Building a Surrogate Model for Rock Blasting Application

Wei Fu, Jason Furtney, Jorge Valencia

wei@itascacg.com

Overview

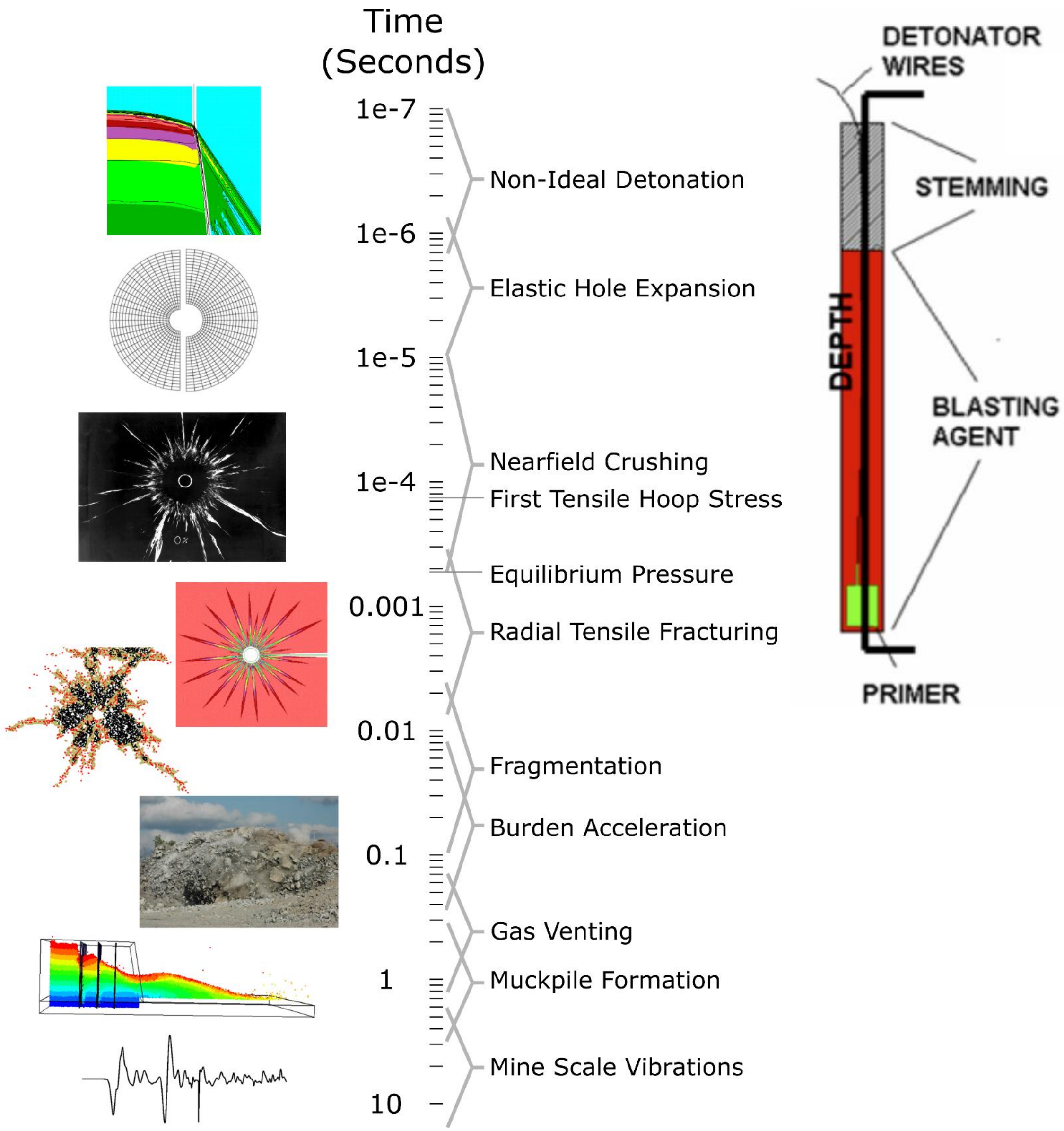
- *Why Build Surrogate Model?*
- *Numerical Model Development*
- *Design of Experiments*
- *Training a Surrogate Model*
- *Informing the Discontinuum Model*

Pressures
- 5 GPa in detonation
- 100 kPa atmospheric pressure

Lengths
- 0.1 mm shock front
- 10 m bench height

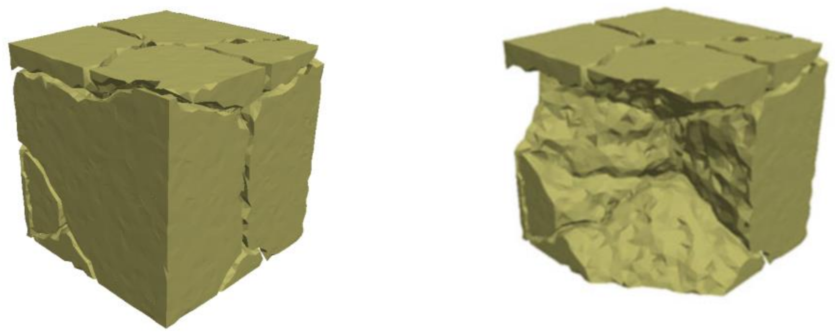
There is no single numerical model that can optimally address all these scales

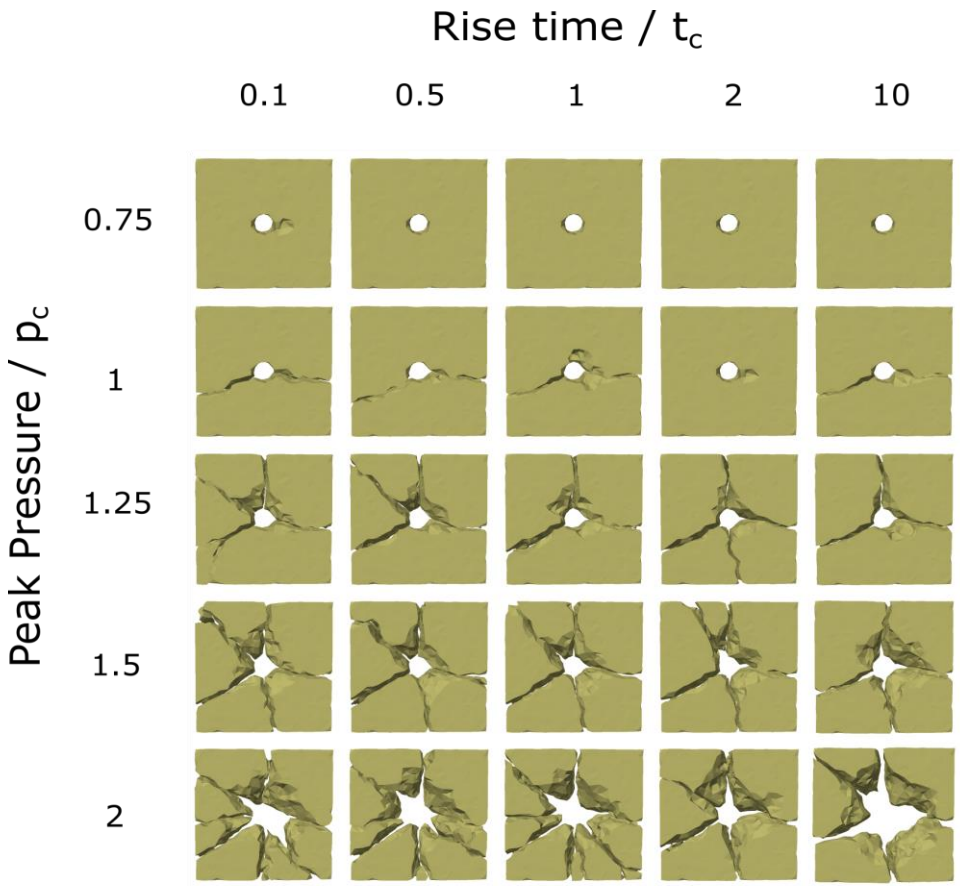
Blasting Time-Scales



Discrete Element Modeling of Rock Fragmentation

- Rock specimens subjected to explosive loading
- *PFC3D* model to simulate the fracturing process
- 25 x 25 x 10 cm rock specimens
- Spherical-grain, parallel-bonded material
- Particle diameter ~ 4.25 mm ~100,000 particles

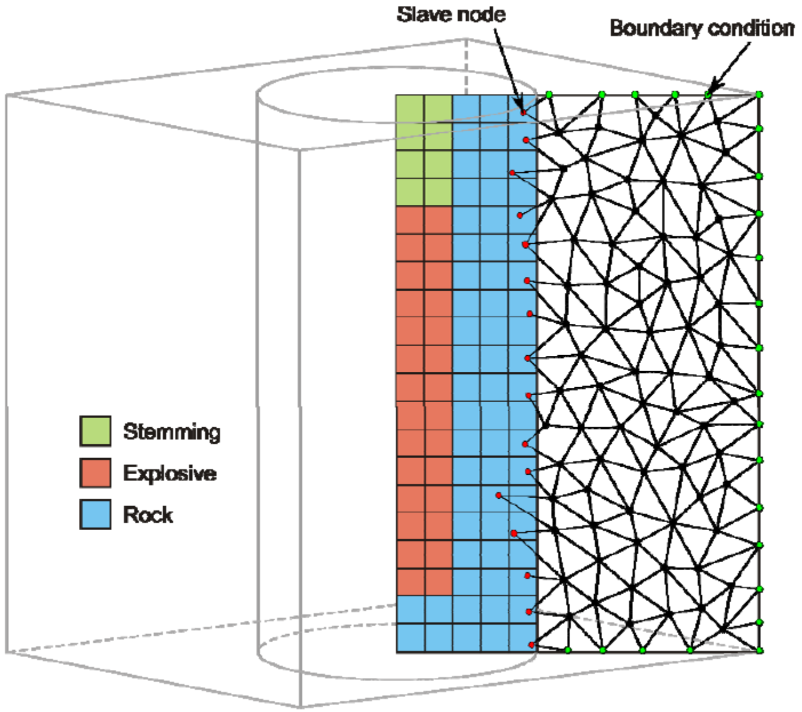


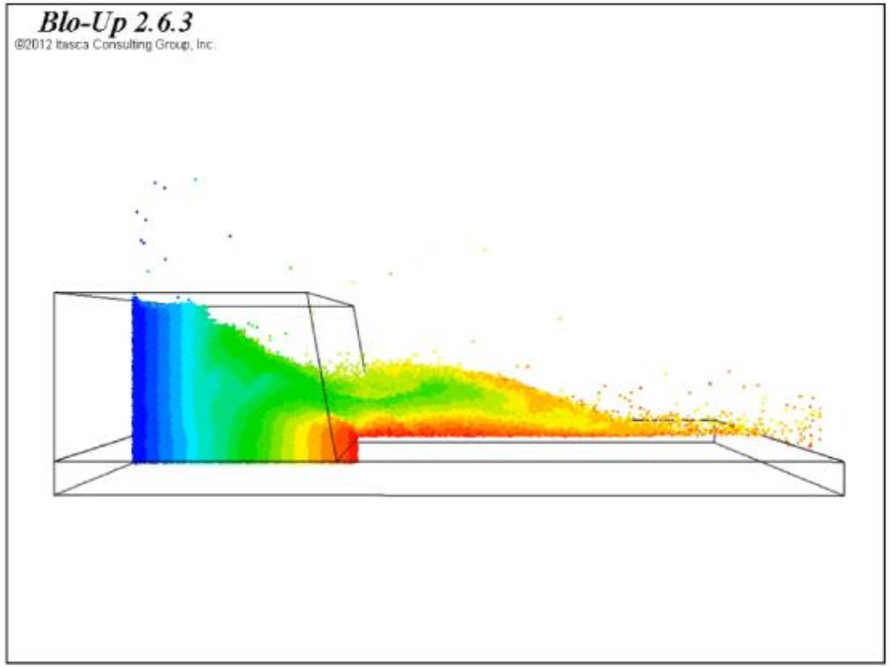


Furtney, J., & Aglawe, J. (2021). PFC3D modeling of rock fragmentation by pressure pulse. In *Recent Advances in Computational Mechanics and Simulations: Volume-I: Materials to Structures* (pp. 237-246). Springer Singapore.

