

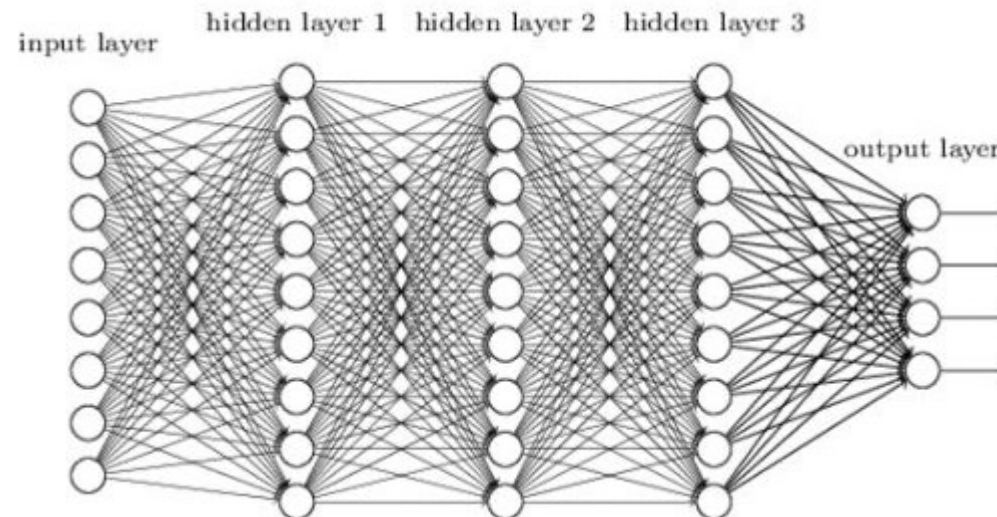


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Using machine learning, experimental observations, and numerical modeling to better understand the crushed zone in rock blasting

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Overview

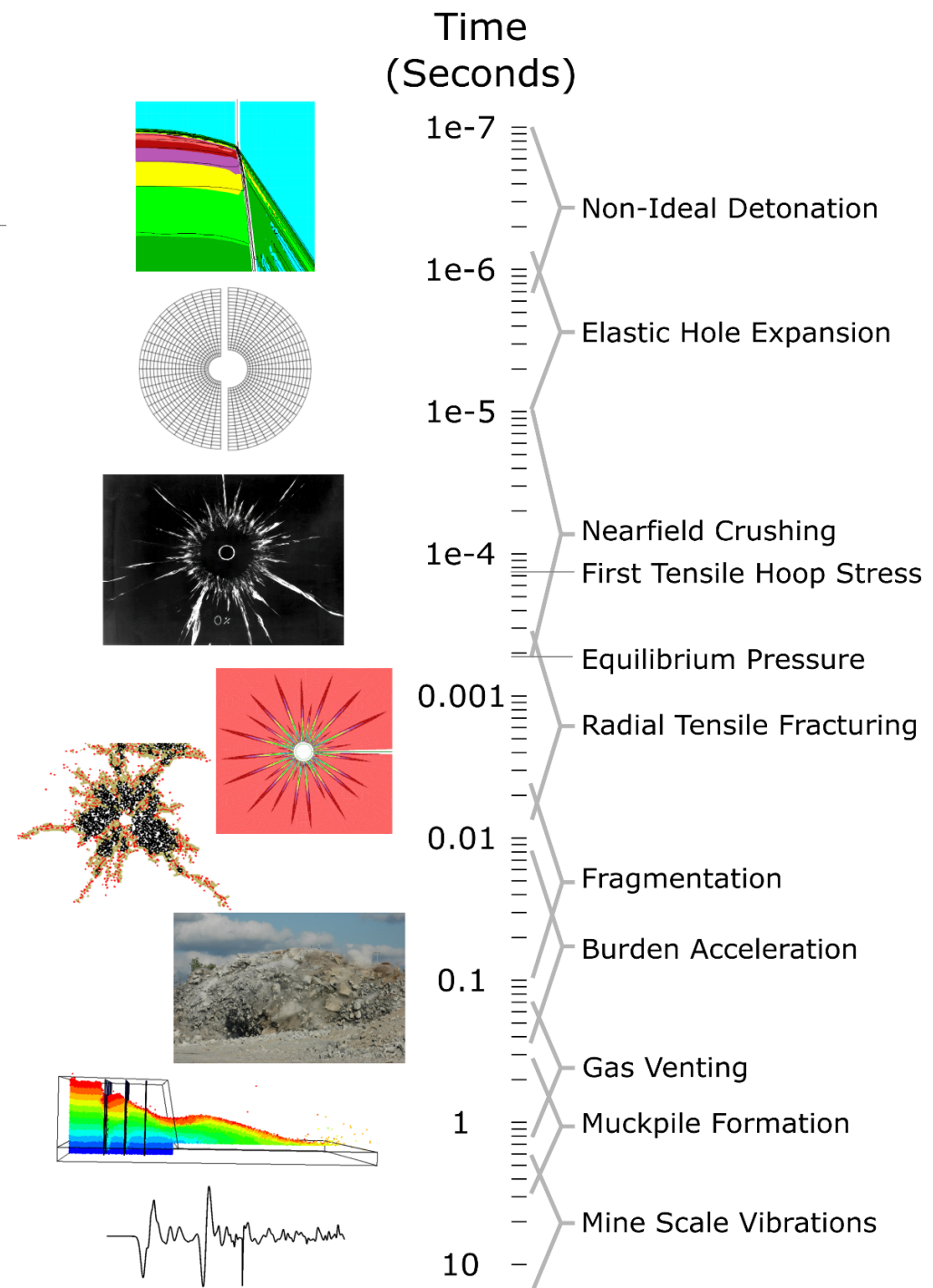


Rock Blasting

The physical processes occurring in rock blasting span six orders of magnitude in length-scale, time-scale and pressure.

