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A Fast-running Physics-Based Tool for Explosives in Tunnels

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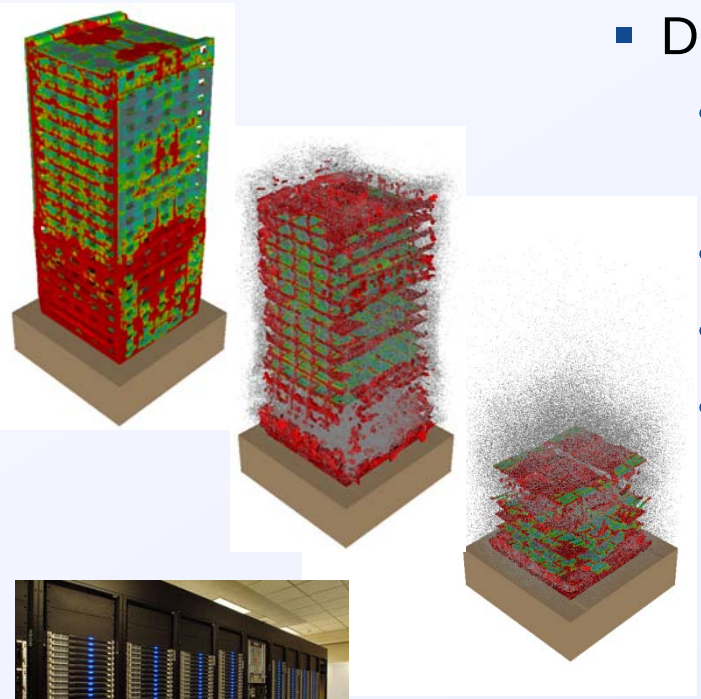
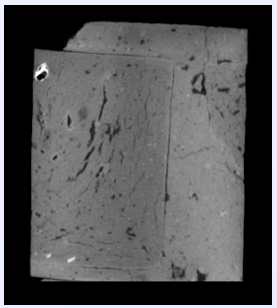
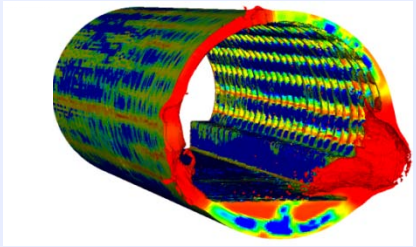
Motivation: structural-blast analysis is complex and time-consuming; stakeholders and decision makers want more expedient tools



- Detailed analysis requires
  - Wide range of subject matter expertise
  - Careful materials characterization
  - Explosive testing and validation
  - High fidelity simulation

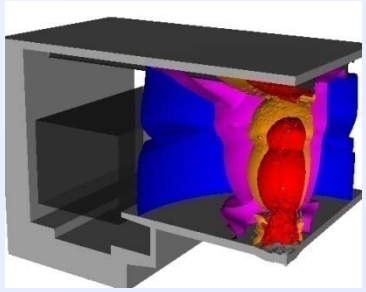


Non-destructive Evaluation



Hera Linux Cluster
127.2 TF - AMD;
13,824 processors

ALE3D Hydrocode



High Explosive Application Facility

A detailed understanding of theory, modeling and testing can be leveraged to develop fast-running tools

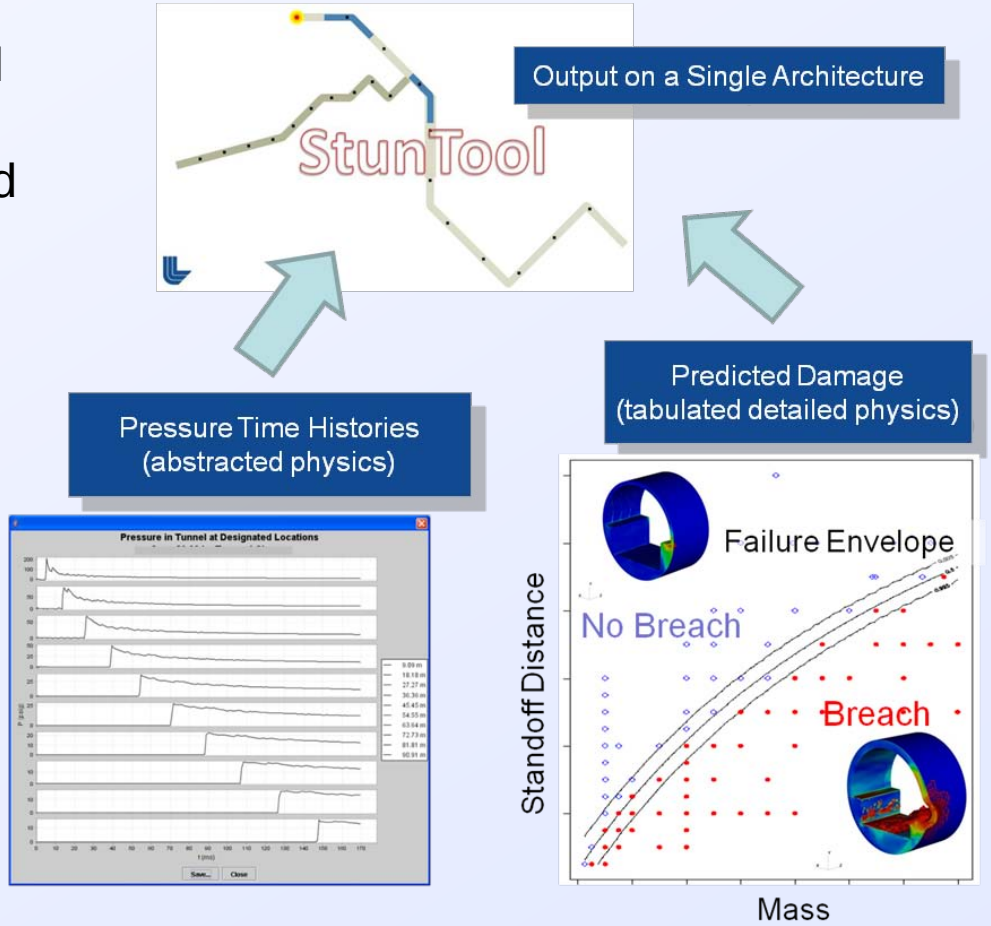
Fast running model two-part methodology:

Tools built from statistical emulation and simplified physics

- Two-part methodology:
  1. Reduced dimensionality in physical models
  2. Tabulated results from fully-coupled 3D analyses (“lookup table”)

- Two-part methodology addresses
  - Multiple scenarios
  - Uncertainty/variability over large number of variables

- Combined onto *a single* architecture



Speed via reduced dimensionality: fast running tunnel model

- The code employs a simpler algorithm that captures the essential physics and can be run on a single-processor PC
- Tool is a 1-3/4D ALE hydrocode – spherical flow region coupled to axial flow in tunnel
  - accounts for wall drag and radiative and convective heat transfer
- Arbitrary boundary conditions allowed at tunnel entrance and exit
  - Rigid barrier
  - Flow-through
  - Choked flow

1D Equations of Motion

$$\frac{d(\rho A)}{dt} + \rho A \frac{\partial u}{\partial x} = \alpha S \phi / H_v$$