Blast Layout Optimization Using PFC (BLO-UP)

Lattice simulation based on PFC for rock blasting process





SPONSORED BY:

AEL Mining Services · ANGLO AMERICAN · DYNO Dyno Nobel · LKAB · RioTinto

Project Partners:

AEL Mining Services · ITASCA Consulting Group, Inc. · SMI JKMRC Julius Kruttschnitt Mineral Research Centre

Why Surrogate Model?

- Despite many advantages, complex numerical models of rock blasting are difficult to set up, time consuming to run, and typically only consider limited scenarios.
  - Steep learning curve
  - May be impractical for field practitioners

- Surrogate models are fast and can predict outputs of a complex process for a range of input parameters, and they can be used for
  - probabilistic analysis,
  - numerical pre-conditioning,
  - application by field practitioners,
  - understand functional relationships

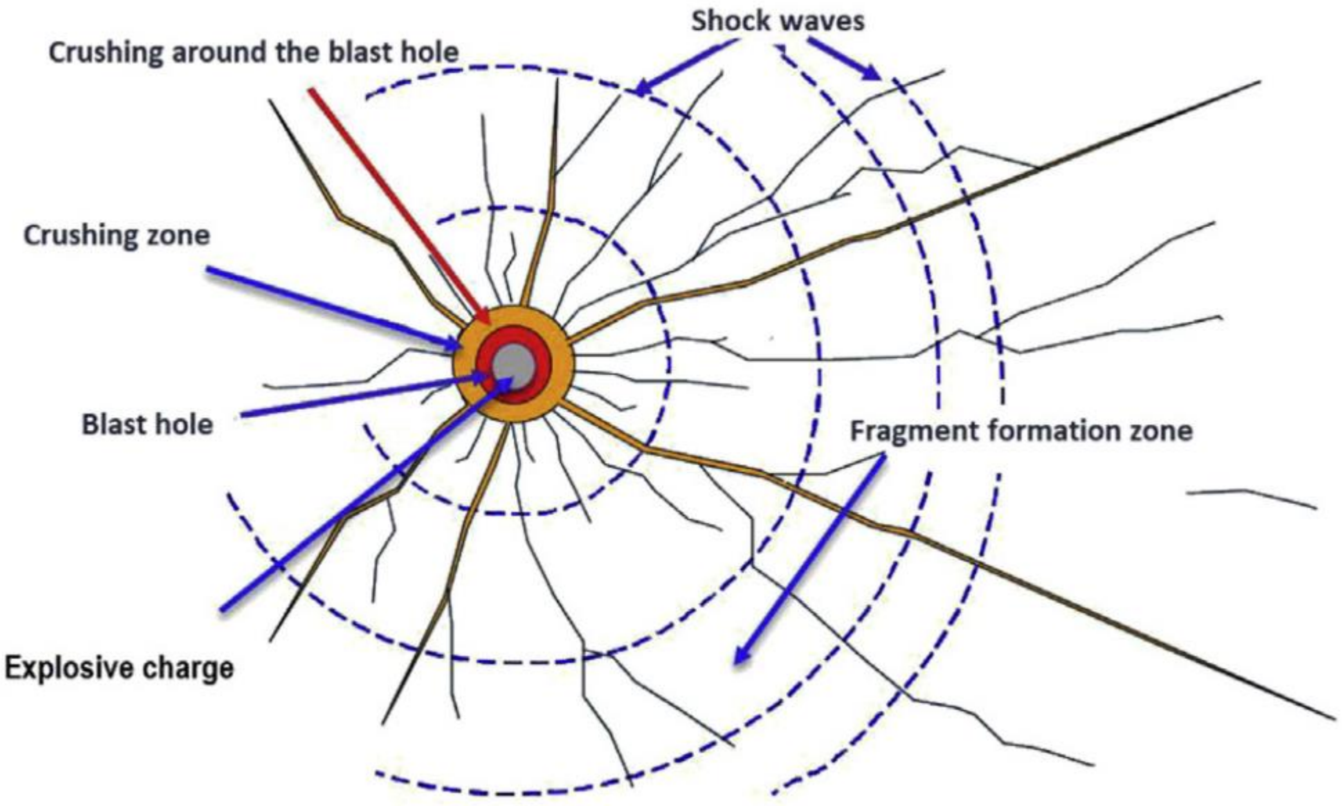
Overview

- *Why Build Surrogate model?*
- *Numerical Model Development*
- *Design of Experiments*
- *Training a Surrogate Model*
- *Informing the Discontinuum Model*

Rock Blasting Modeling

Key processes:

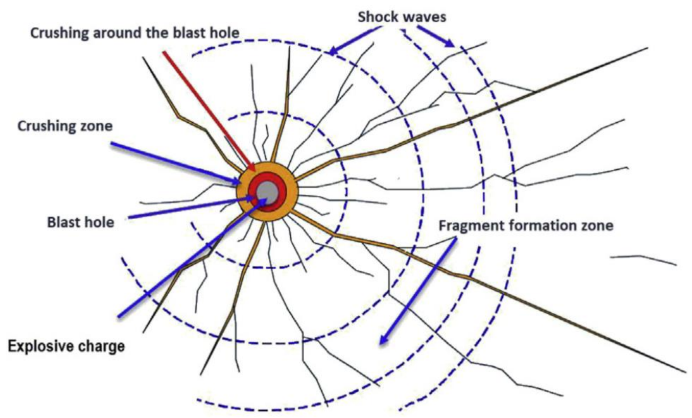
1. Crushed zone development due to the explosive induced stresses near the wellbore (near-field)
2. Rock fracturing and fragment acceleration due to the explosive energy
3. Rock fragment movement and muckpile formation (far-field)



Schematic illustration of processes occurring in the rock around a blasthole (Kabwe, 2018)

ITASCA™

Rock Blasting Modeling



Key processes:

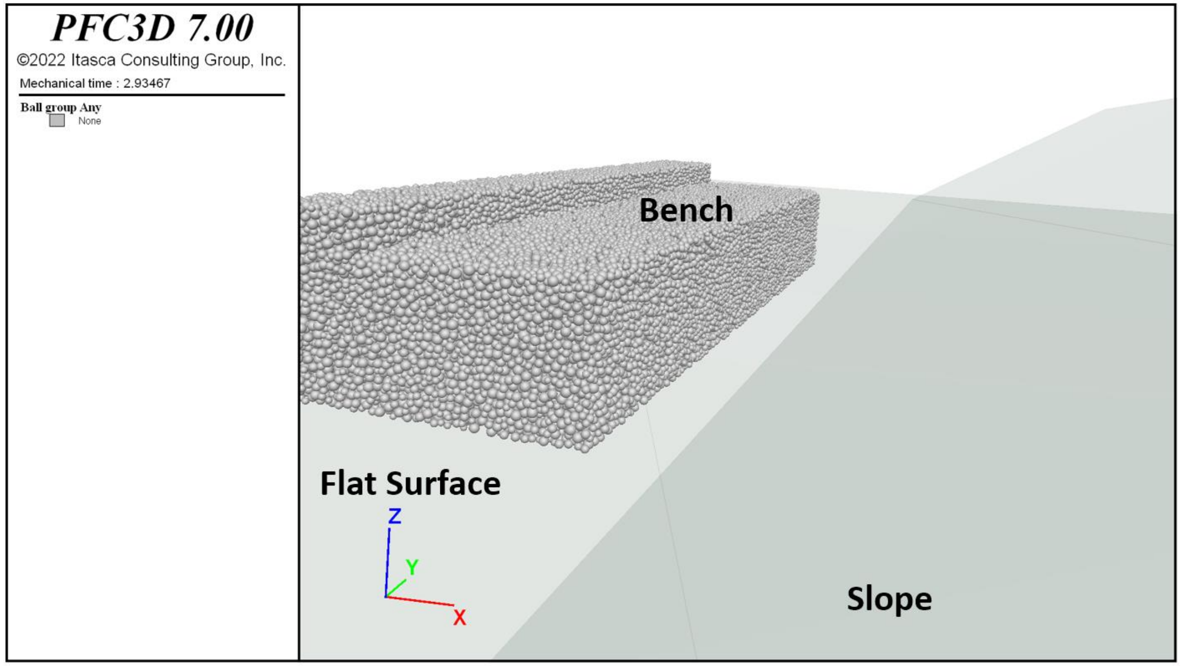
1. Crushed zone development due to the explosive induced compressive stresses near the wellbore (near-field)
2. Rock fracturing and fragment acceleration due to the explosive energy
3. Rock fragment movement and muckpile formation (far-field)

- Simplification is needed

Illustration of a blasting site

Far-Field: Model Rock Movement and Muckpile Formation

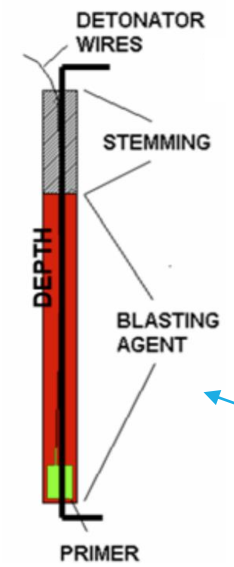
- *PFC3D* is suitable to simulate the rock movement and muckpile formation
- Including both near-field and far-field processes in one blasting model is challenging and computationally prohibitive
- Can we approximate the near-field process?

