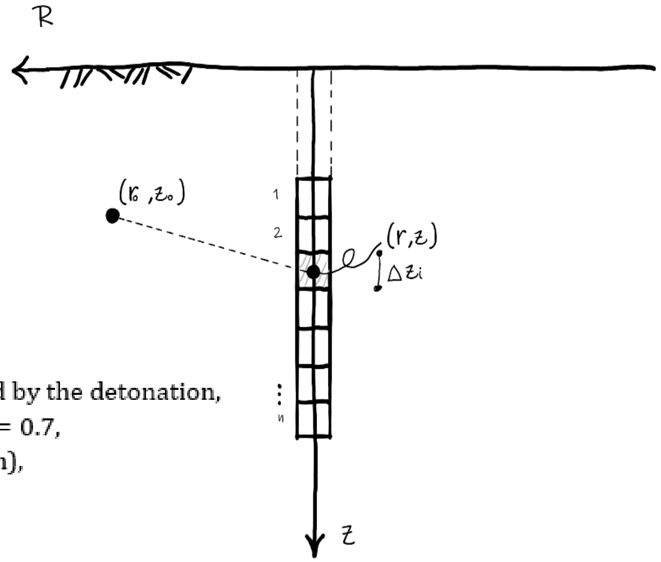
Relative Bulk Strength (RBS) The energy per unit volume of an explosive compared to ANFO when ANFO = 1.00 at a density of 0.82 g/cc.

- Holmberg - Persson equation (HP-PPV)

$$PPV = 2Kq^{\alpha}(\Delta z)^{\alpha} \sum_{\Delta z_i = 1}^{n} \left(\frac{1}{((r - r_o)^2 + (z - z_o)^2)^{\frac{\beta}{2}}} \right)$$



Predicted Iso vibration contours (mm/s) using H-P model (distances in meters)



PPV: Peak particle velocity (m/s) produced by the detonation,
K: site constant assumed typically as $K = 0.7$,
q: explosive charge concentration (kg/m),
α: site constant (usually $\alpha = 0.7$),
β: site constant (usually $\beta = 1.4$),

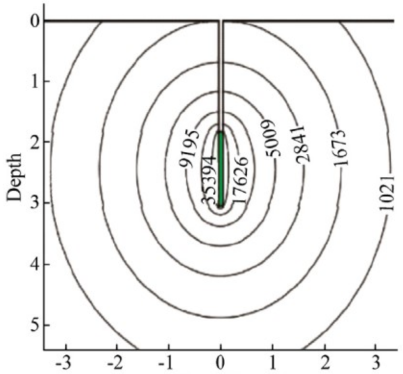
Assessment methodologies

University of Kentucky (UKERT - I) → Semi-empirical

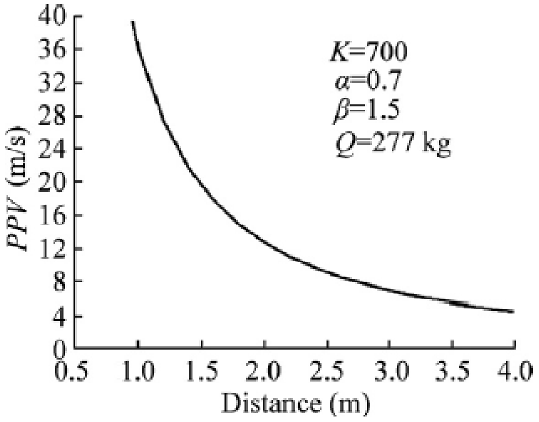
- Silva, Worsey, Lusk
  1. Static materials properties (UCS)
  2. Dynamic material properties
  3. PPV-Damage limit Forsyth equation (Dynamic)