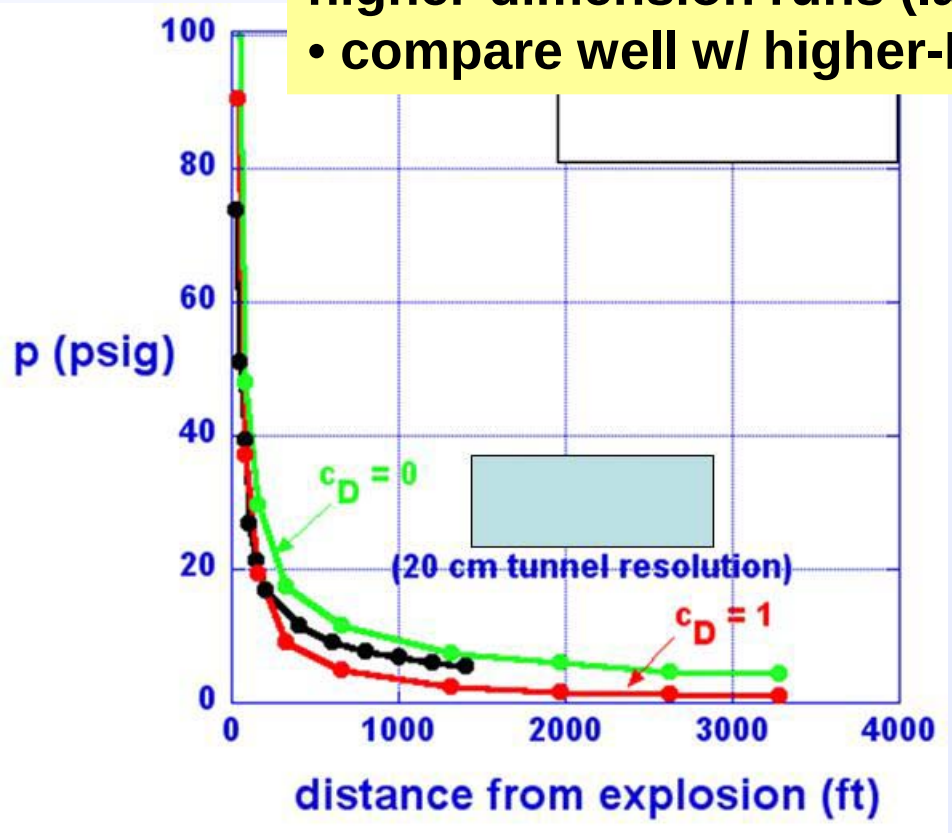
$$\frac{du}{dt} + \frac{1}{\rho}\frac{\partial \sigma_X}{\partial x} + \frac{(\sigma_X - \sigma_T)}{\rho A}\frac{\partial A}{\partial x} + Fu|u| = 0$$

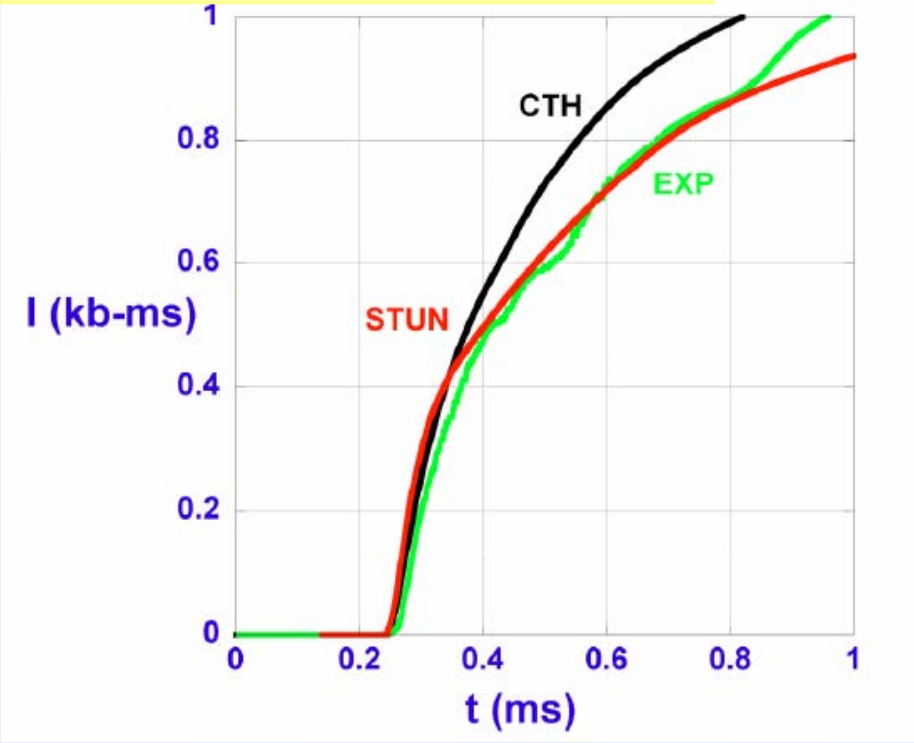
$$\frac{d(e + q + \frac{1}{2}u^2)}{dt} + \frac{1}{\rho A}\frac{\partial(\sigma_X u A)}{\partial x} = 0$$

Reduced Order

Fast-run comparison with 3-D Hydrocode Calculation and Experiment

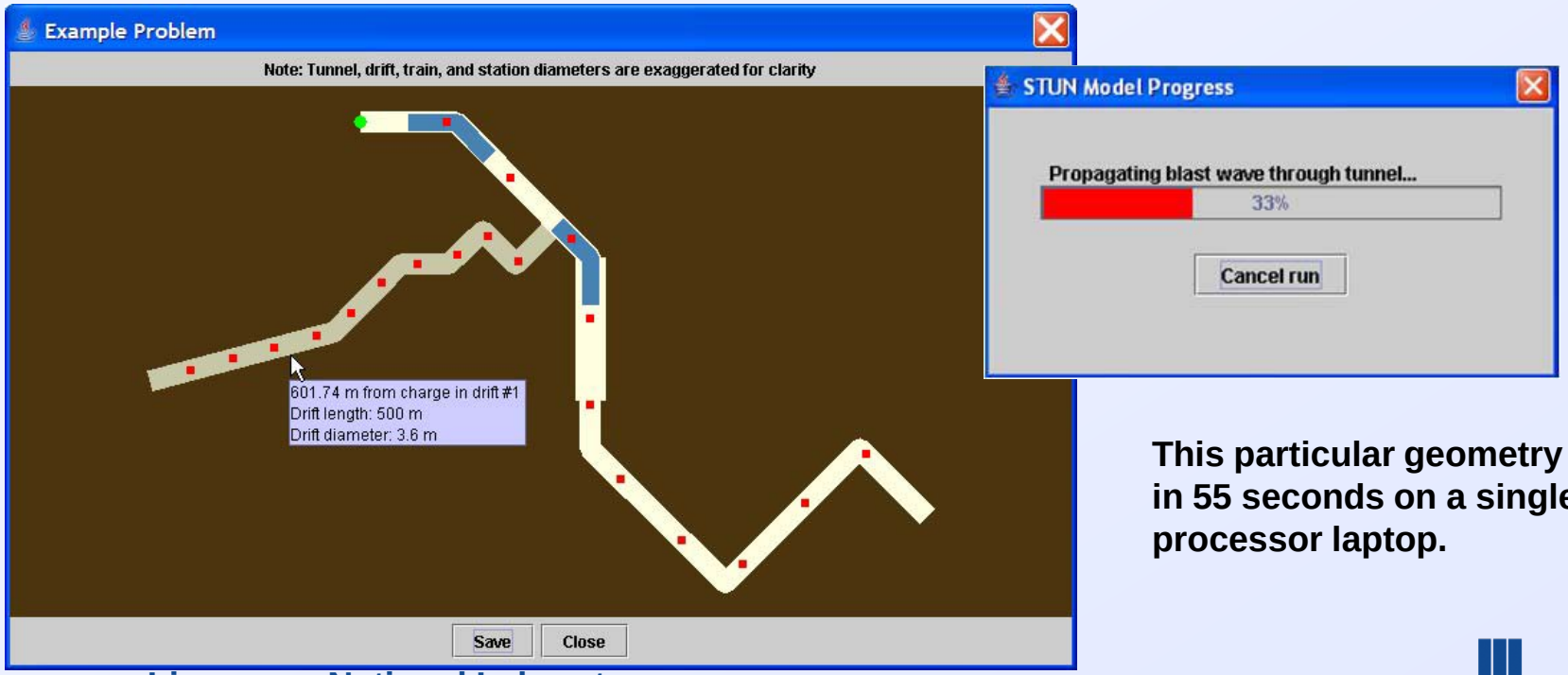
Fast-run tunnel modeling results
- **requires several orders of magnitude less CPUs than higher-dimension runs (laptop vs cluster)**
- **compare well w/ higher-D & experimental results**