The interactive-physical processes involved are time-dependent, non-linear, difficult to quantify experimentally and occur in a discontinuous, heterogeneous medium.

Blasting Sub-Problems: Non-ideal detonation, crushing, fracturing, vibrations, damage, burden movement, fly-rock, gas flow, and fumes



Crushed Zone

- ❖ Near the blasthole, the explosive induces compressive stresses that are well beyond the strength of the rock leading to the development of a crushed zone
- ❖ The presence of fines may influence positively or negatively the downstream mineral recovery
- ❖ Crushing consumes explosive energy that would otherwise do useful work fracturing and moving the rock

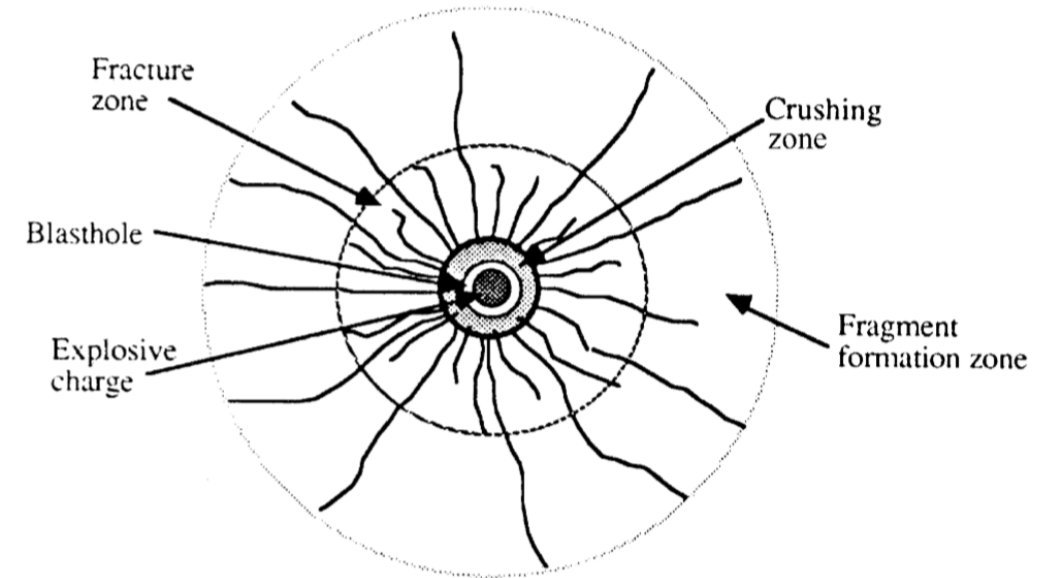
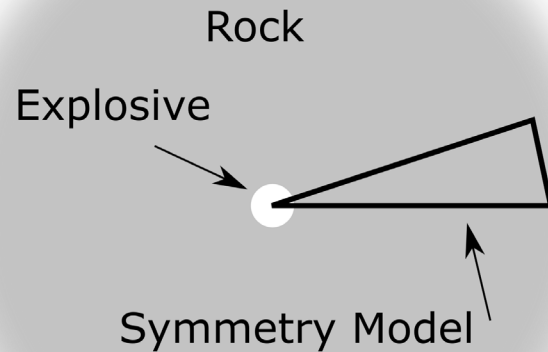


Fig. 1. Schematic illustration of processes occurring in the rock around a blasthole, showing formation of crushing zone, fracture zone and fragment formation zone [11].