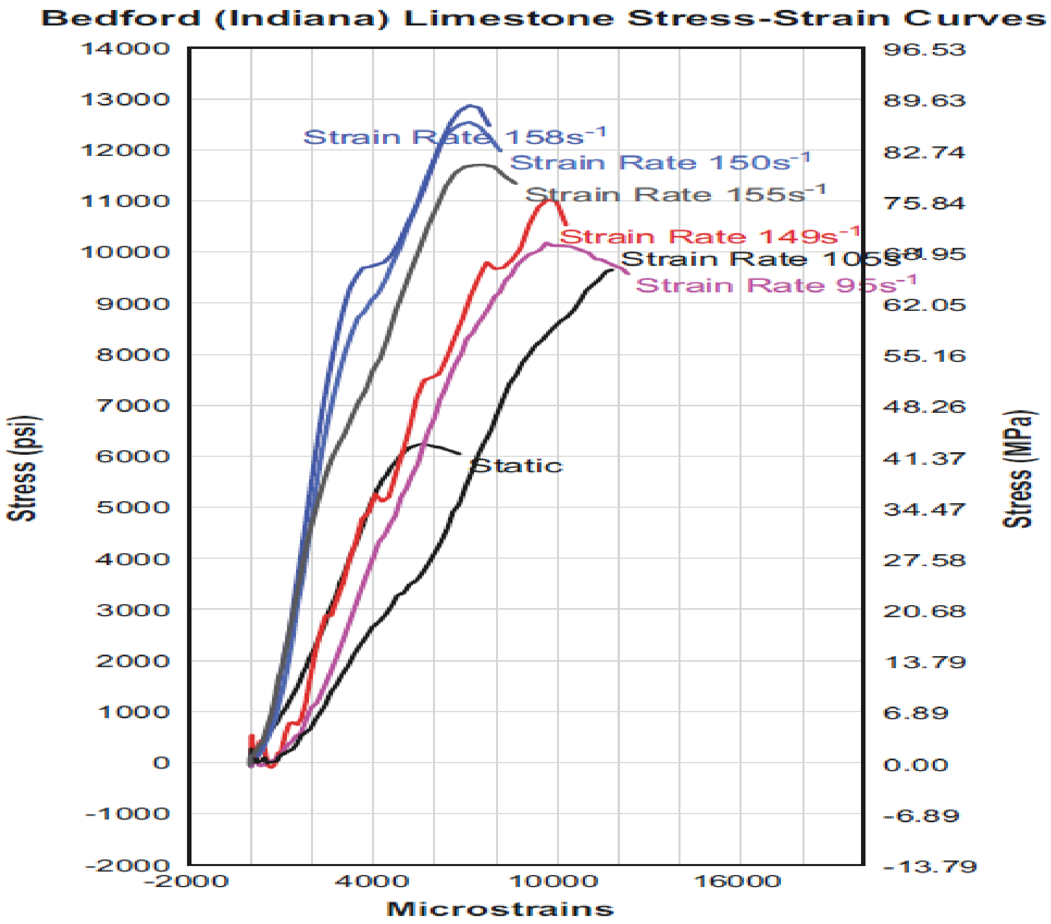
$$PPV_{max} = 0.1 \times UCS \frac{V_p}{E}$$

  4. Iso-Vibration contours (HP-PPV)



Predicted Iso vibration contours (mm/s) using H-P model (distances in meters)





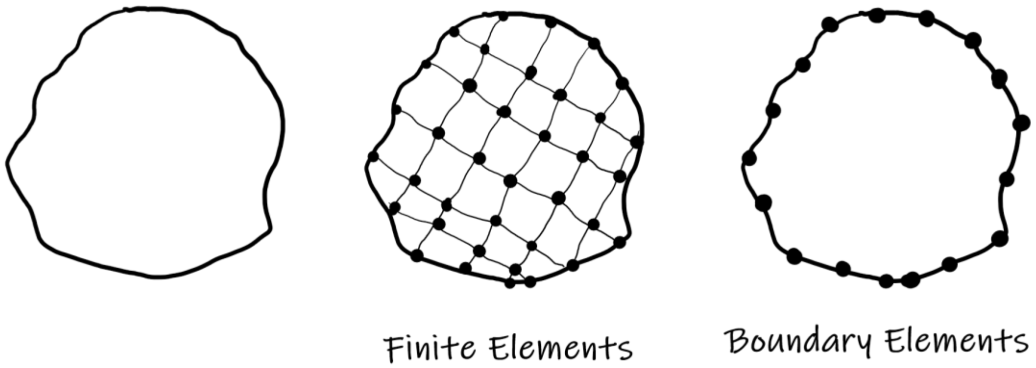
  5. Compare PPV limit Vs generated

Assessment methodologies

University of Kentucky (UKERT - II) → Theoretical (Numerical analysis)