Fast-run reduced dimensionality model is flexible

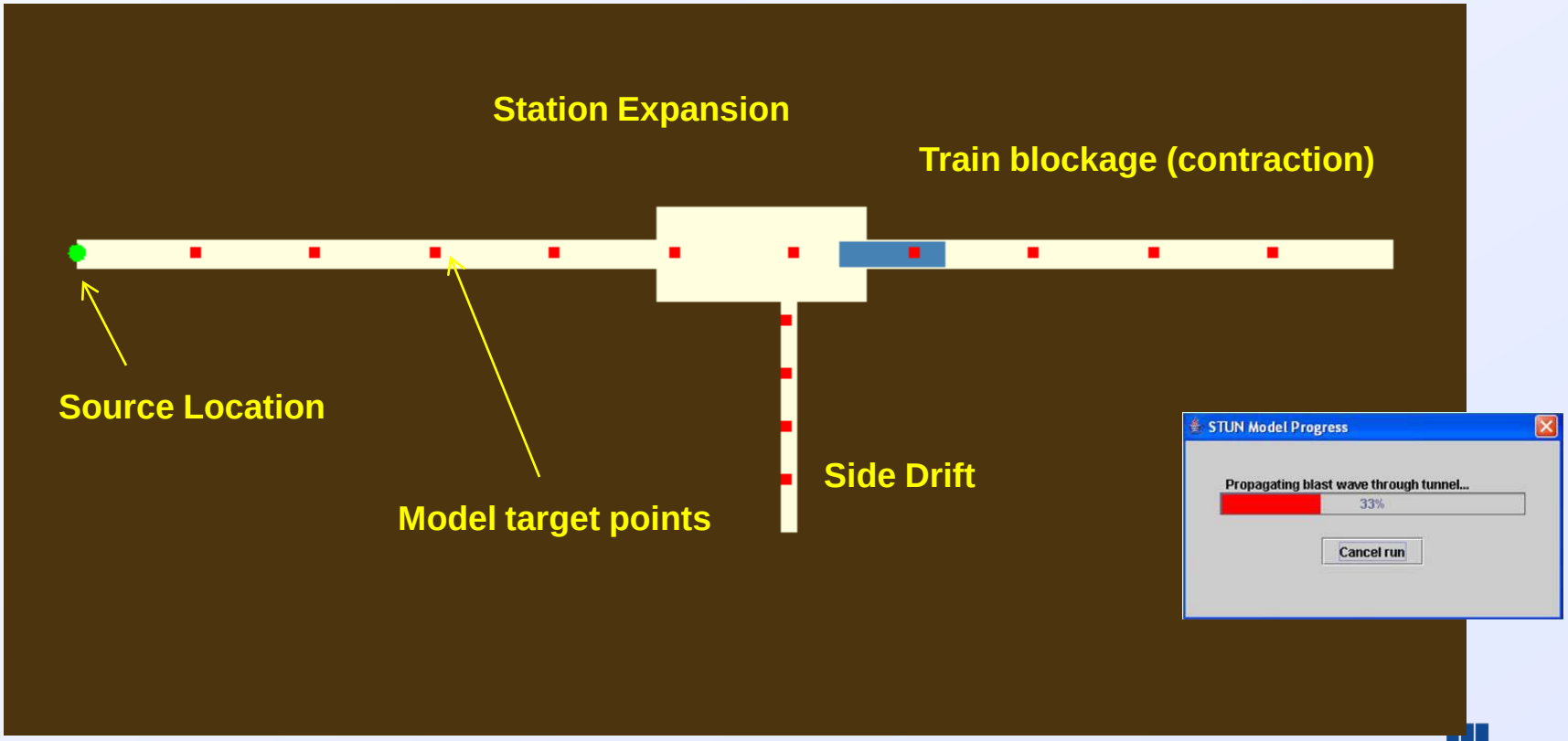
- **Variable cross section with time-dependent radial wall motion**
- **Allows inclusion of in-line chambers or rooms (expansions and constrictions)**
- **Arbitrary number of doglegs of any angle**
- **Connected side drifts**



This particular geometry ran in 55 seconds on a single processor laptop.

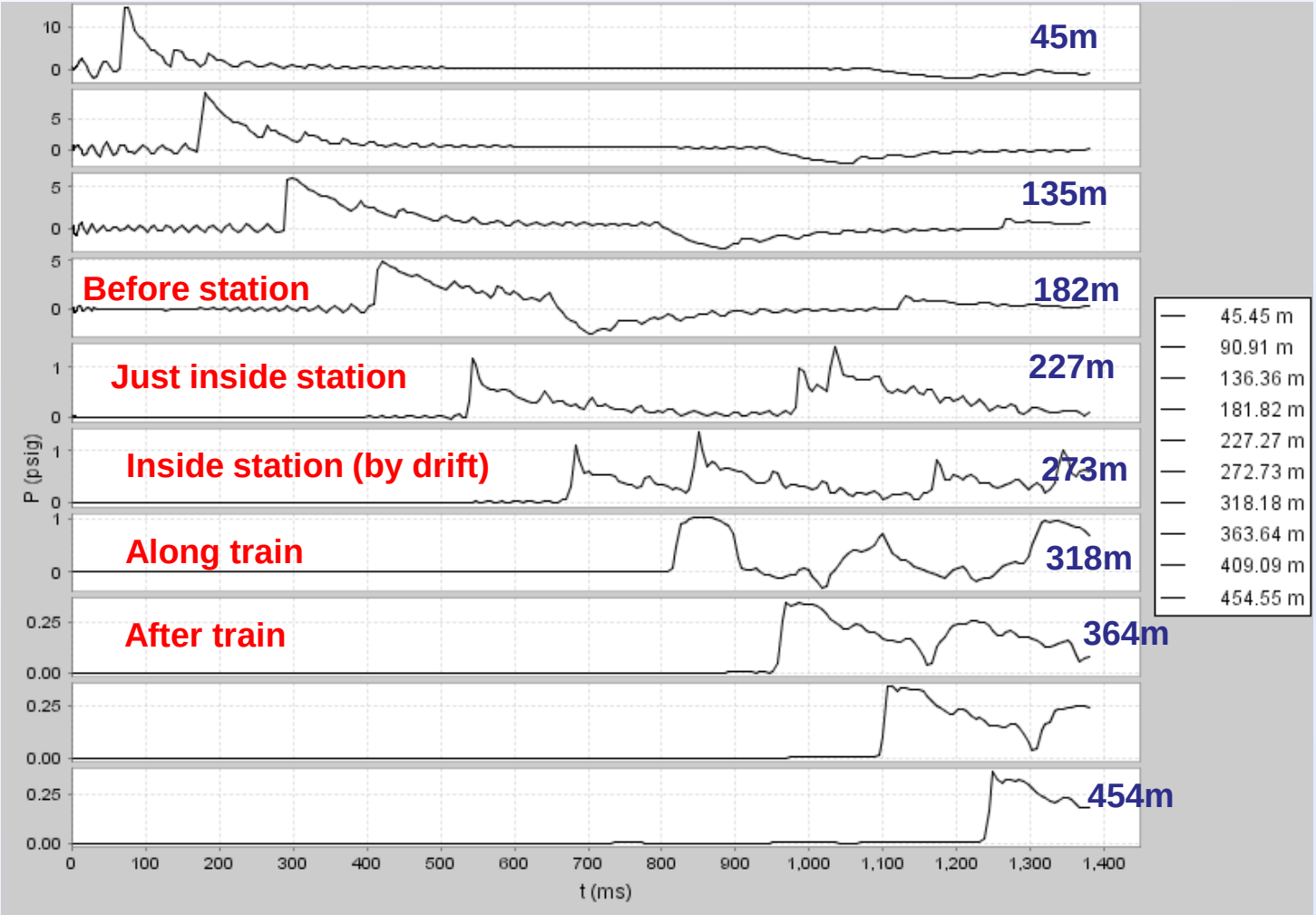
Fast-run Example 2:
Can add station-train-drift complexity

- 500m long tunnel with station expansion (at 220m), train contraction (at 290m) and a side drift (at 270m)