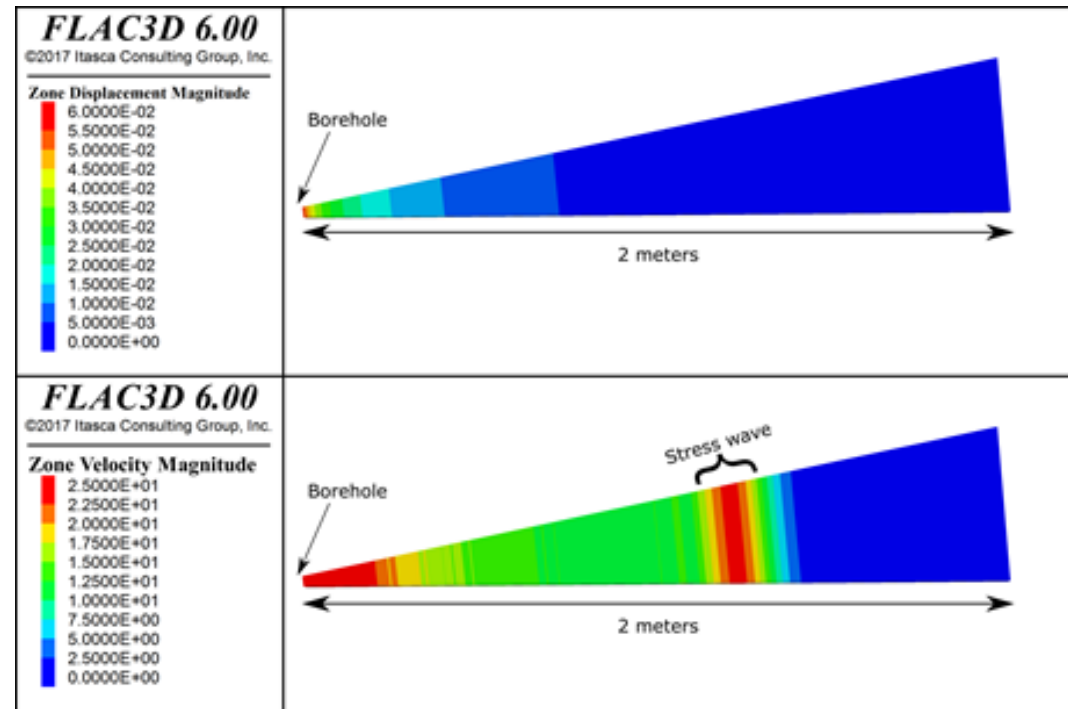
Small-Scale Model



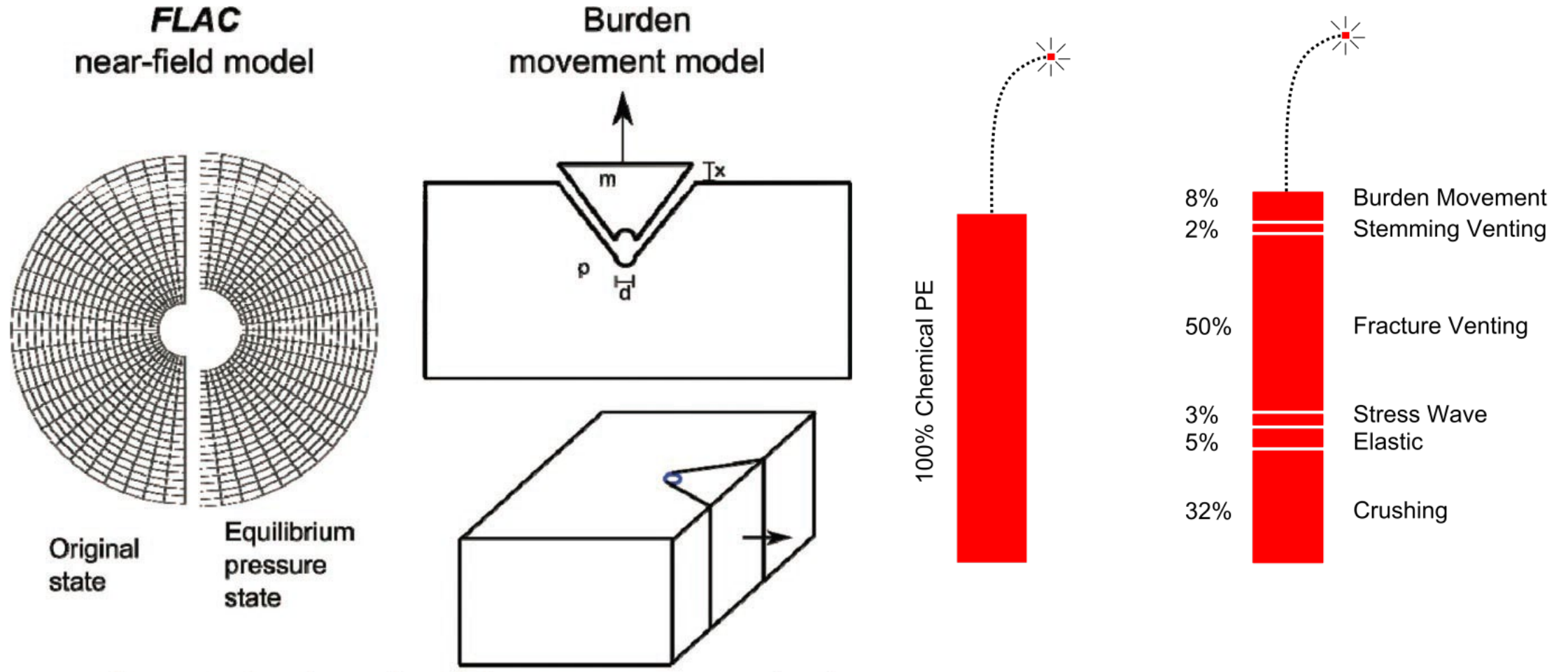
Quantify explosive rock interaction

How much of the energy of the explosive gets into vibrations?