- Schaefer, Kumar, Silva

Finite Elements Vs Boundary Elements

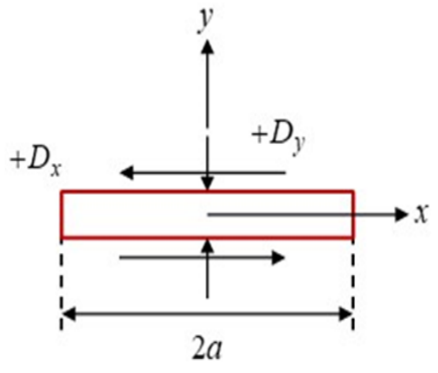


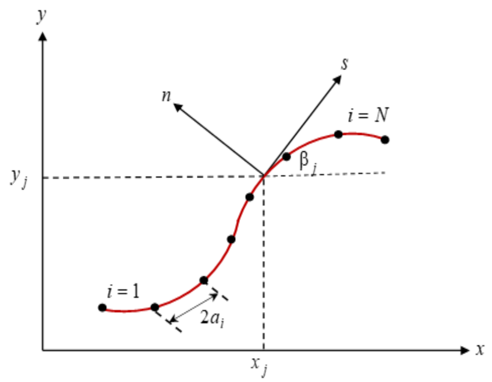
FEM: requires that the whole region be divided into a network of elements. Find the solution at the nodes. System of linear algebraic equations the unknows (values at the nodes) are expressed in terms of the known values at the boundary. Large set of equations "simple" equations.

Boundary Elements: only the boundary is divided into elements. Numerical solution derivate from analytical solutions, satisfy approximately the boundary conditions in each element on the boundary. Small set of equations but more "complex" equations.

Assessment methodologies

Displacement Discontinuity Method





$$D_x = u_x(x,0_-) - u_x(x,0_+)$$

$$D_y = u_y(x,0_-) - u_y(x,0_+)$$

D_i: Displacement discontinuity

u_i : Displacement components

Unknows

Stresses

$$\sigma_s^i = \sum_{j=1}^{N} A_{ss}^{ij} \cdot D_s^j + \sum_{j=1}^{N} A_{sn}^{ij} \cdot D_n^j$$

$$\sigma_n^i = \sum_{j=1}^{N} A_{ns}^{ij} \cdot D_s^j + \sum_{j=1}^{N} A_{nn}^{ij} \cdot D_n^j$$

Boundary

Displacements

$$u_s^i = \sum_{j=1}^{N} B_{ss}^{ij} \cdot D_s^j + \sum_{j=1}^{N} B_{sn}^{ij} \cdot D_n^j$$

$$u_n^i = \sum_{j=1}^{N} B_{ns}^{ij} \cdot D_s^j + \sum_{j=1}^{N} B_{nn}^{ij} \cdot D_n^j$$

Assessment methodologies

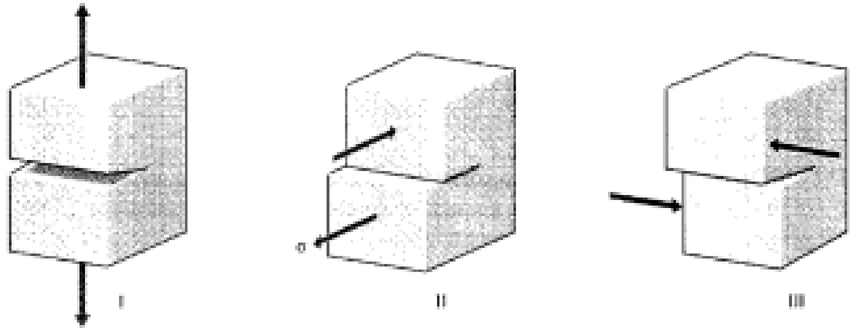
Displacement Discontinuity Method

- The fracture is framed within the methodology of the linear elastic fracture mechanics (LEFM) approach