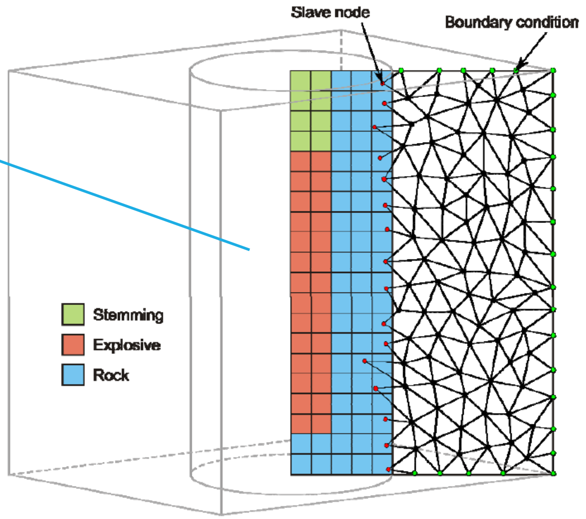


Near-Field: Model Rock and Borehole Deformation

Modeling Simplification

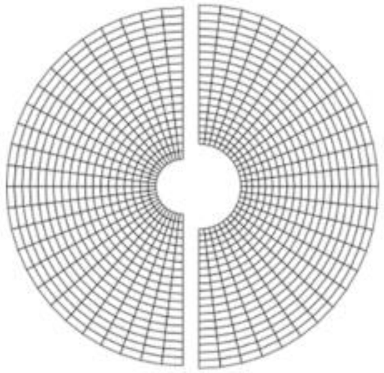
3D Model





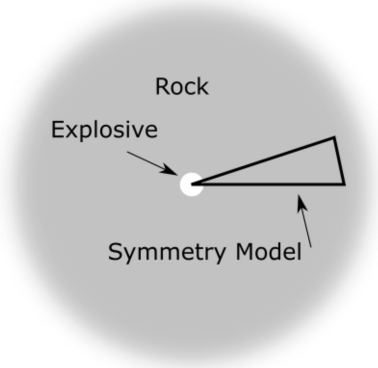
2D Model

(Plane-strain assumption)



Symmetry Model

(Radial Symmetry)



Near-Field: Model Rock and Borehole Deformation

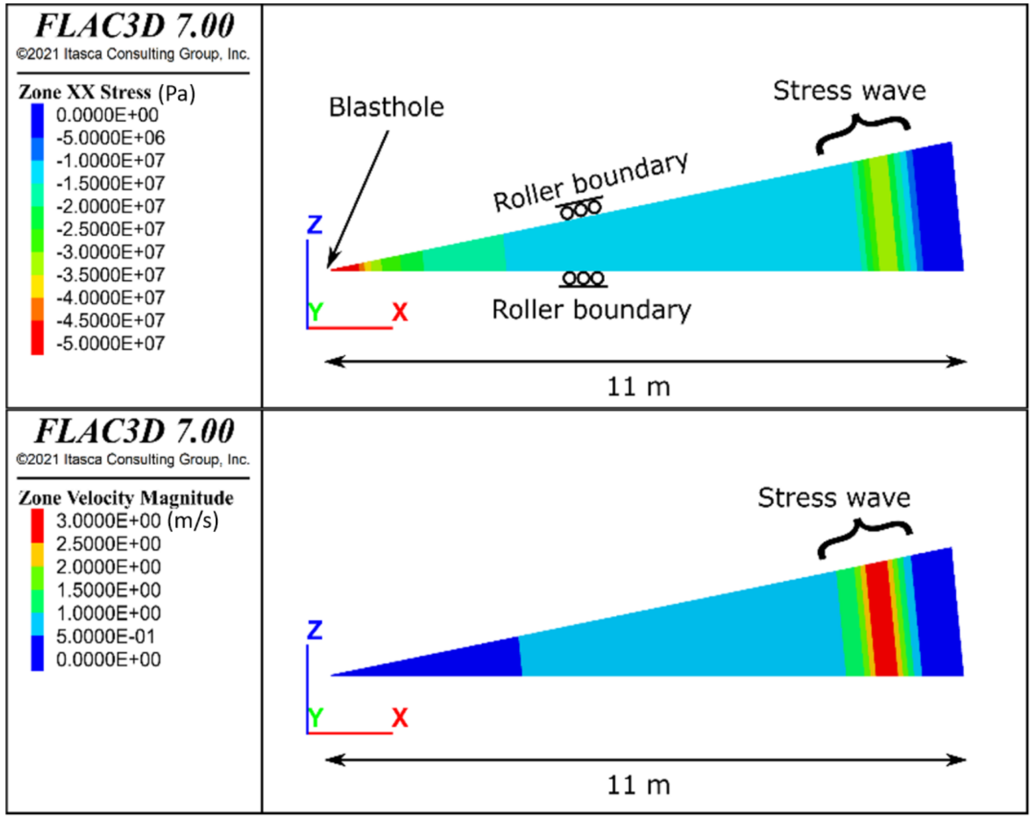
Axisymmetric model (FLAC3D), which represents the detonation along with the elastic and plastic deformation in early stage. Dynamic mode with Mohr Coulomb constitutive model is used to describe the near-field rock.

Key Inputs:

- Explosive type
- Blasthole Radius
- Rock properties: E, UCS, density, friction

Key Outputs:

- Equilibrium pressure
- Final borehole diameter

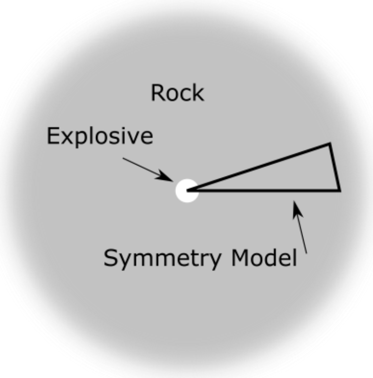


Quantify explosive-rock interaction

Model Burden Movement

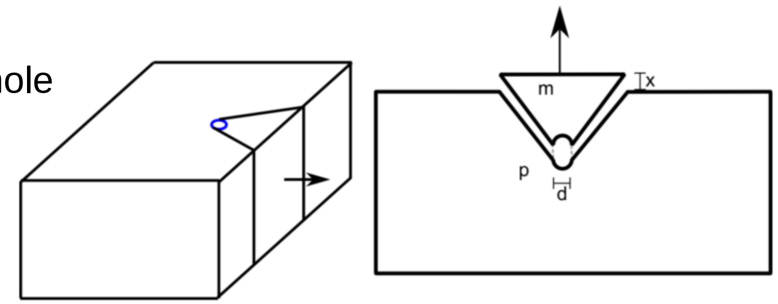
Model Simplification: Developing Analytical model to predict rock movement

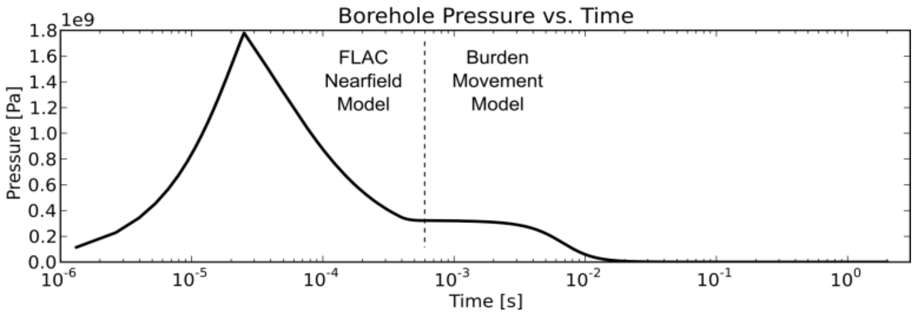
FLAC3D model



- Equilibrium Pressure
- Final borehole diameter

Burden Movement Model





Burden Velocity

Coupled Analytical Model for Burden Movement

$$\ddot{x} = 2rl_e p/m$$

$$\dot{V} = 2rl_e\dot{x} + l_e w u_f + \phi(\pi r^2 + 2rx)u_s$$

$$\phi = 1 - r(1-\phi_0)/(x+r)$$

- expansion of the borehole cavity
- flow into the fracture network
- flow through the stemming

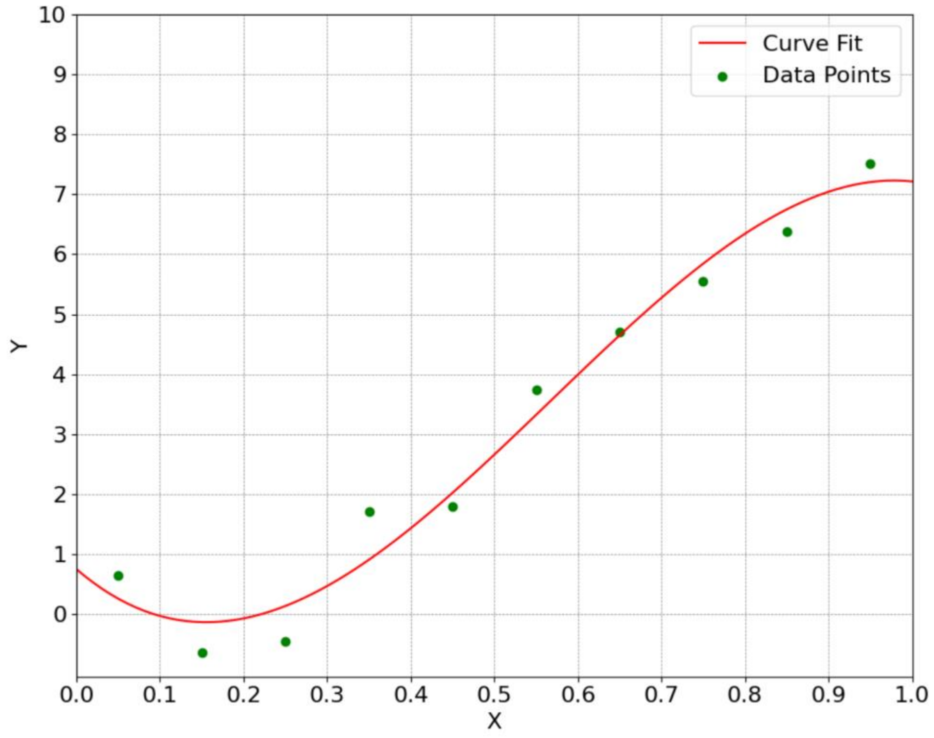
Overview

- *Why Build Surrogate model?*
- *Numerical Model Development*
- *Design of Experiments*
- *Training a Surrogate Model*
- *Informing the Discontinuum Model*