- Use the product equation of state and a non-ideal detonation model
- Rock properties: E, UCS, and rho



Energy Partition



Crush Zone Index (CZI)

- 92 crushed zone measurements (Esen, et al., 2003)
- Dimensional analysis which relates explosive and rock properties to the crushed zone size.
- The ratio of original hole radius, r_0 , to the radius of the crushed zone, r_c , is given as,

$$CZI = \frac{P_b^3}{K\sigma_c^2}$$

$$\frac{r_0}{r_c} = 1.231(CZI)^{-0.219}$$

P_b Borehole pressure

K Dynamic modulus

σ_c Compressive strength

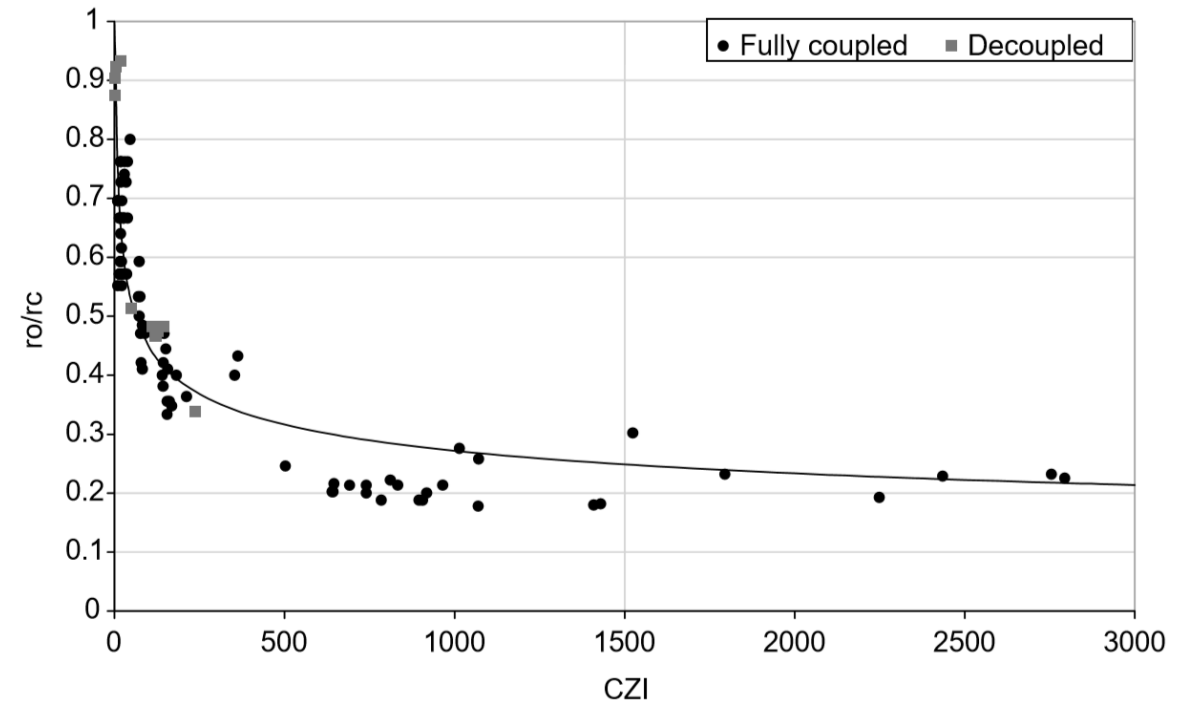
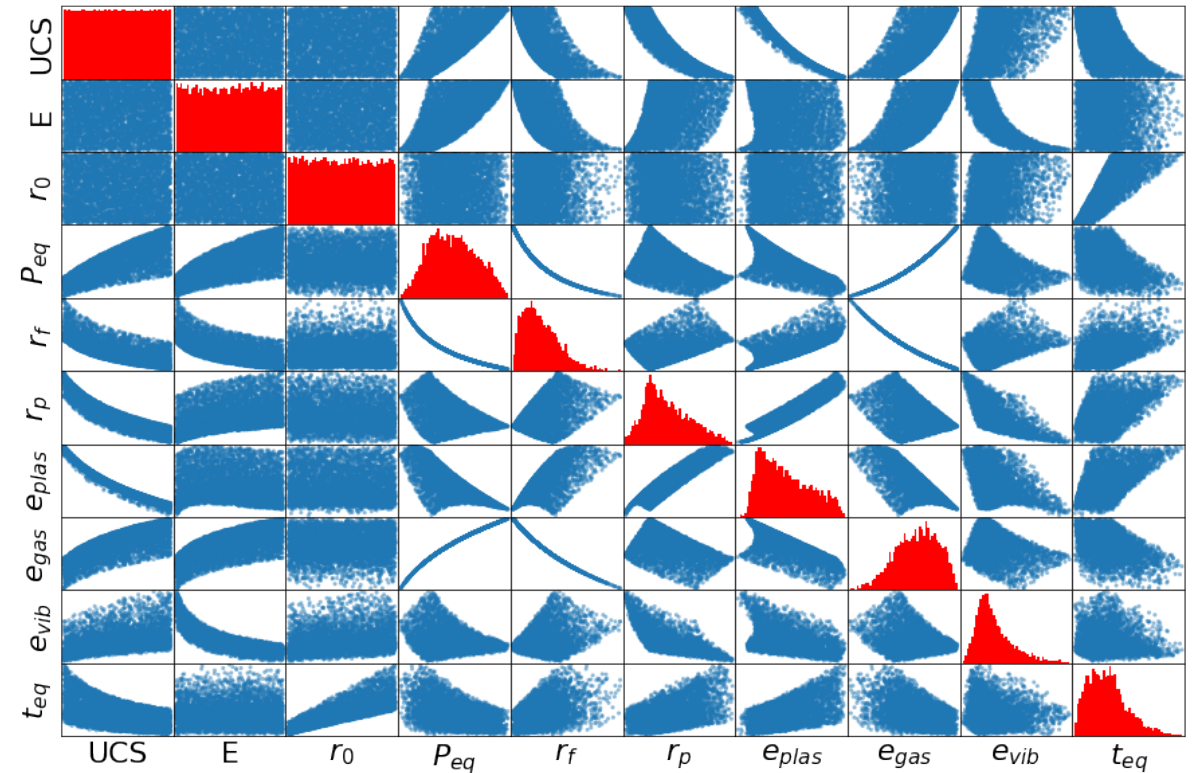