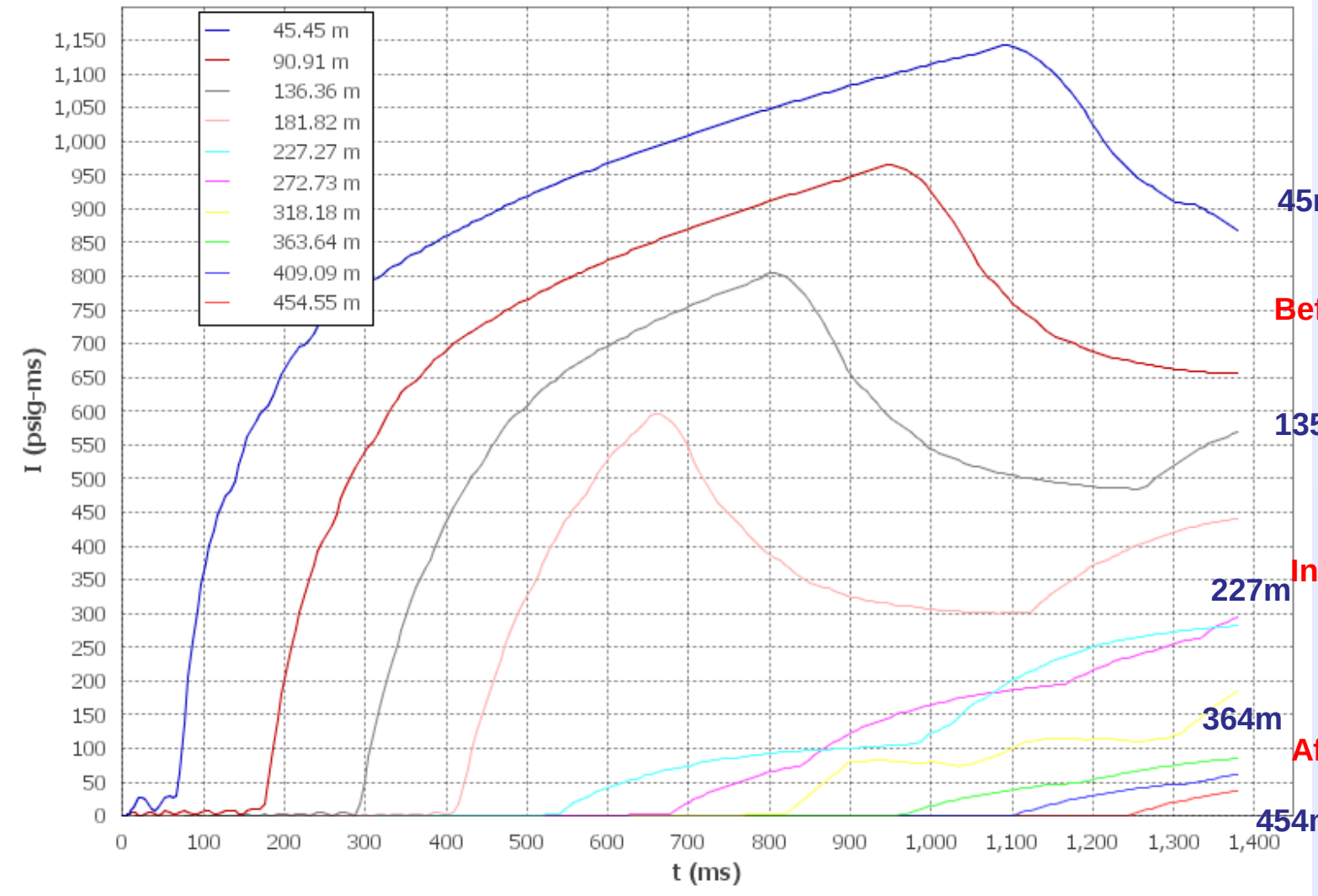
Reduced Order

Fast-run Example 2:
Shock down a 500m long tunnel-station-train system



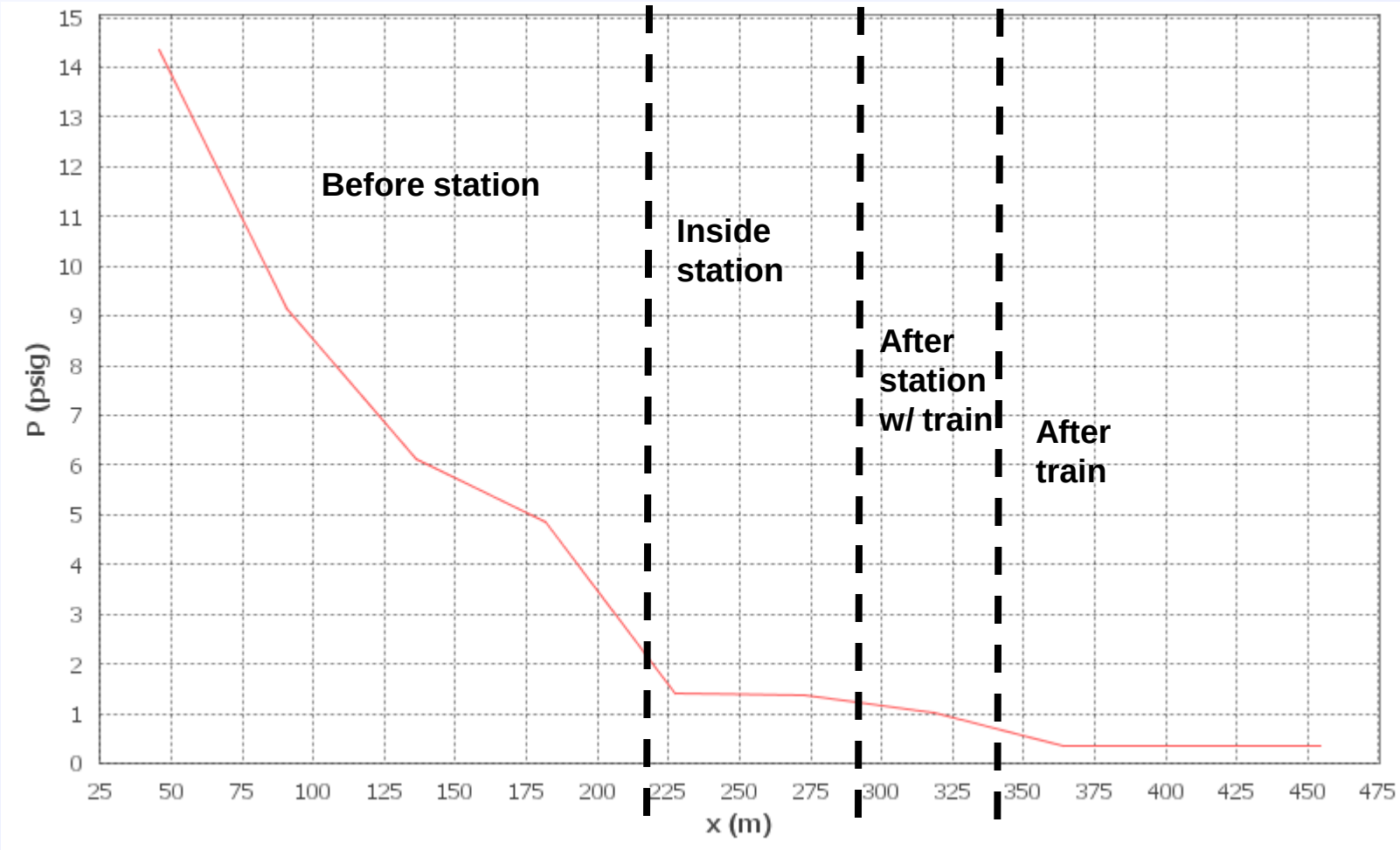
Reduced Order

Fast-run Example 2:
Impulse per unit area down a 500m tunnel/station



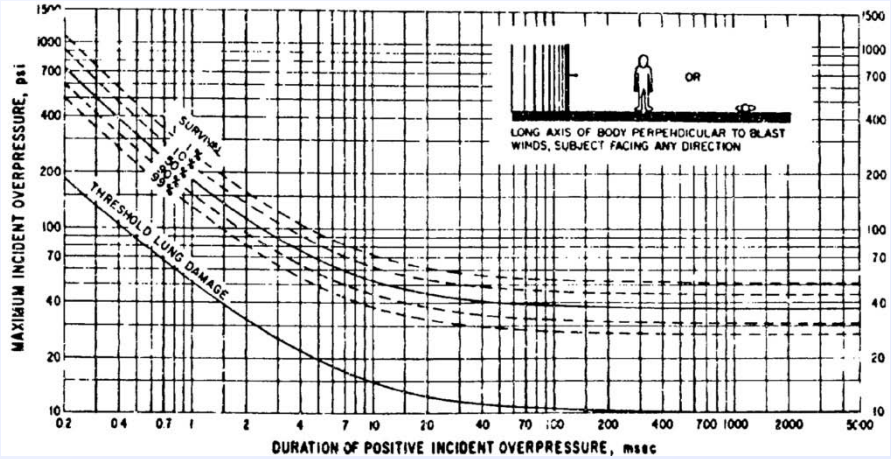
Reduced Order

Fast-run Example 2:
Peak pressure along 500m long tunnel/station/train