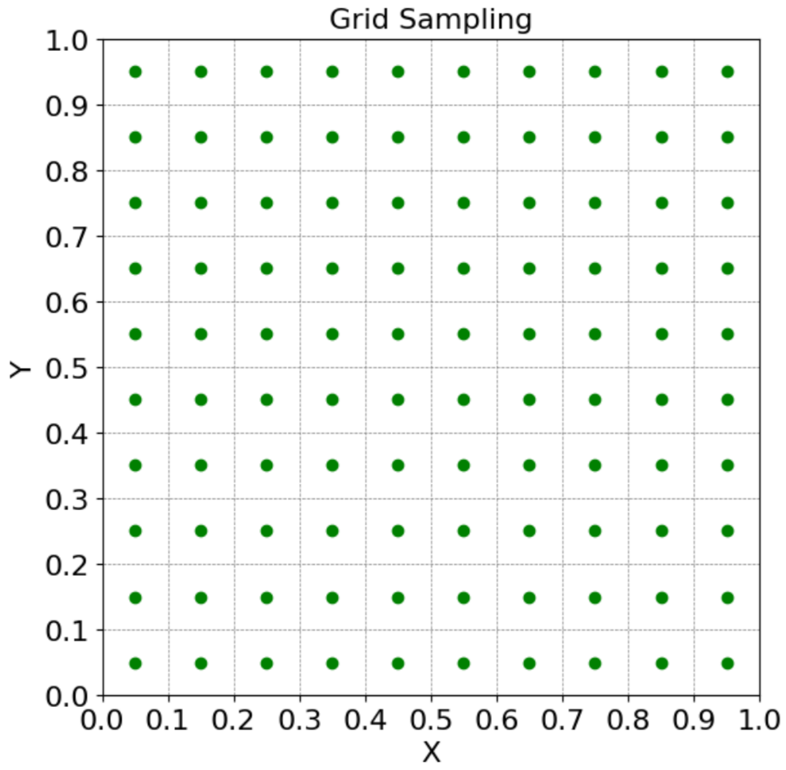
Design of Experiments: Sampling

Grid Sampling:
Explore the entire parameter space of a model

Grid sampling in 1D



Grid sampling in 2D

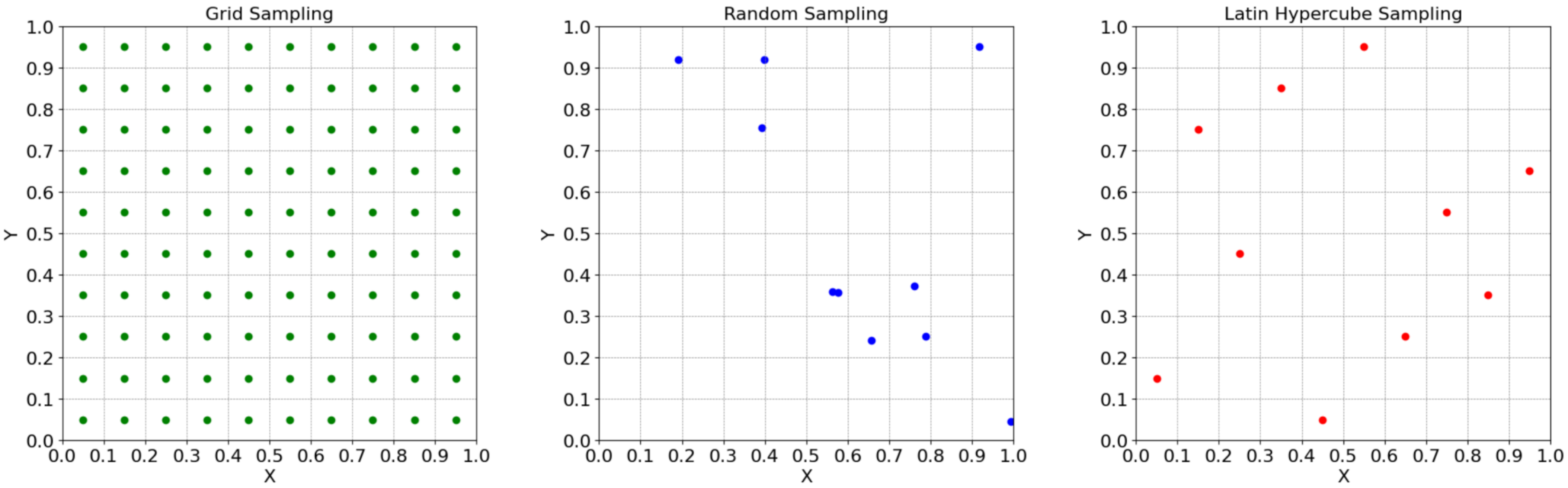


Grid sampling in nD

10^n

Latin Hypercube Sampling

Random sampling: new sample points are generated randomly, without taking into account the previously generated sample points
Latin hypercube sampling (LHS): each sample occurs exactly once in each row and exactly once in each column: well spread-out



A	B	C
C	A	B
B	C	A

LHS minimizes redundancy and ensures a more even and representative coverage of the search space

How Much Data Do I Need?

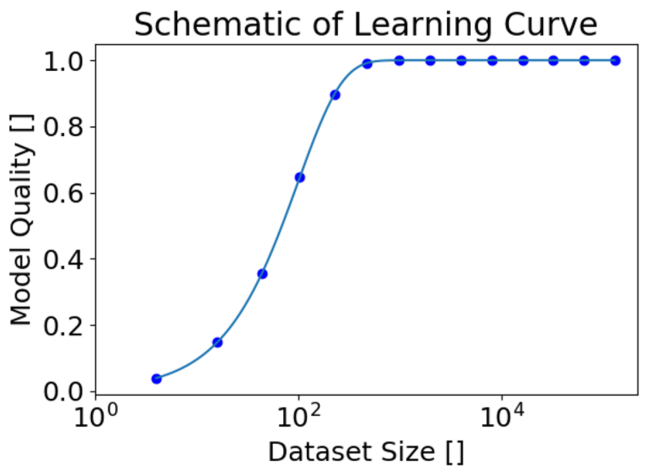
It is difficult to know beforehand how many data points are needed to get a good model fit.

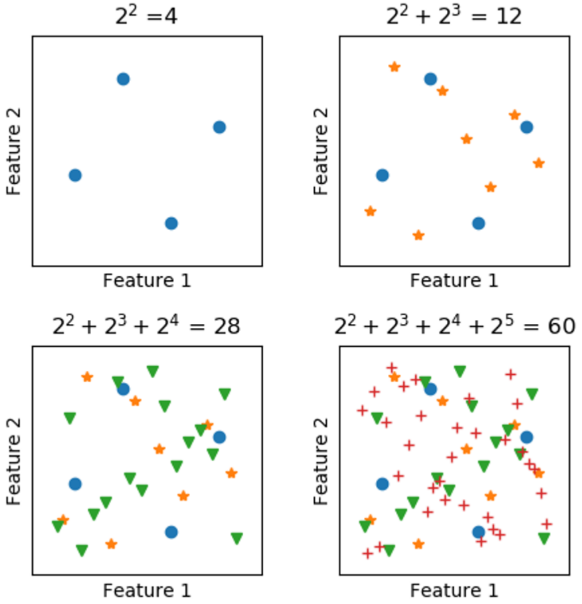
Latin hypercube sampling is used to optimally sample a parameter space

We use a sequence of latin hypercubes, each double the size of the previous

We generate synthetic data in this order and look at the learning curve as data comes in

Run *FLAC3D* 10,000 times with a range of input parameters





ITASCA™

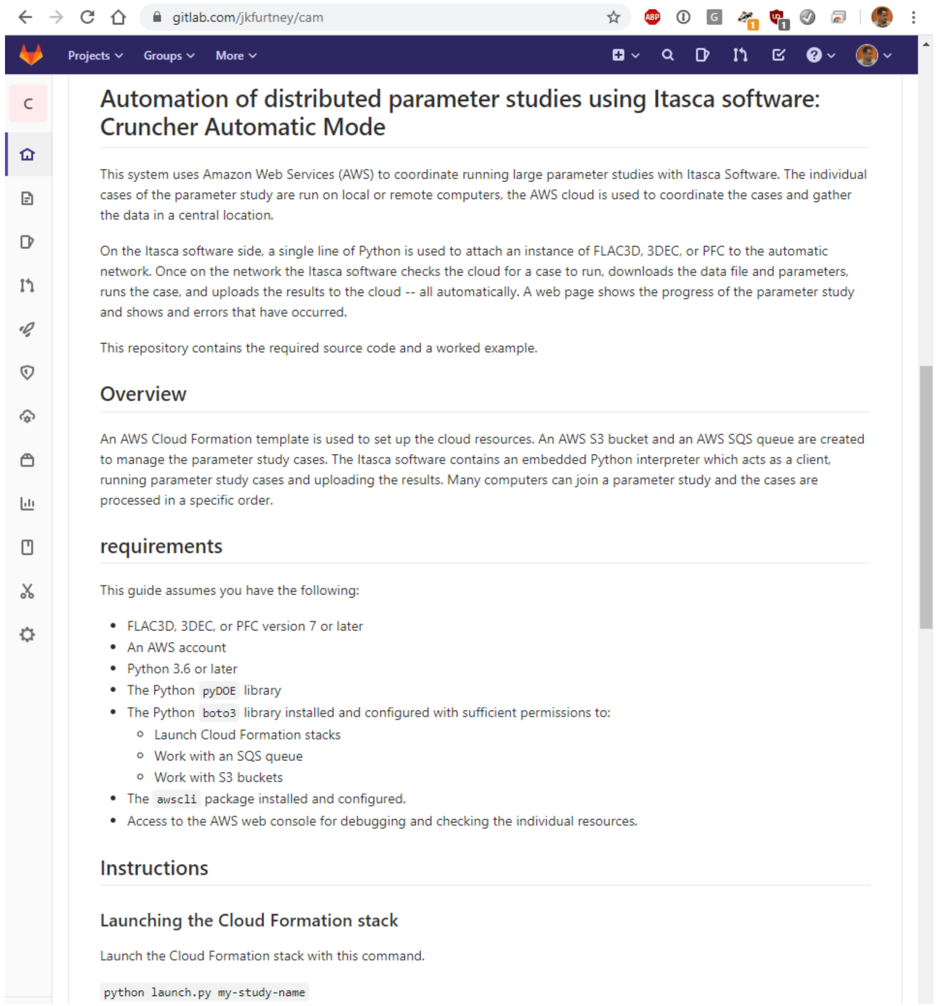
Automatic System for Running Simulations

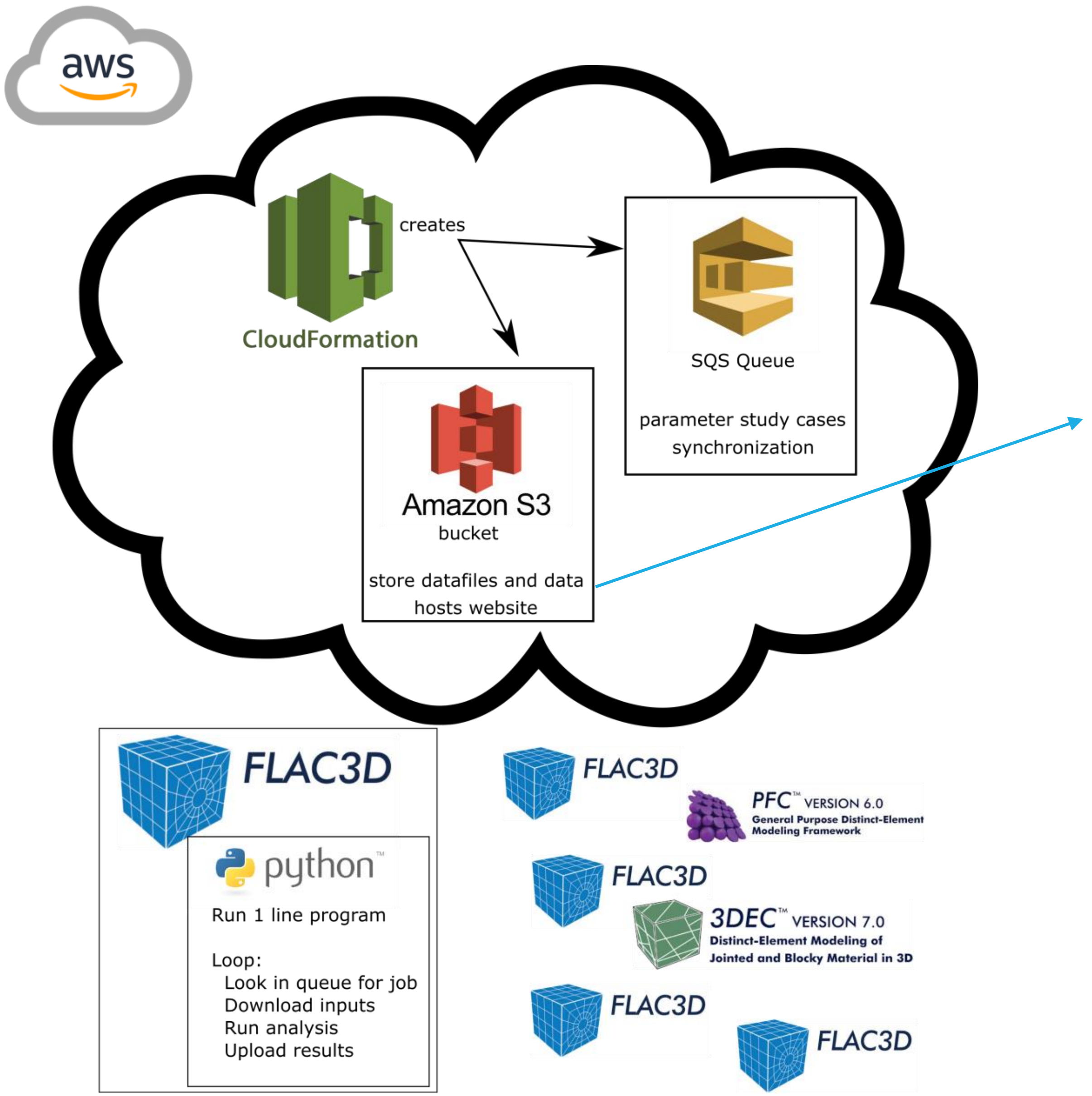
Queueing system for running Itasca software datafiles (jobs)