Fig. 4. Relationship between CZI and r_0/r_c for 92 model scale test blasts.

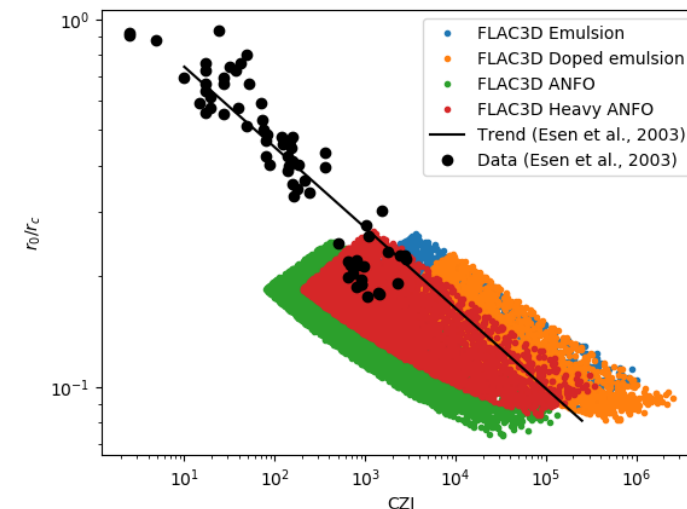
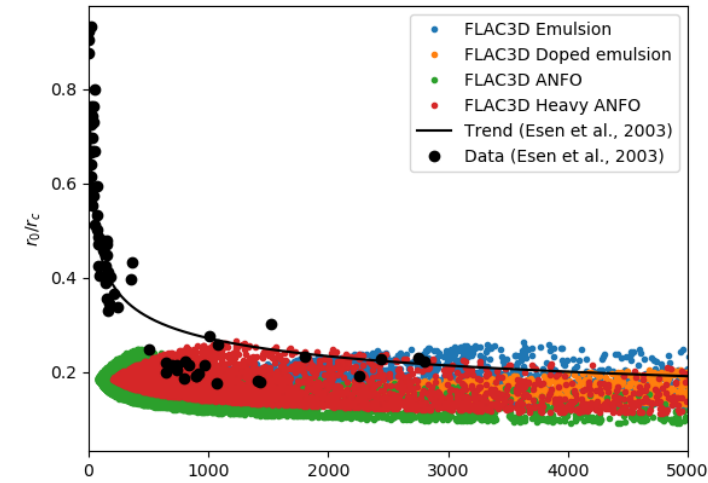
Numerical Parameter Study

- 40,000 cases run with numerical model
- 4 different explosive types
 - ANFO, emulsion, doped emulsion and heavy ANFO
- Use Latin hypercube sampling to vary:
 - Young's Modulus
 - Density
 - UCS
 - Borehole Radius
- Cloud based job queue system for distributed computing of parameter study cases
 - Edge computing



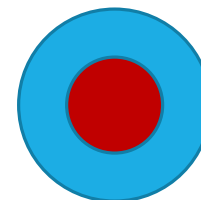
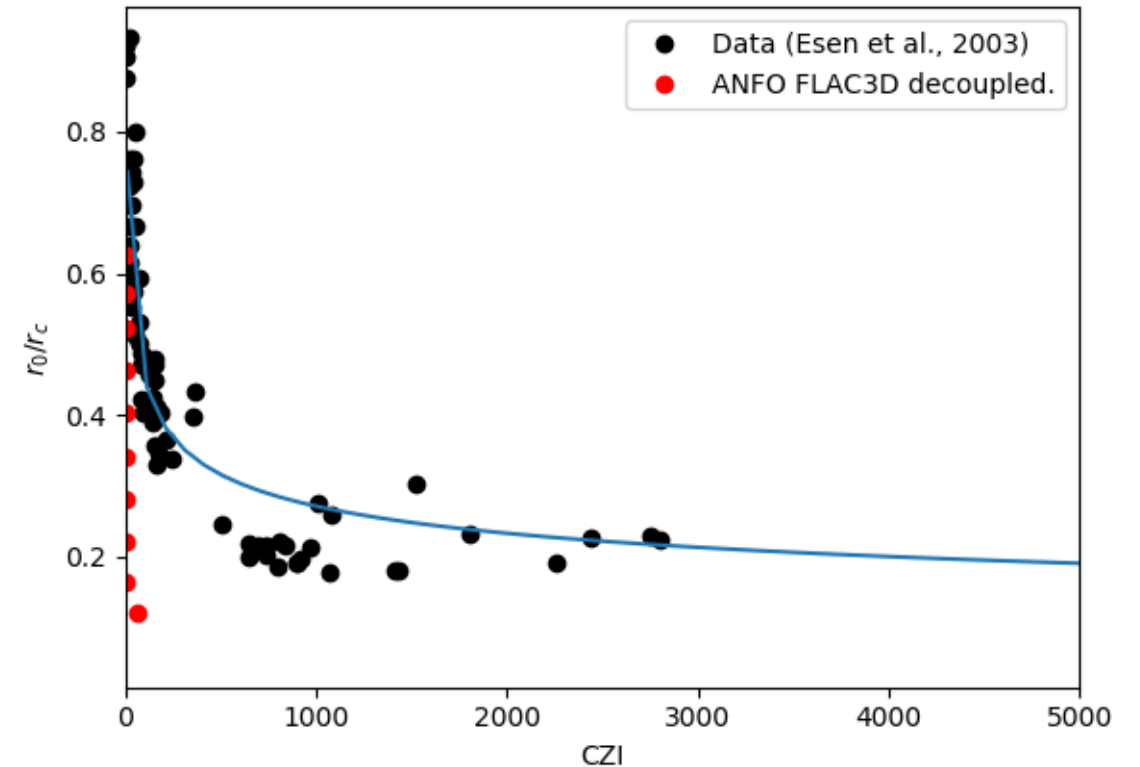
Comparison of Data and Numerical Results