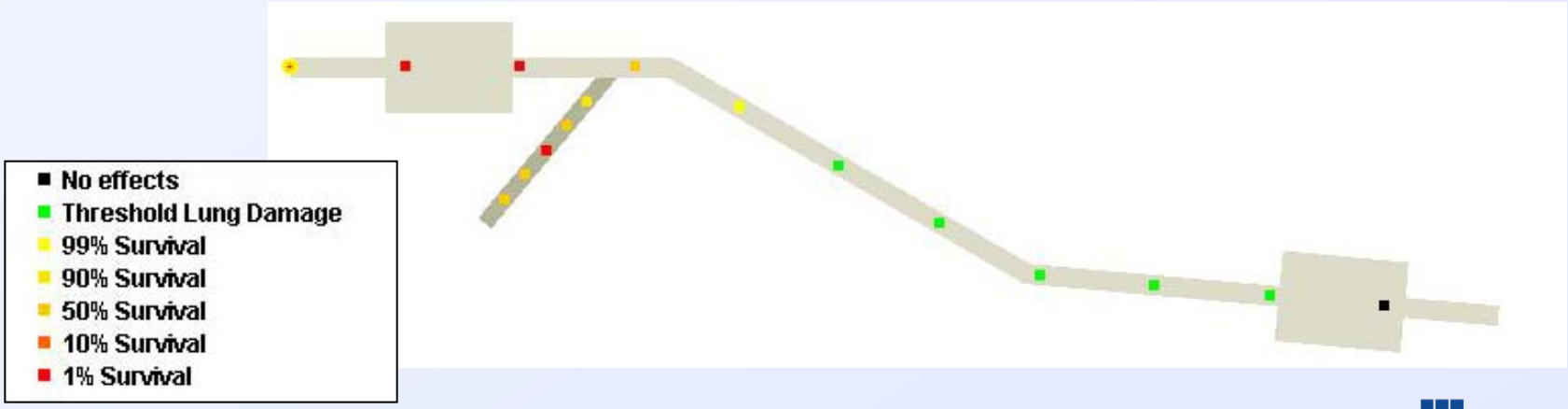


Blast Survivability

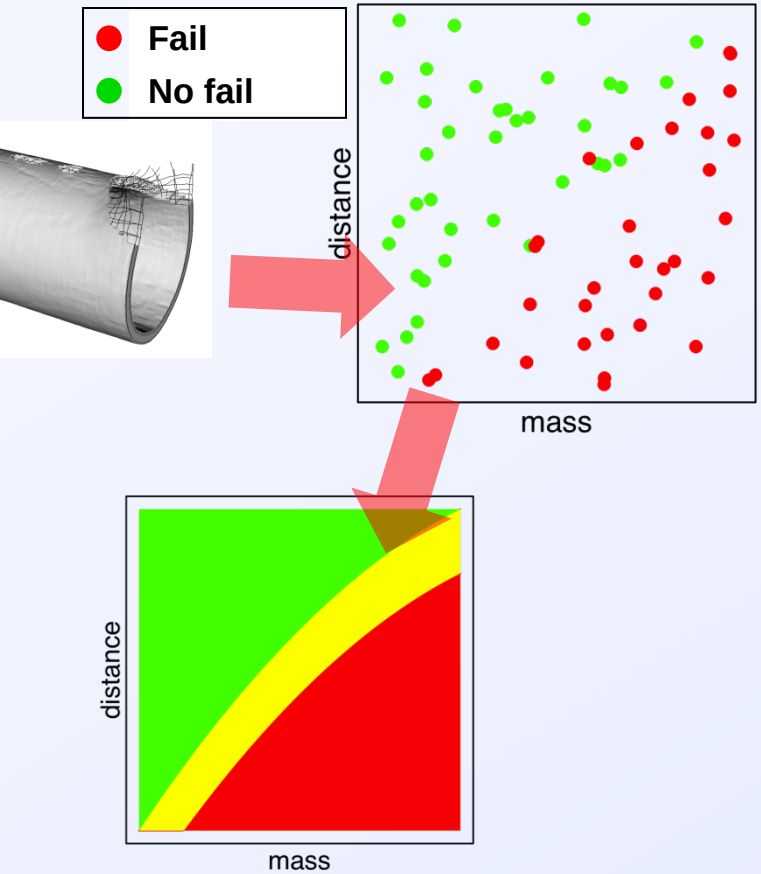
- Bowen curves relate survival probability to maximum overpressure, exposure duration and body orientation



- Survivability tracked and plotted at target points along tunnel



Method 2:
Classifier allows rapid 'lookup' of higher fidelity structure failure analysis