- Submit a job to the queue and an available computer will automatically download the files, run the job, and upload the results
- Scales to any number of computer, the computer can be anywhere in the world
- Put a computer into *Automatic Mode* by running a one-line Python command
- Error tolerant
- Use spare computation capacity for something productive
- Parameter studies to support machine learning models

- Source code and a worked example on Gitlab
  - https://gitlab.com/jkfurtney/cam

- Machine Learning
  - Develop fast regression models for geotechnical problems
  - Hierarchical Latin hypercube sampling





Cruncher Automatic Mode

Not secure | cam.itascacloud.com

Cruncher Automatic Mode Network

To join the network: Copy and paste the following line into the **IPython** console of *FLAC3D* 7.0 (Menu Bar->Panes->IPython Console).

```
import six; six.exec_(six.moves.urllib.request.urlopen('http://cam.itascacloud.com/cam.py').read())
```

18538 Jobs in Queue

14446 Jobs Finished

Jobs Running or Stopped

Computer	Start Time	File	Case ID
OHoppyDay	Dec 6, 2019 5:35 PM (2 days ago)	twelve_layers.py	pfile-58e05db8-c562-4d70-bef9-10bf351773f6.json
Ziggy	Dec 8, 2019 1:12 AM (7 hours ago)	twelve_layers.py	pfile-5af9e6d6-e955-457b-8a6e-5a8335d1c5b7.json
VIFILFELL	Dec 8, 2019 8:16 AM (a minute ago)	twelve_layers.py	pfile-ee5ad29e-f9c9-43b2-9523-6ac0cc6a9901.json
SolarFlare	Dec 8, 2019 8:17 AM (a few seconds ago)	twelve_layers.py	pfile-572acd00-fc36-4cd6-ae67-87ca2b8c4777.json
SlimJim	Dec 8, 2019 8:14 AM (4 minutes ago)	twelve_layers.py	pfile-74a1b245-086a-43c4-ae91-d1f0f23ad289.json
ABITA	Dec 8, 2019 8:15 AM (2 minutes ago)	twelve_layers.py	pfile-33f16446-47de-4b56-97e7-6fc0089f2573.json
Funky	Dec 8, 2019 8:17 AM (a minute ago)	twelve_layers.py	pfile-58418f99-a5fb-41f5-8e77-5e211a5012ba.json
Mario	Dec 8, 2019 8:15 AM (3 minutes ago)	twelve_layers.py	pfile-b9f83db7-4398-4fae-9ff8-73421f42bd3a.json
Nova	Dec 8, 2019 8:16 AM (a minute ago)	twelve_layers.py	pfile-e1e938c9-e4b8-4d5f-9fd7-5b01b63cccbf.json
SunSpot	Dec 8, 2019 8:16 AM (a minute ago)	twelve_layers.py	pfile-8fcc1127-c912-4da4-add3-6e6f41188c07.json

Errors

Computer	Start Time	End Time	Case ID	Error Message
SlimJim	Dec 8, 2019 1:11 AM	Dec 8, 2019 1:16 AM	pfile-6f8be06f-6668-4145-abf9-8046e157481f.json	▶ Details
Nova	Dec 8, 2019 1:07 AM	Dec 8, 2019 1:10 AM	pfile-1b08c8a6-da36-4f1d-9a49-f34f296c11c8.json	▶ Details
ABITA	Dec 8, 2019 1:12 AM	Dec 8, 2019 1:16 AM	pfile-c435a92a-61e0-48e4-ac49-eff573a2fe54.json	▶ Details
SunSpot	Dec 8, 2019 1:28 AM	Dec 8, 2019 1:31 AM	pfile-9b867b18-1ed1-4f44-aae0-88ea7bd8fecb.json	▶ Details
Nova	Dec 8, 2019 1:13 AM	Dec 8, 2019 1:16 AM	pfile-013de79f-b365-4679-bef2-44f64399a5be.json	▶ Details

Overview

- *Why Build Surrogate model?*
- *Numerical Model Development*
- *Design of Experiment*
- *Training a Surrogate Model*
- *Informing the Discontinuum Model*

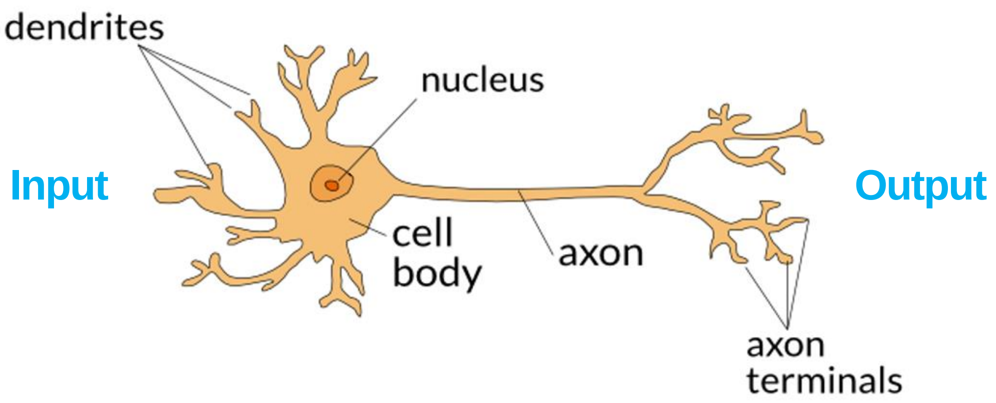
Artificial Neural Network: Single Neuron Model

Biological neuron has 3 basic functionality:

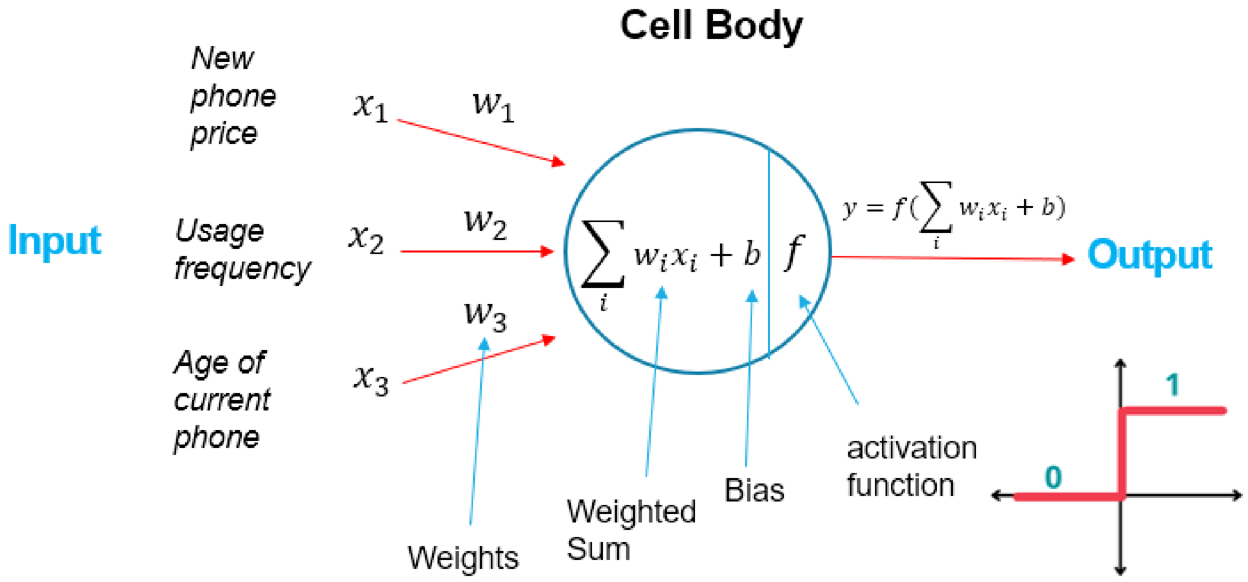
1. Receive signal
2. Process the signal (e.g., decide whether we need to send information or not)
3. Pass the signal to the target cell (which can be another neuron)

Mathematical Model:
simplified model for information flow in neuron

Illustration of a Biological Neuron



Mathematical Model of an Artificial Neuron



https://appliedgo.net/perceptron/

Artificial Neural Network: Single Neuron Model

Biological neuron has 3 basic functionality:

1. Receive signal
2. Process the signal (e.g., decide whether we need to send information or not)
3. Pass the signal to the target cell (which can be another neuron)