- Only “matching” in the crushing regime
- The CZI model does not have the details of the explosive
- There is some ambiguity about where the crushed zone is.
 - Taken as radius within which 90% of the plastic energy dissipation occurs
- Simple constitutive behavior – no volumetric collapse



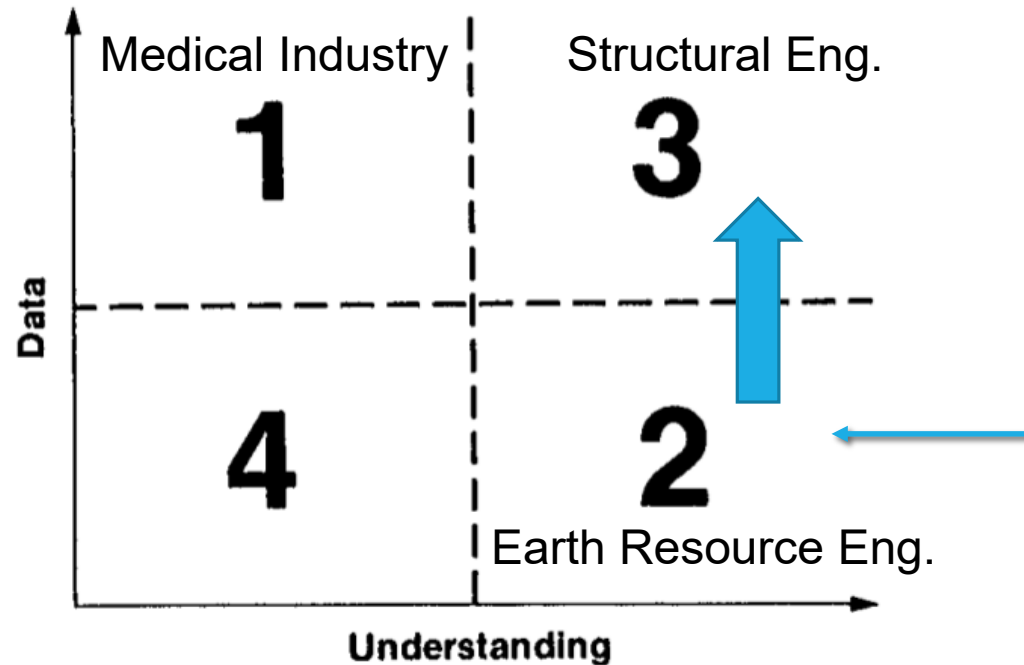
Decoupled Explosive

- Annulus of air between explosive and rock
- Explosive expands adiabatically to rock wall
- Pre-splitting and trim blasting
- Transition to the regime where no compressive failure occurs – direct fracturing



Data Limited Regime (Starfield and Cundall, 1988)

STARFIELD and CUNDALL:



In Earth resource engineering, we are slowly leaving the data limited regime via IoT, remote sensing, MWD, and cloud computing, but fundamentally we cannot see into the Earth.

Fig. 1. Holling's [1] classification of modelling problems.