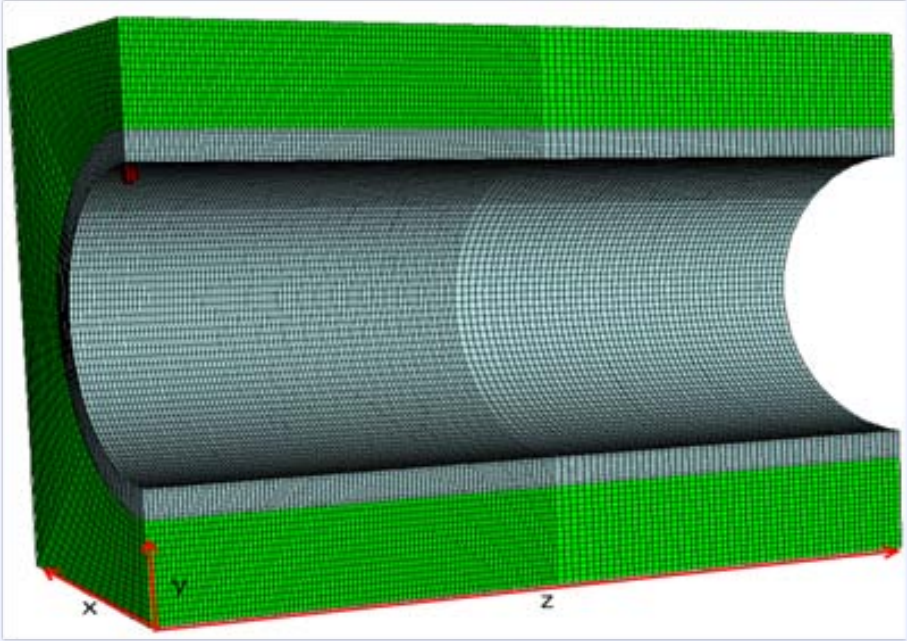


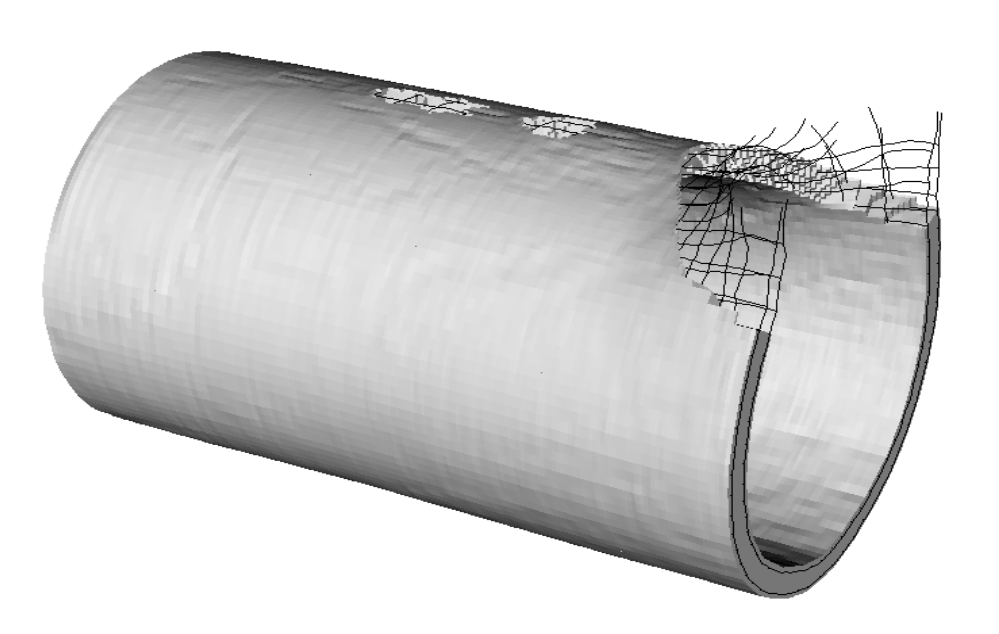
- **Failure prediction requires:**
  - **Clearly defined response criteria**
  - **Advanced sampling**
- **Statistical classifier can :**
  - **Intelligently select new points for evaluation**
  - **Combine simulation data with expert knowledge to predict damage**

Method quickly provides risk prediction based on previous detailed analysis.

Sample high performance simulations

- 3D model mesh of a hypothetical tunnel as used in a high fidelity hydrocode simulation of tunnel failure.
- A breached tunnel example; the 'breach' is defined by a dual criteria capturing tensile and compressive failure. Here multiple breaches occurred.

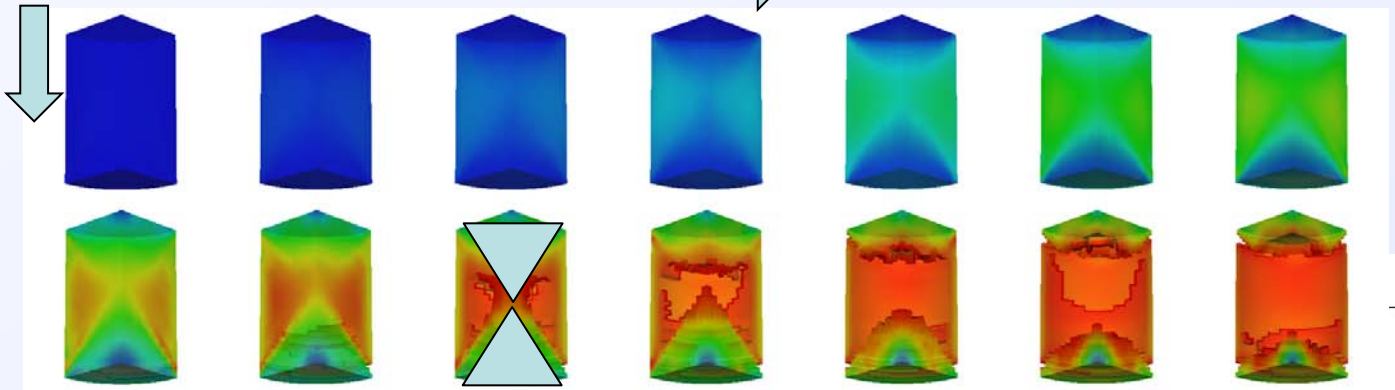




Breach criteria from high strain rate concrete tests

- Split Hopkinson Pressure Bar (SHPB)
- Dilation threshold 0.85%

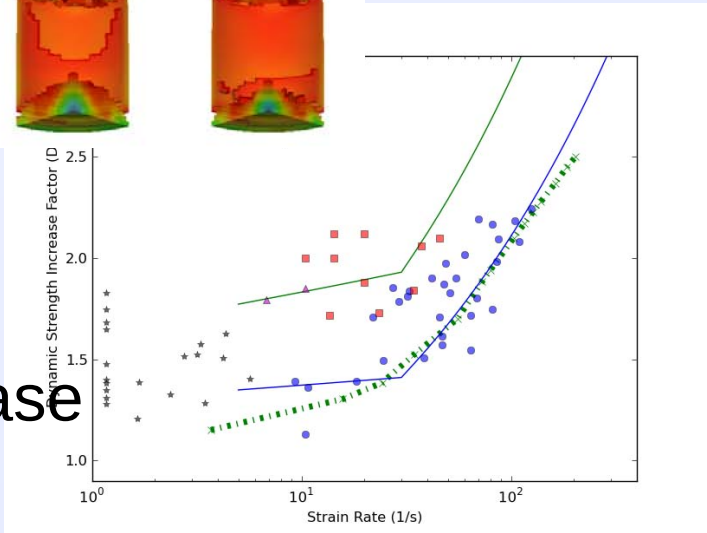
Increasing strain rate



Failure "faulting" cones

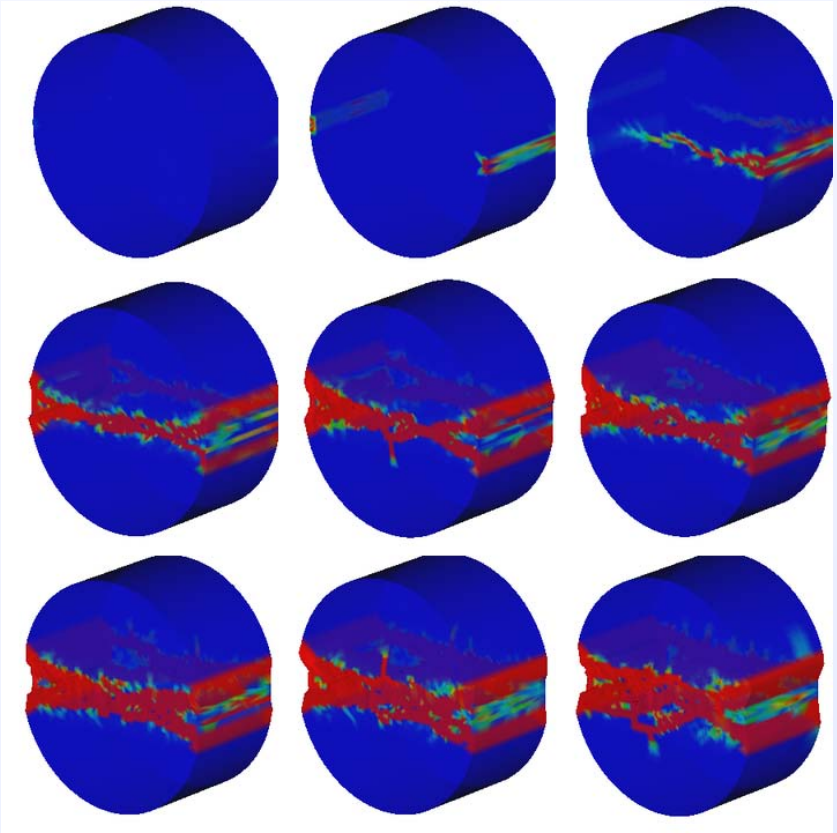
Impulse from below: wave propagation in long bar

Dynamic Strength Increase (DIF)