Mathematical Model:
simplified model for information flow

Mathematical Model of an Artificial Neuron

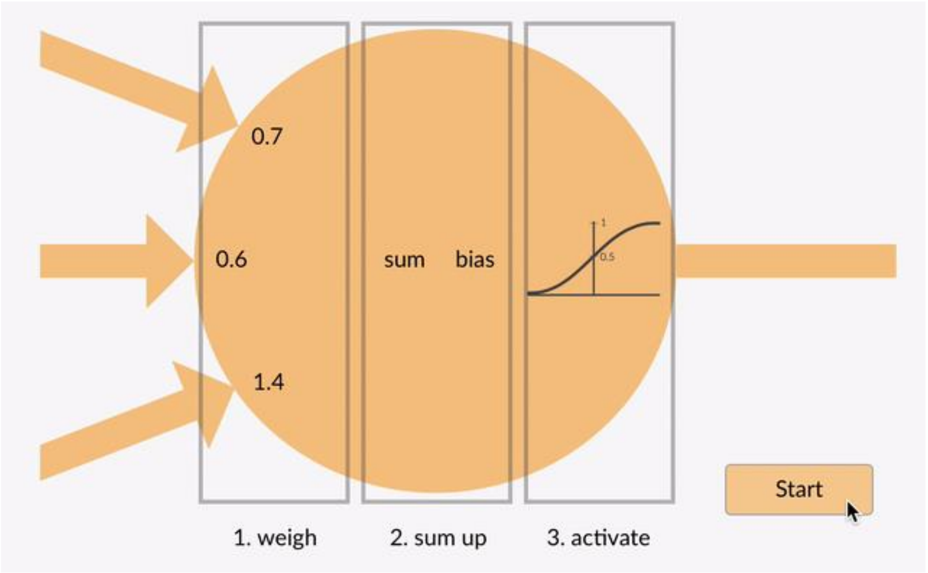
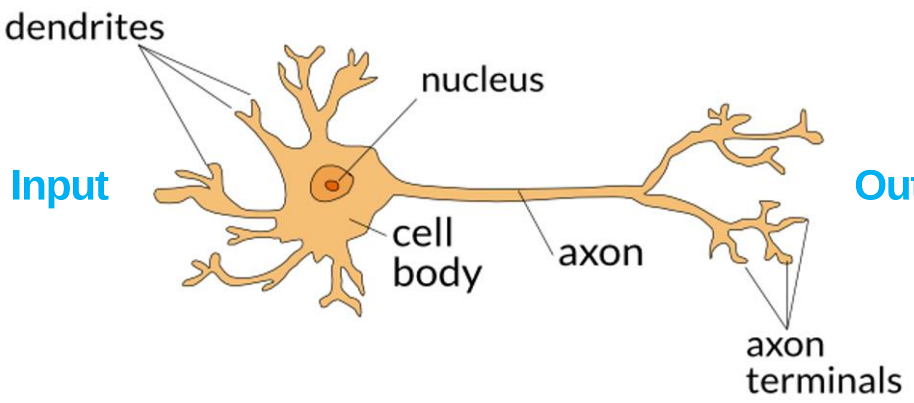


Illustration of a Biological Neuron

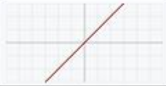
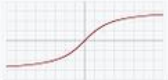
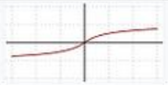
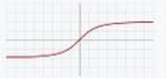
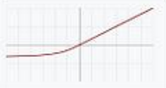
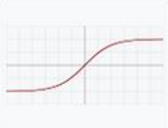
Input



Output

https://appliedgo.net/perceptron/

Activation Functions

Name	Plot	Equation	Derivative (with respect to x)	Range	Order of continuity	Monotonic	Monotonic derivative	Approximates identity near the origin
Identity		$f(x) = x$	$f'(x) = 1$	$(-\infty, \infty)$	C^∞	Yes	Yes	Yes
Binary step		$f(x) = \begin{cases} 0 & \text{for } x < 0 \\ 1 & \text{for } x \geq 0 \end{cases}$	$f'(x) = \begin{cases} 0 & \text{for } x \neq 0 \\ ? & \text{for } x = 0 \end{cases}$	$\{0, 1\}$	C^{-1}	Yes	No	No
Logistic (a.k.a. Sigmoid or Soft step)		$f(x) = \sigma(x) = \frac{1}{1+e^{-x}}$ [1]	$f'(x) = f(x)(1 - f(x))$	$(0, 1)$	C^∞	Yes	No	No
TanH		$f(x) = \tanh(x) = \frac{(e^x - e^{-x})}{(e^x + e^{-x})}$	$f'(x) = 1 - f(x)^2$	$(-1, 1)$	C^∞	Yes	No	Yes
ArcTan		$f(x) = \tan^{-1}(x)$	$f'(x) = \frac{1}{x^2 + 1}$	$\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$	C^∞	Yes	No	Yes
ElliotSig[9][10][11] Softsign[12][13]		$f(x) = \frac{x}{1 + \lvert x \rvert}$	$f'(x) = \frac{1}{(1 + \lvert x \rvert)^2}$	$(-1, 1)$	C^1	Yes	No	Yes
Inverse square root unit (ISRU)[14]		$f(x) = \frac{x}{\sqrt{1 + \alpha x^2}}$	$f'(x) = \left(\frac{1}{\sqrt{1 + \alpha x^2}}\right)^3$	$\left(-\frac{1}{\sqrt{\alpha}}, \frac{1}{\sqrt{\alpha}}\right)$	C^∞	Yes	No	Yes
Inverse square root linear unit (ISRLU)[14]		$f(x) = \begin{cases} \frac{x}{\sqrt{1+\alpha x^2}} & \text{for } x < 0 \\ x & \text{for } x \geq 0 \end{cases}$	$f'(x) = \begin{cases} \left(\frac{1}{\sqrt{1+\alpha x^2}}\right)^3 & \text{for } x < 0 \\ 1 & \text{for } x \geq 0 \end{cases}$	$\left(-\frac{1}{\sqrt{\alpha}}, \infty\right)$	C^2	Yes	Yes	Yes
Square Nonlinearity (SQNL)[11]		$f(x) = \begin{cases} 1 & : x > 2.0 \\ x - \frac{x^2}{4} & : 0 \leq x \leq 2.0 \\ x + \frac{x^2}{4} & : -2.0 \leq x < 0 \\ -1 & : x < -2.0 \end{cases}$	$f'(x) = 1 \mp \frac{x}{2}$	$(-1, 1)$	C^∞	Yes	No	Yes
Rectified linear unit (ReLU)[15]		$f(x) = \begin{cases} 0 & \text{for } x < 0 \\ x & \text{for } x \geq 0 \end{cases}$	$f'(x) = \begin{cases} 0 & \text{for } x < 0 \\ 1 & \text{for } x \geq 0 \end{cases}$	$[0, \infty)$	C^0	Yes	Yes	No

https://himanshuxd.medium.com/activation-functions-sigmoid-relu-leaky-relu-and-softmax-basics-for-neural-networks-and-deep-8d9c70eed91e

Artificial Neural network

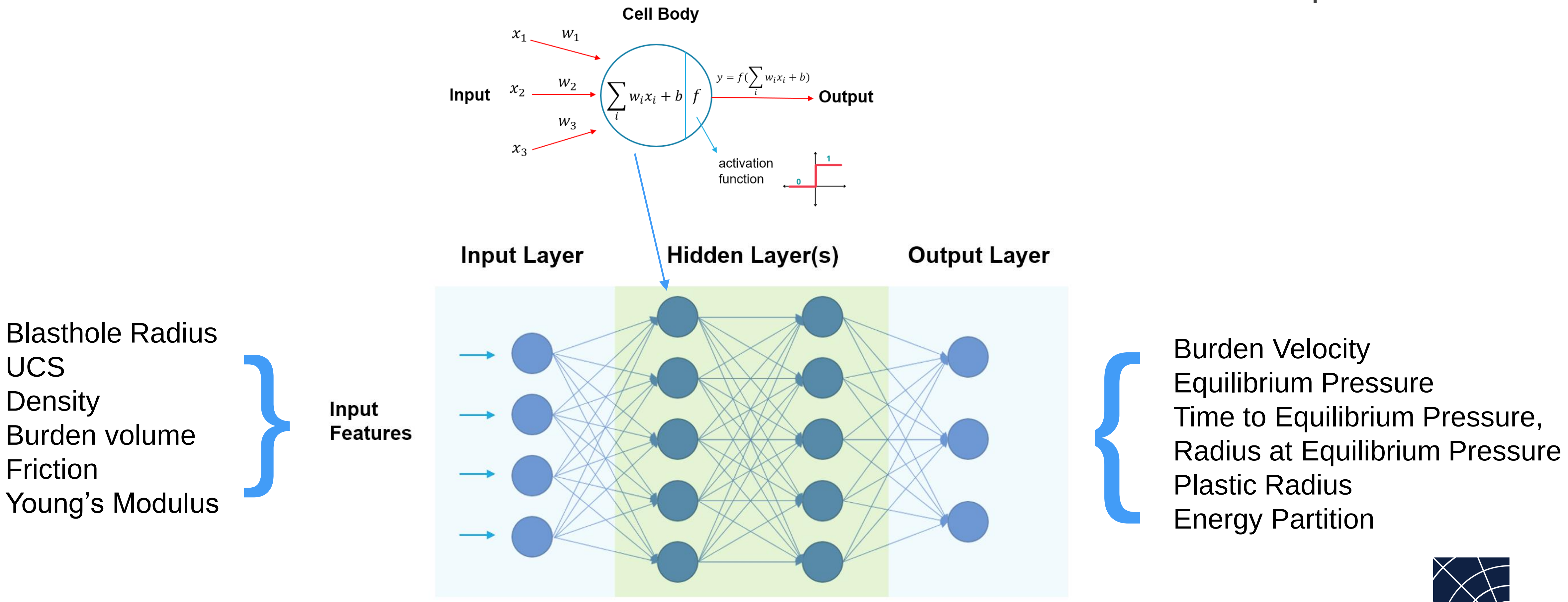
- ANN consists of interconnected layers of artificial neurons
- Capability to learn any nonlinear models
- A number of hyperparameters such as the number of hidden neurons and layers

Blasthole Radius
UCS
Density
Burden volume
Friction
Young’s Modulus

Burden Velocity
Equilibrium Pressure
Time to Equilibrium Pressure,
Radius at Equilibrium Pressure
Plastic Radius
Energy Partition

Artificial Neural network

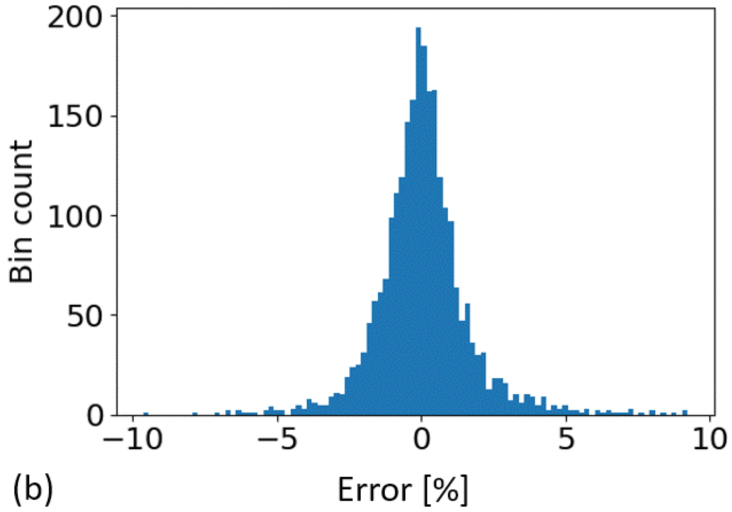
- Iteratively adjust the weights and biases
- Learn the weights to map inputs to the outputs
- Minimize the difference between the network's predictions and the desired outputs



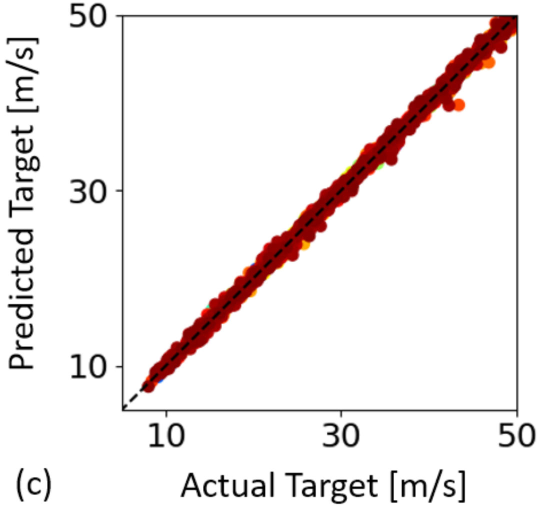
ITASCA™

Training a Neural Network

- A neural network with 3 hidden layers, each comprising 15 nodes, was trained using a dataset of 10,000 FLAC3D model runs
- Input features: Blasthole Radius, UCS, Density, Burden volume, Friction, Young's Modulus
- output features: Burden Velocity, Equilibrium Pressure, Time to Equilibrium Pressure, Radius at Equilibrium Pressure, Plastic Radius, Energy Partition
- The burden velocity prediction has an r2 value of 0.9997. The predictions for burden velocity are within 2.5% of the true value 95% of the time.