- (Irwin 1957) stated that the singularity of the stresses near a crack tip can be indirectly measured with stress intensity factors, SIFs, while defining three modes of fracture openings (I, II, and III), seen previously

$$K_I = \frac{G}{4(1-\nu)}\sqrt{\frac{2\pi}{r}} \cdot D_n(r)$$

$$K_{II} = \frac{G}{4(1-\nu)}\sqrt{\frac{2\pi}{r}} \cdot D_s(r)$$



Normal Opening Shear Sliding Shear Sliding

Assessment methodologies

- Verification using Lithonia Granite parameters. Siskind et al. 1974 USBM report that directly measured the damage radius.

	SI Units	U.S. Customary
Specific Gravity	2.63	2.63
Weight Density	2630 kg/m^3	164 lb/ft^3
Longitudinal Propagation Velocity, in situ	5550 m/sec	18,200 ft/sec
Longitudinal Bar Velocity	2740 m/sec	9,000 ft/sec
Tensile Strength	3.10×10^6 N/m^2	450 lb/in^2
Compressive Strength	207×10^6 N/m^2	30,000 lb/in^2
Modulus of Rigidity	10.3×10^9 N/m^2	1.5×10^6 lb/in^2
Young's Modulus	20.7×10^9 N/m^2	3.0×10^6 lb/in^2
Poisson's Ratio in situ	0.26	0.26