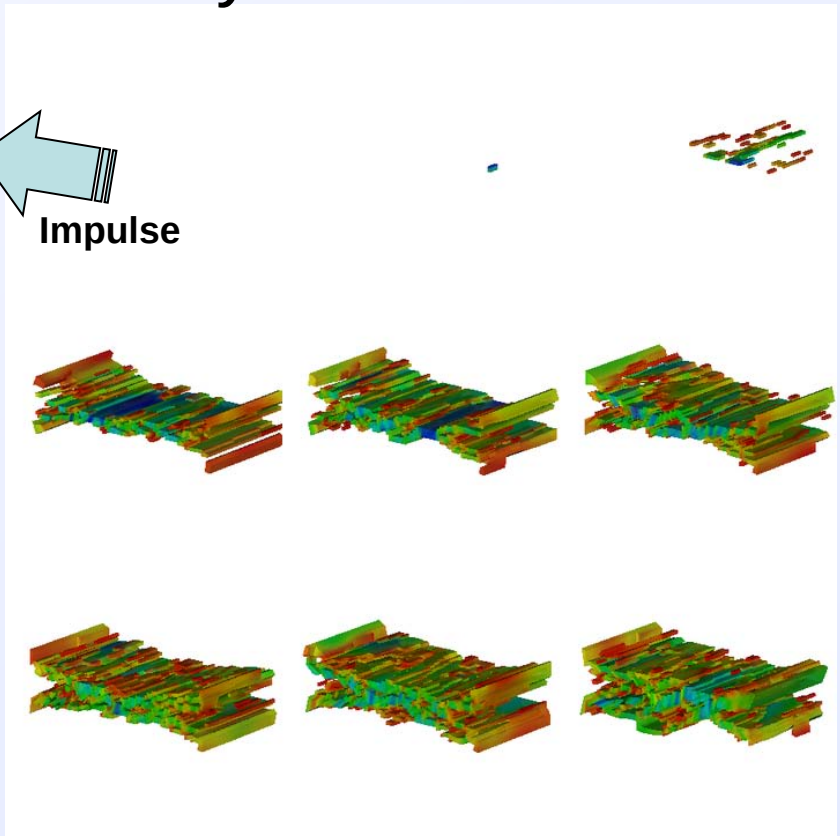


Breach criteria for damage in tension: density drop

Dynamic "Brazilian" split cylinder test

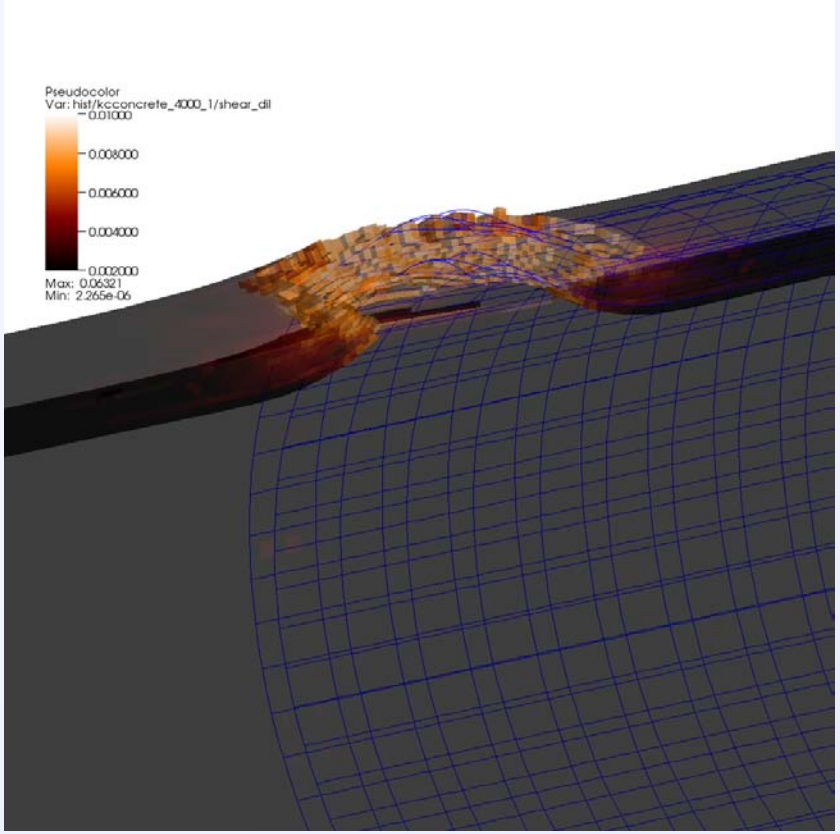


- Density Decrease of 5%

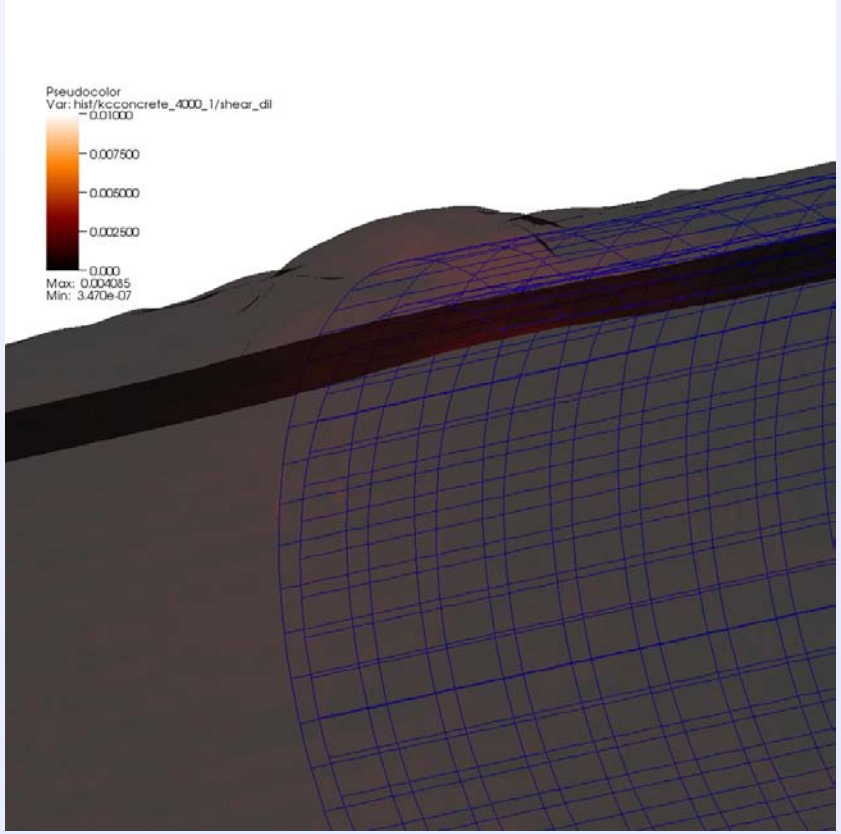


Breach criteria in action: threshold on shear dilation 0.85%

Breach

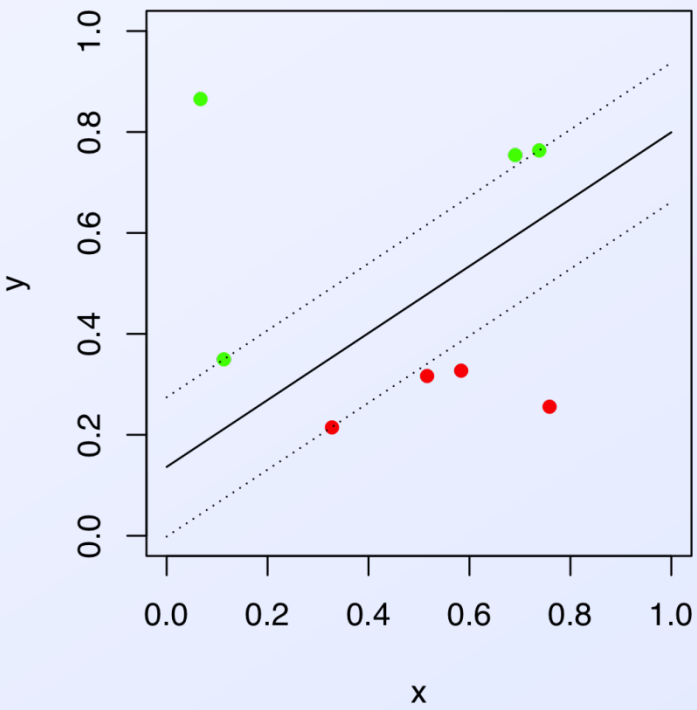


No Breach



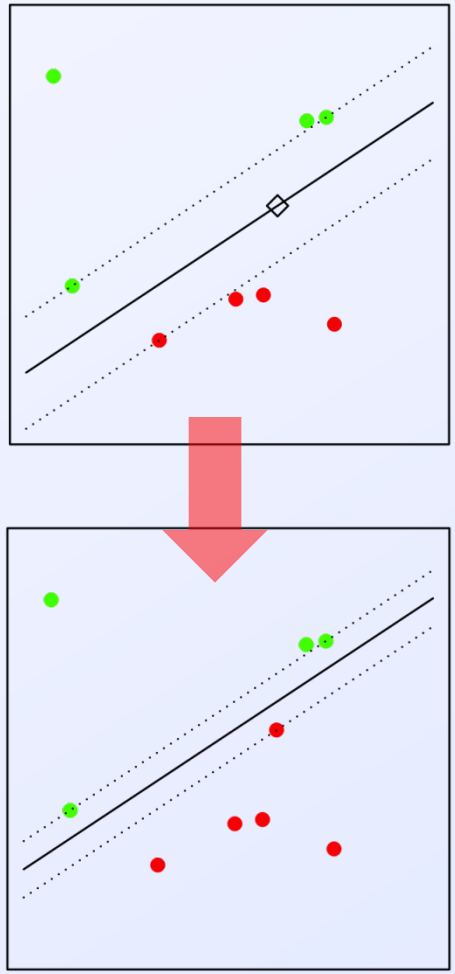
Statistical methodology

- We identify the breach/no breach boundary using Support Vector Machines (SVM).
- An SVM identifies the boundary that maximizes the margin between two classes.
- The shape of our SVM can be constrained based on expert knowledge.



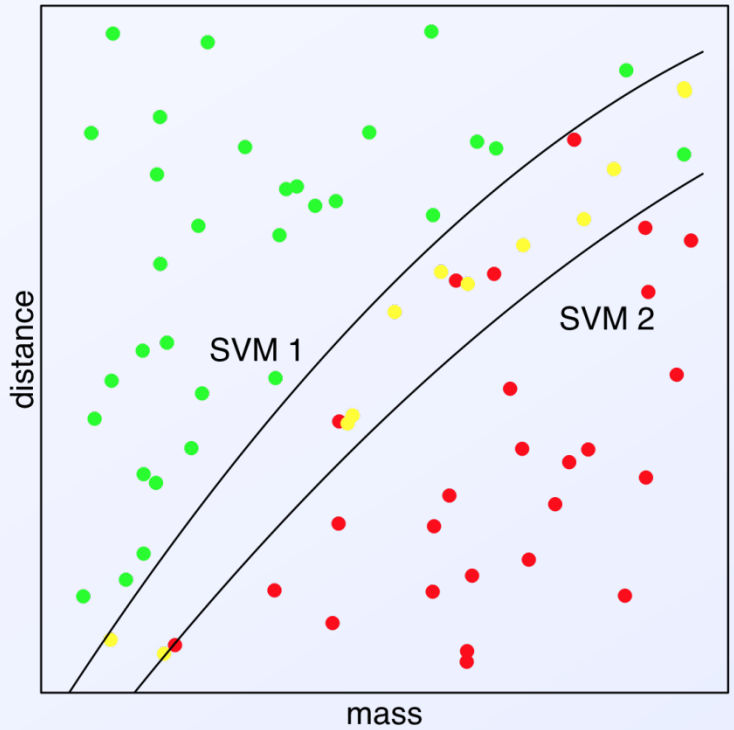
Adaptive Sampling

- After we have our initial points, we use an SVM to identify new points to evaluate.
- The most informative points are those located on the boundary and far from existing points.