(b)

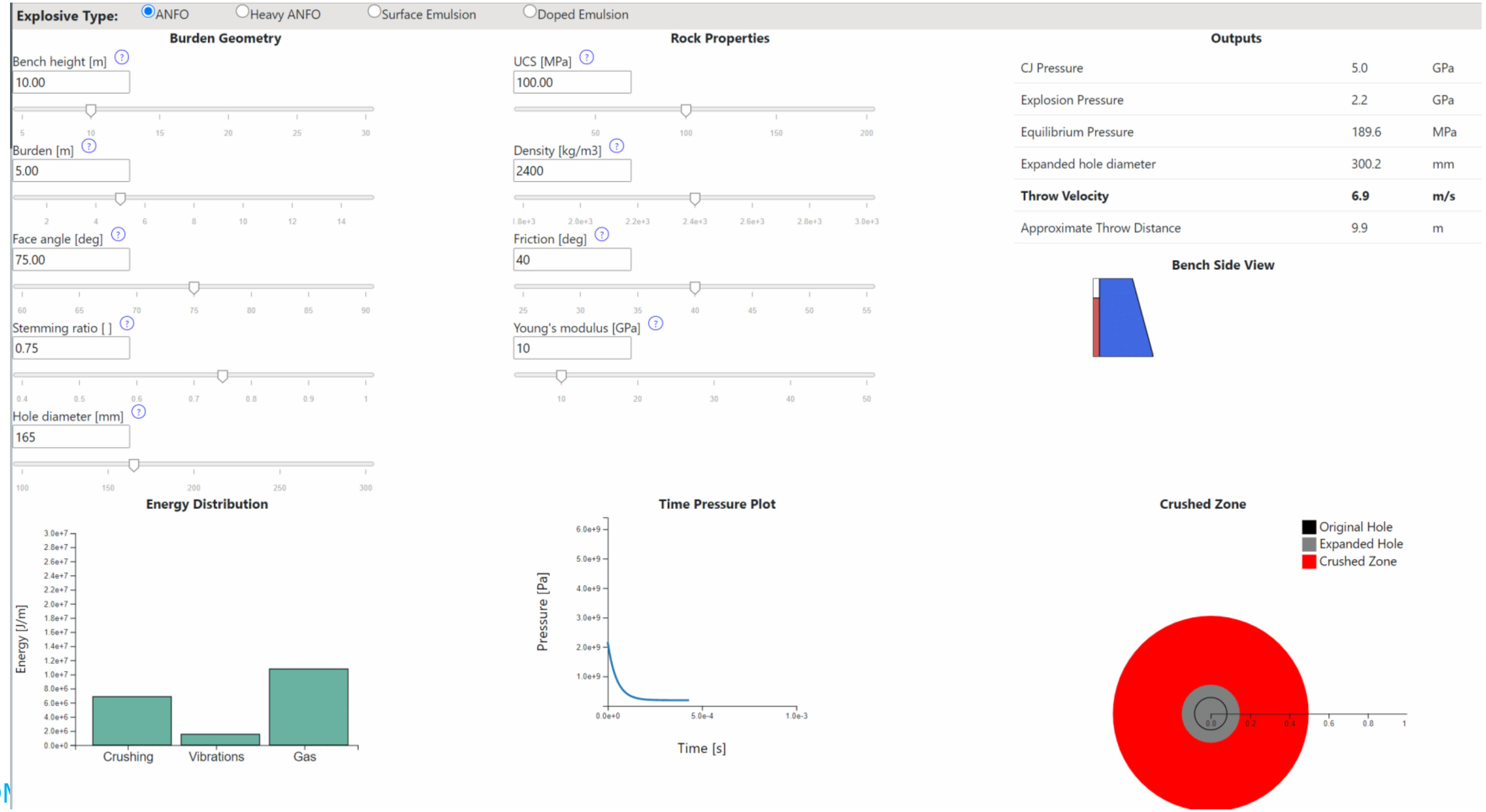


(c)

Training a Neural Network

https://s3.us-east-2.amazonaws.com/icgprojects/2857-16/blast_tool.html

- Webpage implementation of neural network
- Instant results as input sliders are moved
- Good for training or probabilistic analysis



ITASCA™

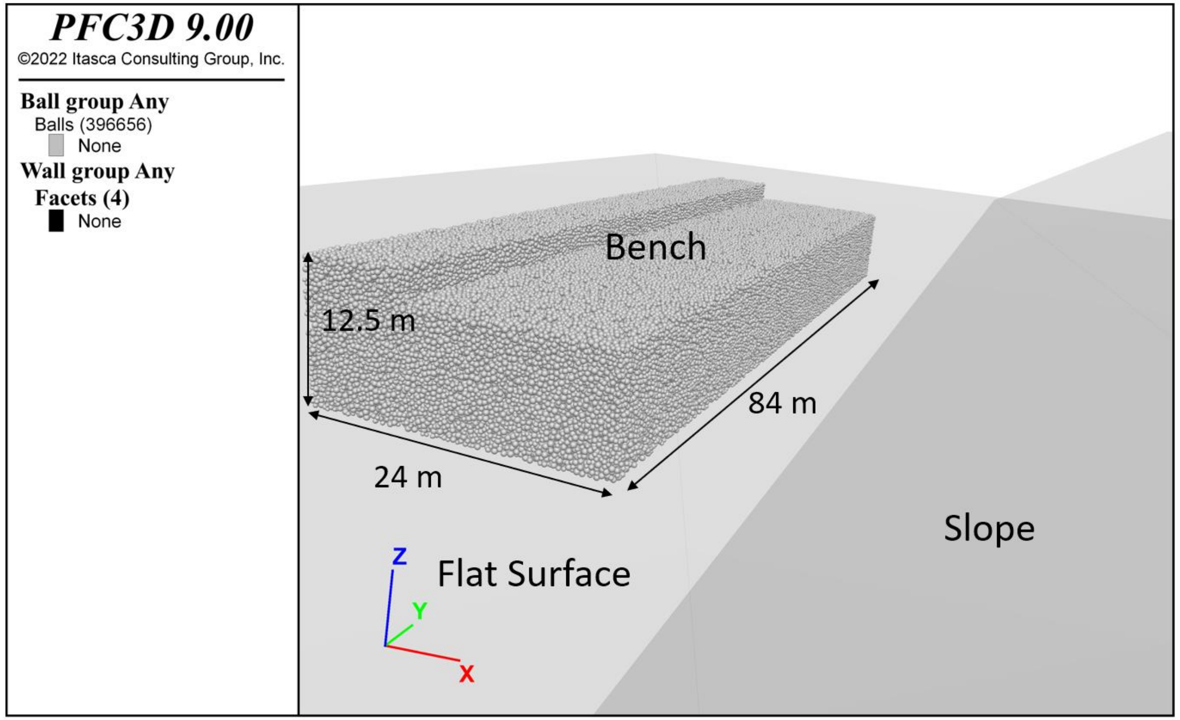
Overview

- *Why Build Surrogate model?*
- *Numerical Model Development*
- *Design of Experiment*
- *Training a Surrogate Model*
- *Informing the Discontinuum Model*

Modeling details

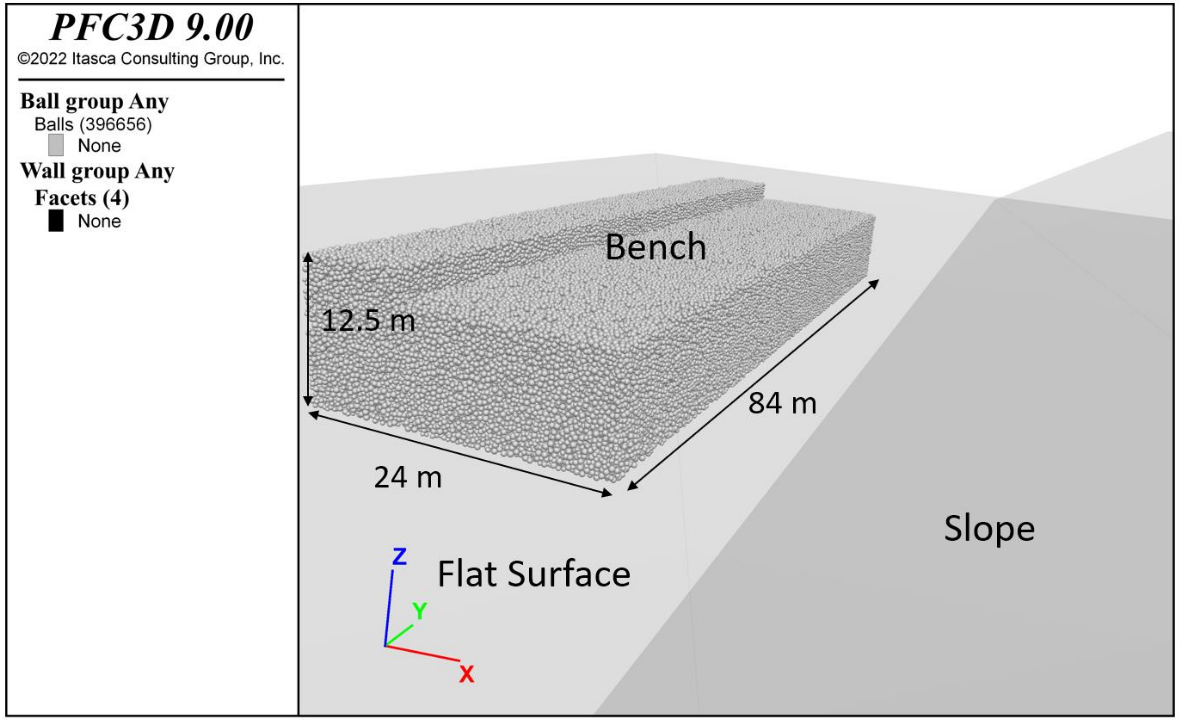
Modeling details:

- PFC balls are used to build benches for cast blasting
- PFC walls are used to represent the mine geometry where the rock will land
- Rolling resistance contact model is used to enhance particle friction and interlocking
- Models are optimized for the throw calculation and muckpile formation only (rock initial velocity obtained from ML prediction)