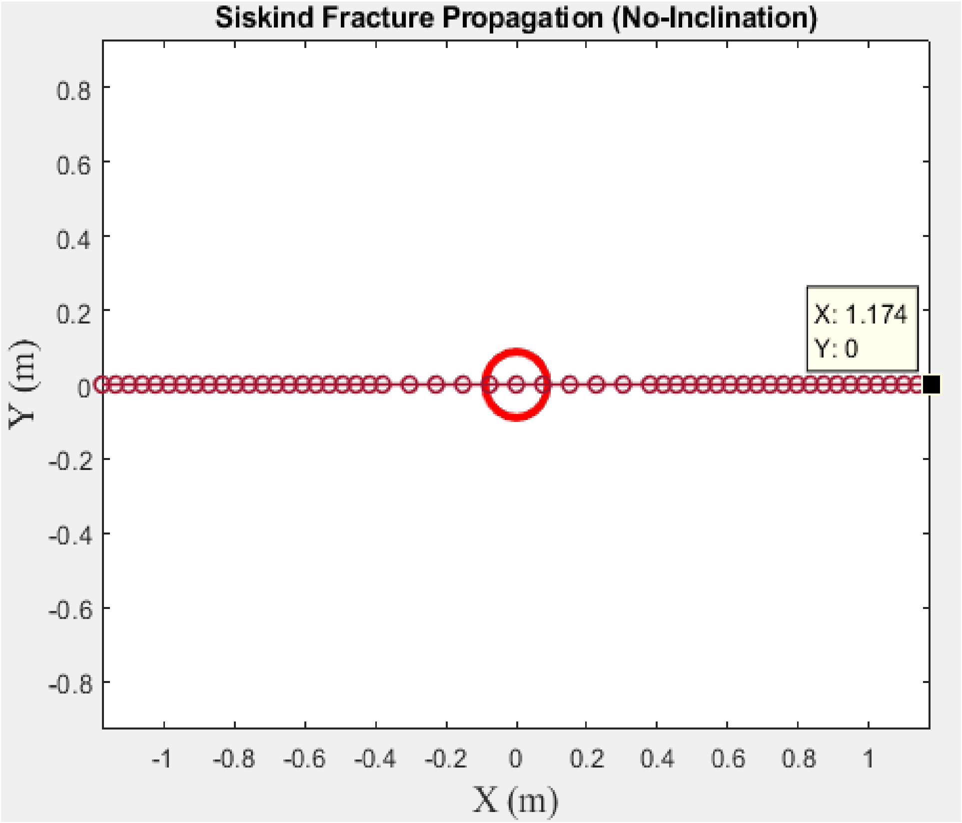
Assessment methodologies

Methodologies Comparison

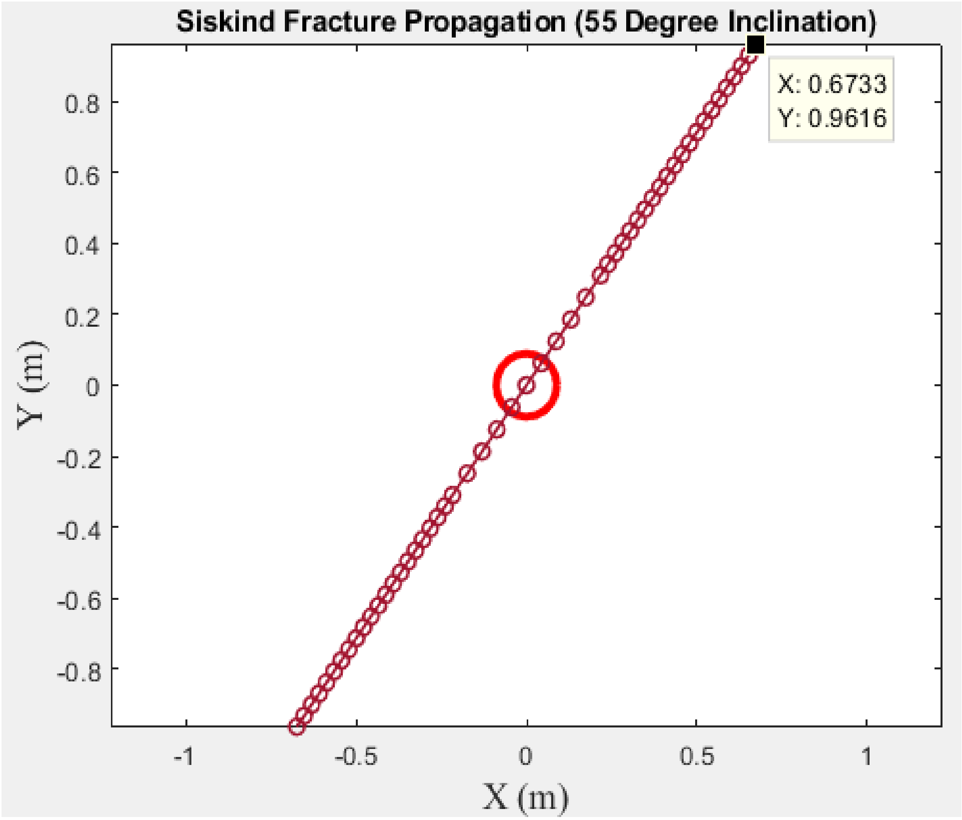
Source/Study	Crack Extension (m)	Comments
Siskind USBM (RI 7901)	1.14 (3.74 ft.)	This was the actual value measured in tests
Forsyth equation (Forsyth)	3.47 (11.38 ft.)	Calculated using static parameters
Holmberg-Persson. (Holmberg et al. 1978)	2.34 (7.68 ft.)	Calculated using the peak particle velocity limit criterion of 1000mm/s
UKERT paper (Silva et al. 2019)	1.67 (5.48 ft.)	Using practical methodology assessment and dynamic properties

Explosive	Crack Extension Calculated (m)	Crushing Zone extension (m)
ANFO	1.40 (4.59 ft.)	0.378 (1.24 ft.)
Emulsion	1.92 (6.3 ft.)	0.712 (2.34 ft.)
Unigel (Dynamite)	1.99 (6.53 ft.)	0.798 (2.62 ft.)