Estimated breach boundary curve

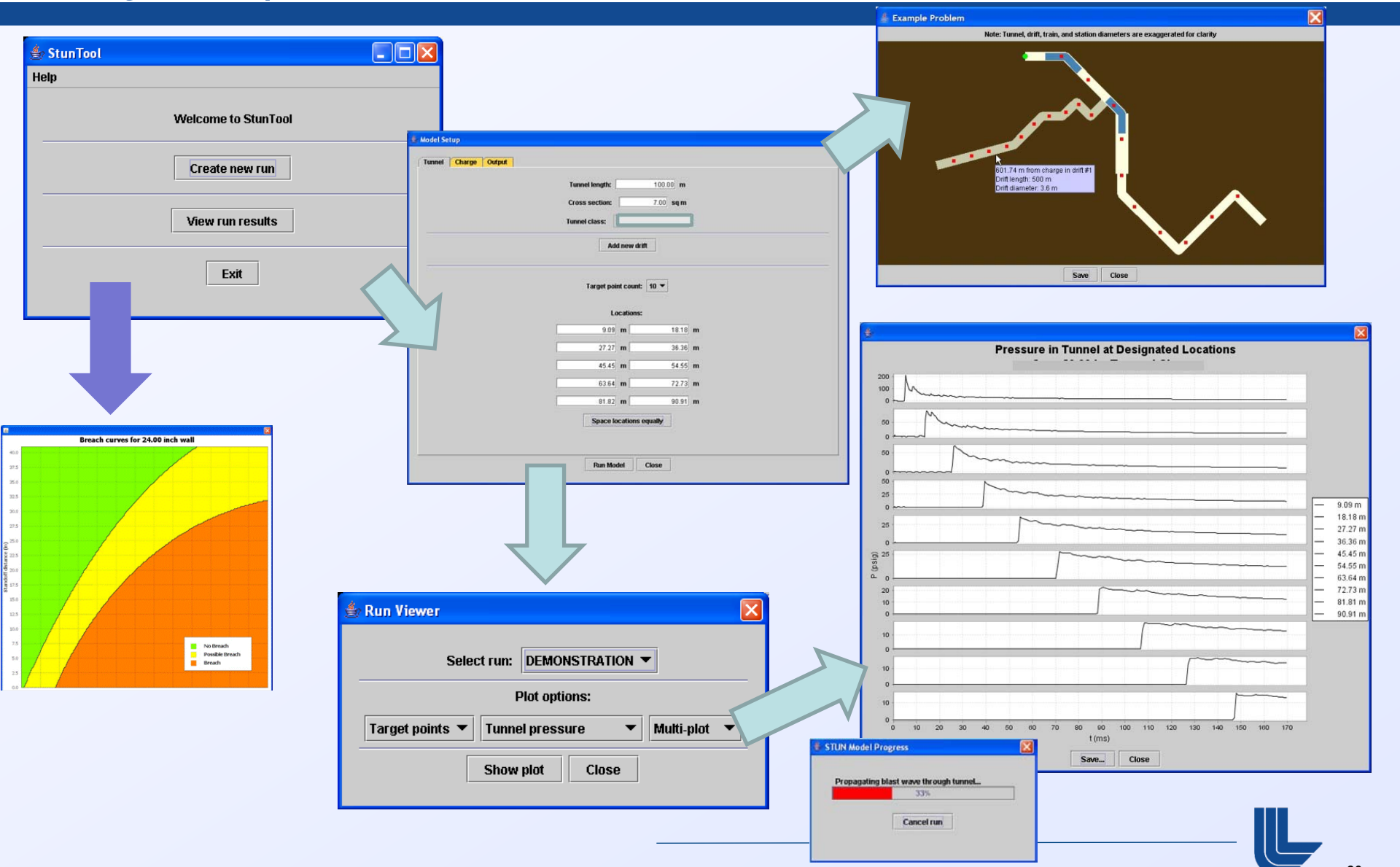
- Data with SVMs



- Final graphic

- **Fail**
- **No fail**
- **Possible fail**

Single GUI platform handles both Methods 1 and 2



Summary and Conclusions

- Fast-running tools leveraged from a detailed understanding of theory, modeling and testing of blast-structure interaction.
- Such tools predict *specific* responses quickly and allow for uncertainty quantification.
- Two different approaches considered:
  - a reduced dimensionality approach providing theory based-analysis,
  - and a statistical approach over large parameter space providing rapid lookup of output in presence of uncertainty.
- Both approaches can be integrated into single unified platform
- In future work, we plan to further refine our parametric classification method.