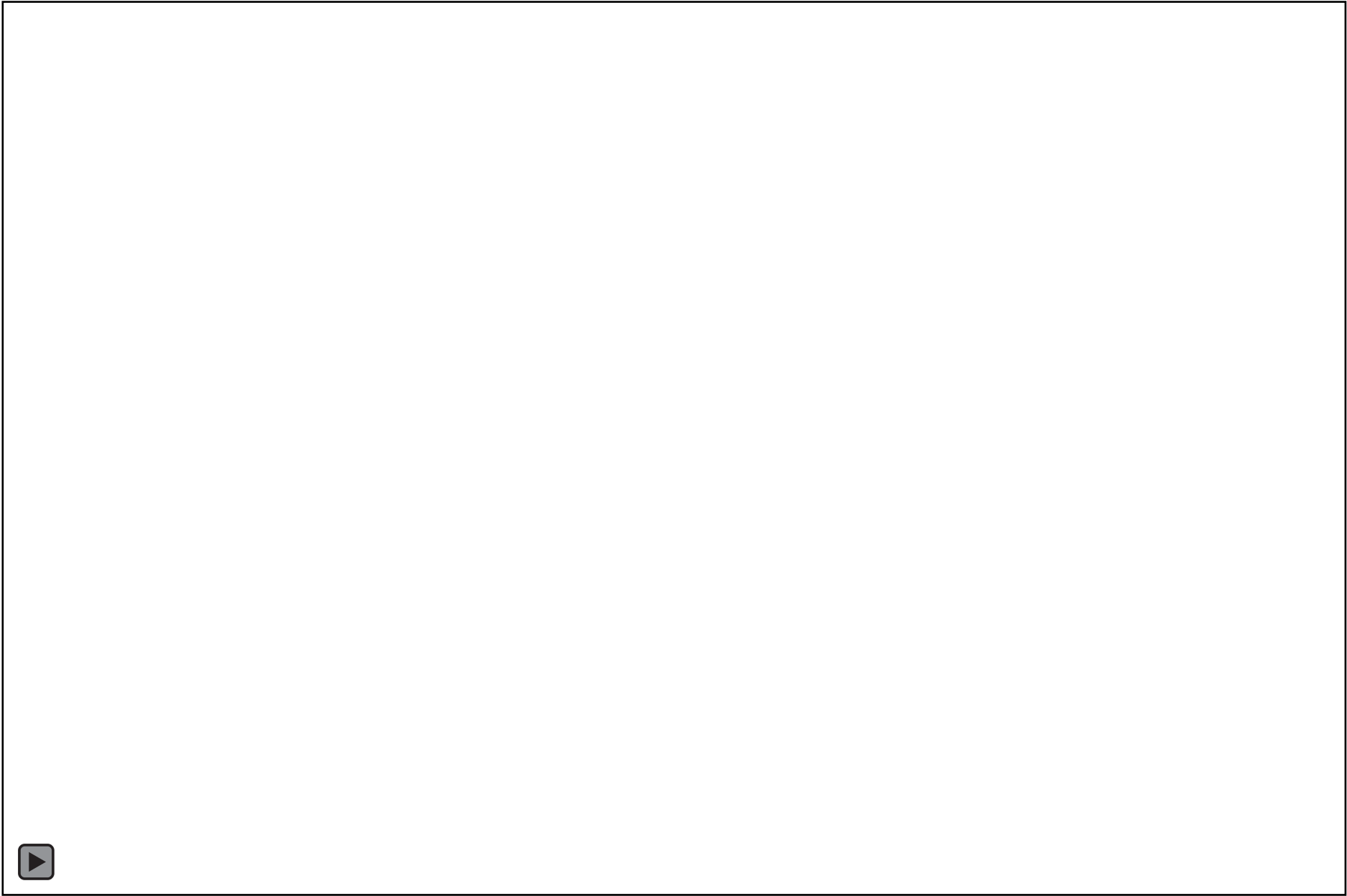
Machine Learning and Surrogate Models

In traditional numerical analysis we explicitly solve known equations forward to make predictions

- Machine Learning is the art and science of making predictions **without** explicit programming. The data **is** the model.
- Domain knowledge is still required: feature engineering

Validated numerical models can be used to generate synthetic data which can be used to train machine learning models -- this is a **surrogate model**.

- Fast approximate answer, good for probabilistic analysis, training, numerical preconditioning, or any time a fast-approximate answer is needed.
- A new way to create easy-to-use empirical model.



Conclusions

- The crushed zone size is (mostly) independent of the hole diameter.
- Increasing the rock UCS or modulus decreases the crushed zone size and increases the equilibrium pressure.
- In general, emulsion type explosives do more work at higher pressures and result in lower equilibrium pressures. In contrast, ANFO explosives do less work at higher pressures and have higher equilibrium pressures.
- The crushed zone size alone is not the only relevant explosive-rock characterization. In most cases, the ANFO gives a larger crushed zone than an emulsion, but around 40% less energy is dissipated in plastic flow compared to an emulsion.
- Future work: use this surrogate model to inform a DEM contact model that can account for crushing. Long term: a fully discrete numerical model of blasting.