Assessment methodologies



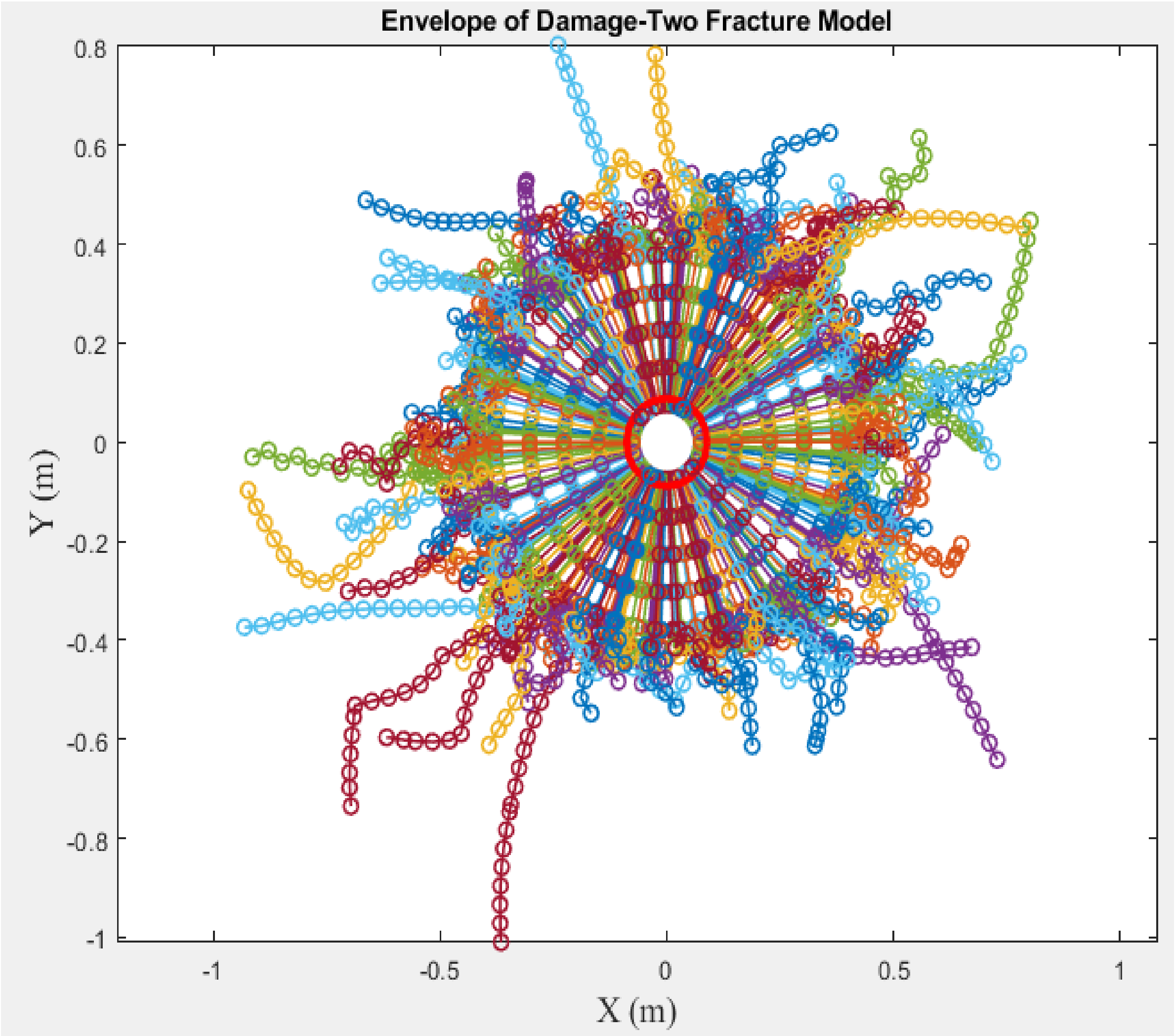
1.174 meters (3.852 feet) with an error of 3.0%