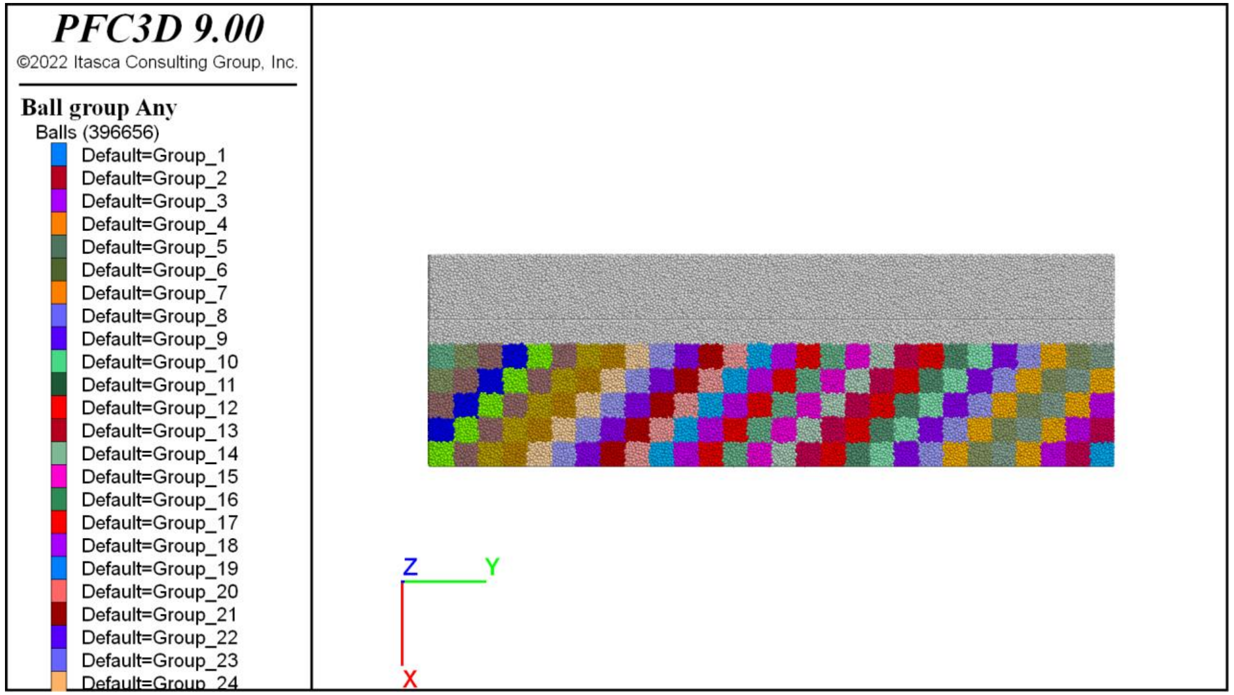
PFC3D Model

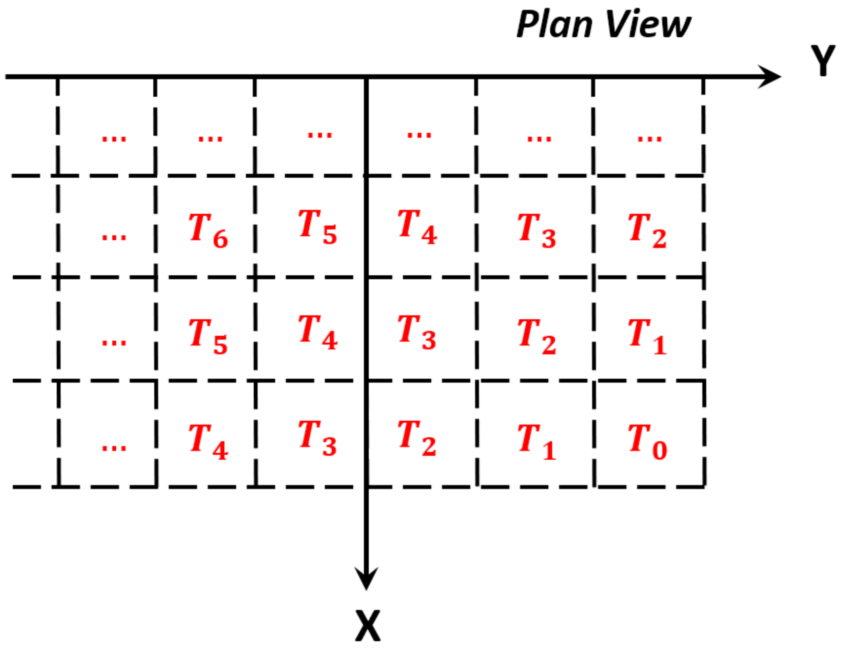
- Bench to be blasted are formed by PFC balls with a relative deviation of 0.5 around a mean value of 0.2 m
- Bench has dimensions of 84 m × 24 m × 12.5 m (length × width × height) and consists of 400,000 balls
- The bench is placed on a flat surface, a 30-degree slope is simulated by a PFC wall
- Model constructed loosely following a video recording of a cast blasting application



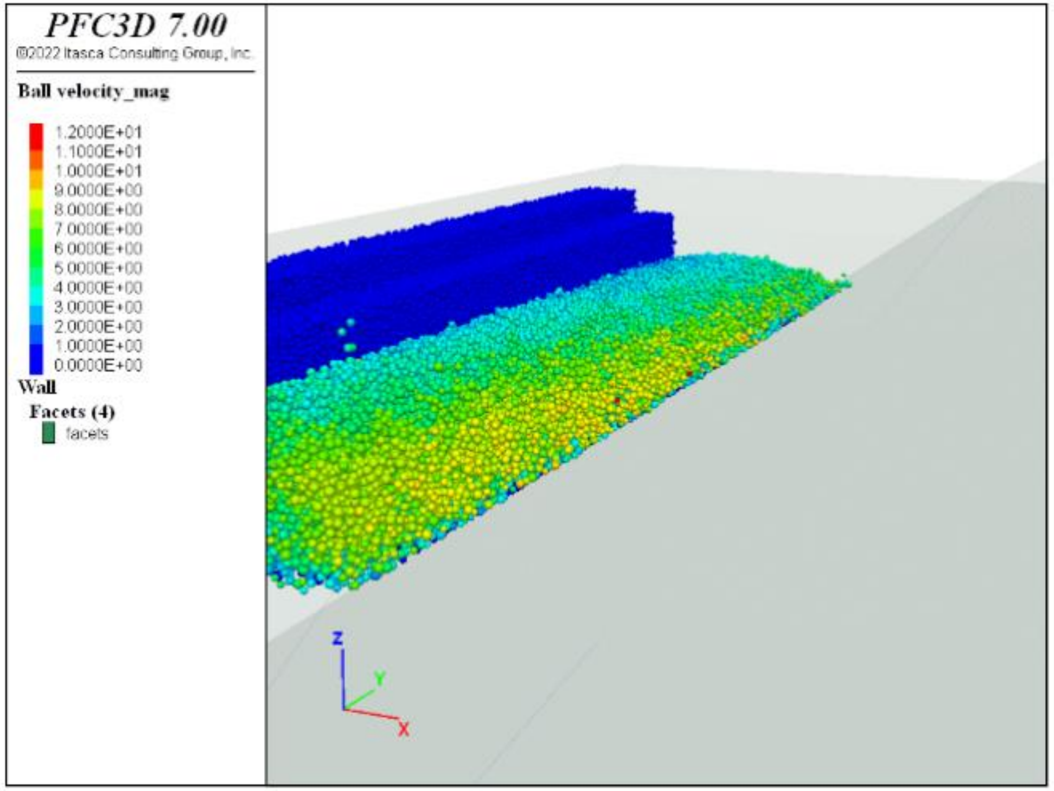
PFC3D Model

- Echelon pattern is used as the firing sequence, with delay time of 30 ms
- The speed for each of the blocks is obtained from the ML prediction.



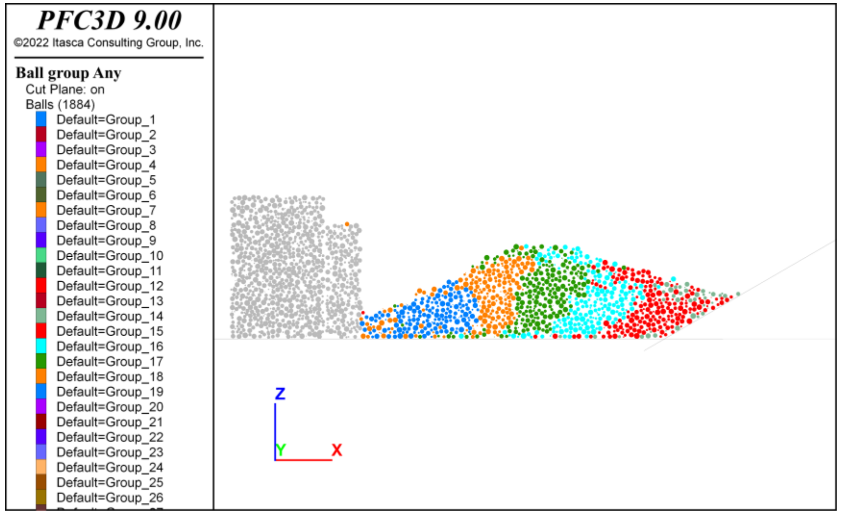


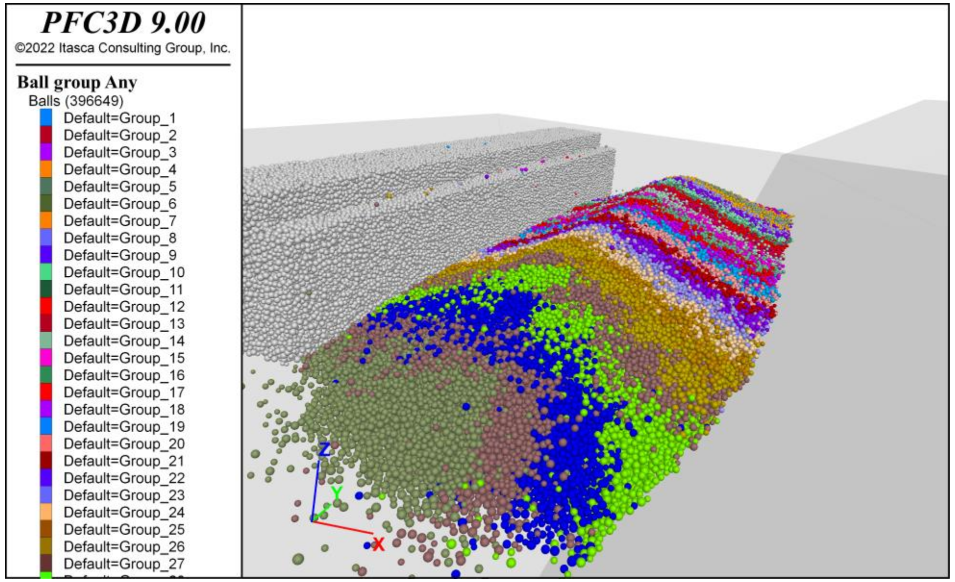
PFC3D Modeling Results



PFC3D Model Results

- Evenly spread rock piles along the length of the bench
- Rocks close to the free surface are more likely to spread
- The simulated muckpile shape generally agrees with the muckpile formation in the video





Conclusions

- A hybrid approach is developed to simulate rock blasting:
  - Small-scale FLAC3D model and analytical model to obtain key parameters (e.g., wellbore deformation, gas pressure, burden velocity)
  - An artificial neural network is trained based on the synthetic dataset
  - Field-scale DEM modeling of blasting becomes feasible and convenient to set up
- Proper simplifications of numerical model to capture first-order impacts
- Sampling and active learning to optimize the number of simulations
- Instant results, good for parametric/probabilistic studies