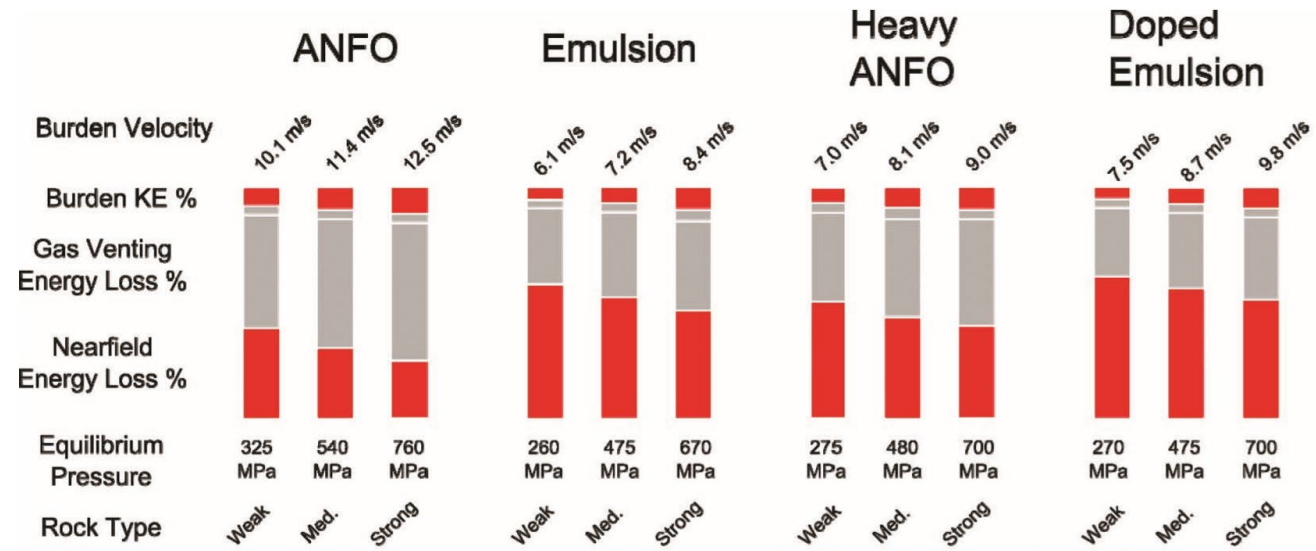
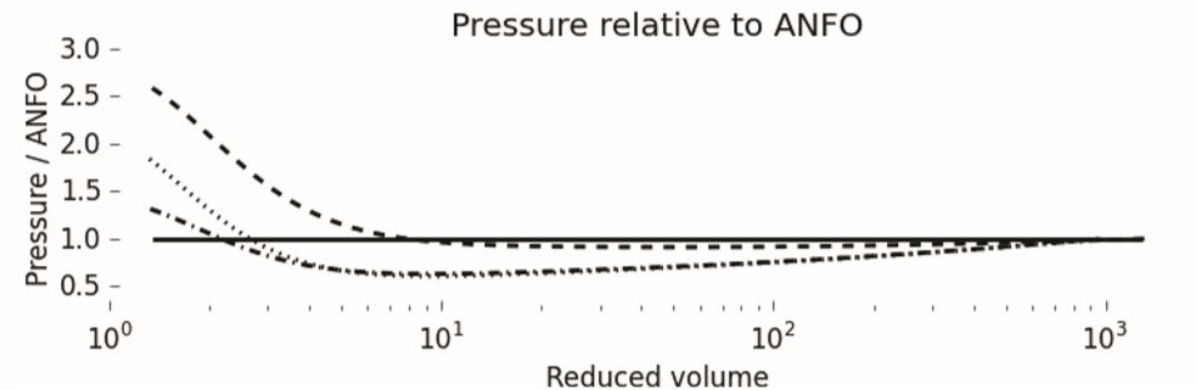
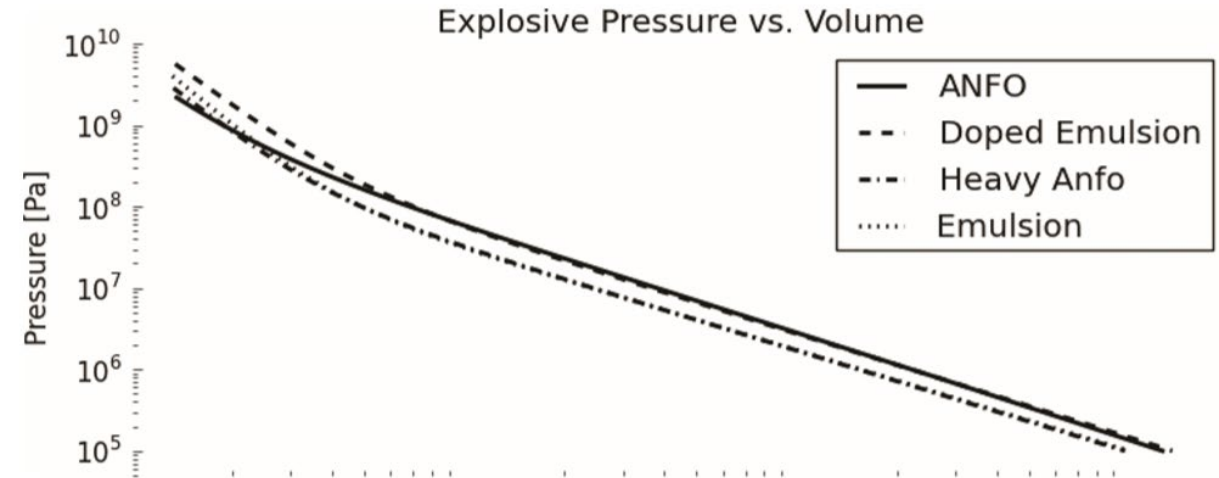
https://jkfurtney.github.io/ml_blasting/



The Influence of Explosive Type

Different explosives release different amounts of energy in the initial detonation vs later expansion

Understanding and quantifying the explosive-rock interaction is important for modeling any subsequent blasting phenomena



Data Analysis