1.174 meters (3.852 feet) with an error of 3.0%

No in-situ stresses present

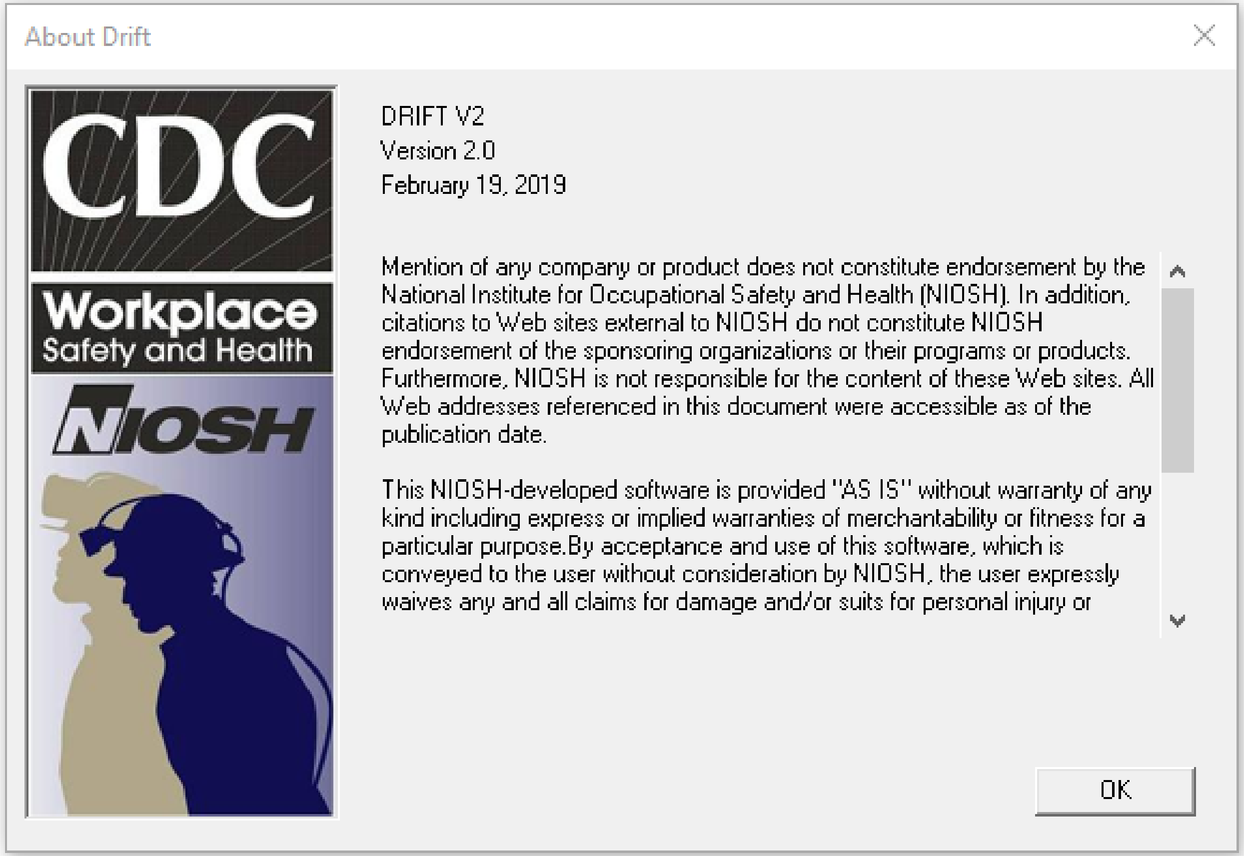
Model Development Multiple Fractures



UKERT - Testing

UKERT - Testing

NIOSH - Application



https://www.cdc.gov/niosh/mining/works/coversheet2035.html

Video – Showing – NIOSH software

Discussion - Conclusions

- Many methodologies available (at least 18 and counting). Recommended to know the principles and applicability of those for specific problems,
- More "elaborate models" more input parameters needed,
- Most of the solutions are deterministic, no accurate when simulating geology related problems. UKERT developing a probabilistic approach to the problem.
- In blasting problems always high variability due to geology, results needed to adopt with caution. Apply engineering criterion and adjust the results.

Acknowledgments/Thanks

Nally & Gibson
N&G
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UK
EXPLOSIVES RESEARCH TEAM

PEM
Moving Kentucky Forward

DYNO
Dyno Nobel