Computational Methods for External Flooding PRA

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Outline of my talk today

- **Definition of Computational Risk Assessment**
- **Computational resources**
- **Simulating physical phenomena via Smoothed Particle Hydrodynamics**
- **Performing assessment via CRA**

Computational Risk Assessment (CRA)

- **Computational Risk Assessment is a focus of current research and development**
- **CRA is a combination of**
  - Probabilistic (i.e., dynamic) scenario creation where scenarios unfold and are not defined a priori
  - Mechanistic analysis representing physics of the unfolding scenarios
- **CRA relies on the availability of computational tools**
  - Processors (hardware)
  - Methods (software)
- **CRA is not simply solving traditional PRA models faster or with higher precision**
  - It is a different way of thinking about the safety problem

Integrating the worlds of physics and probability leads us to predictions based upon an approach called "computational risk assessment"

CRA driving factors

- **Computers are improving**
- **Software is improving**
  - And much of it is free
- **Analysis characteristics including**

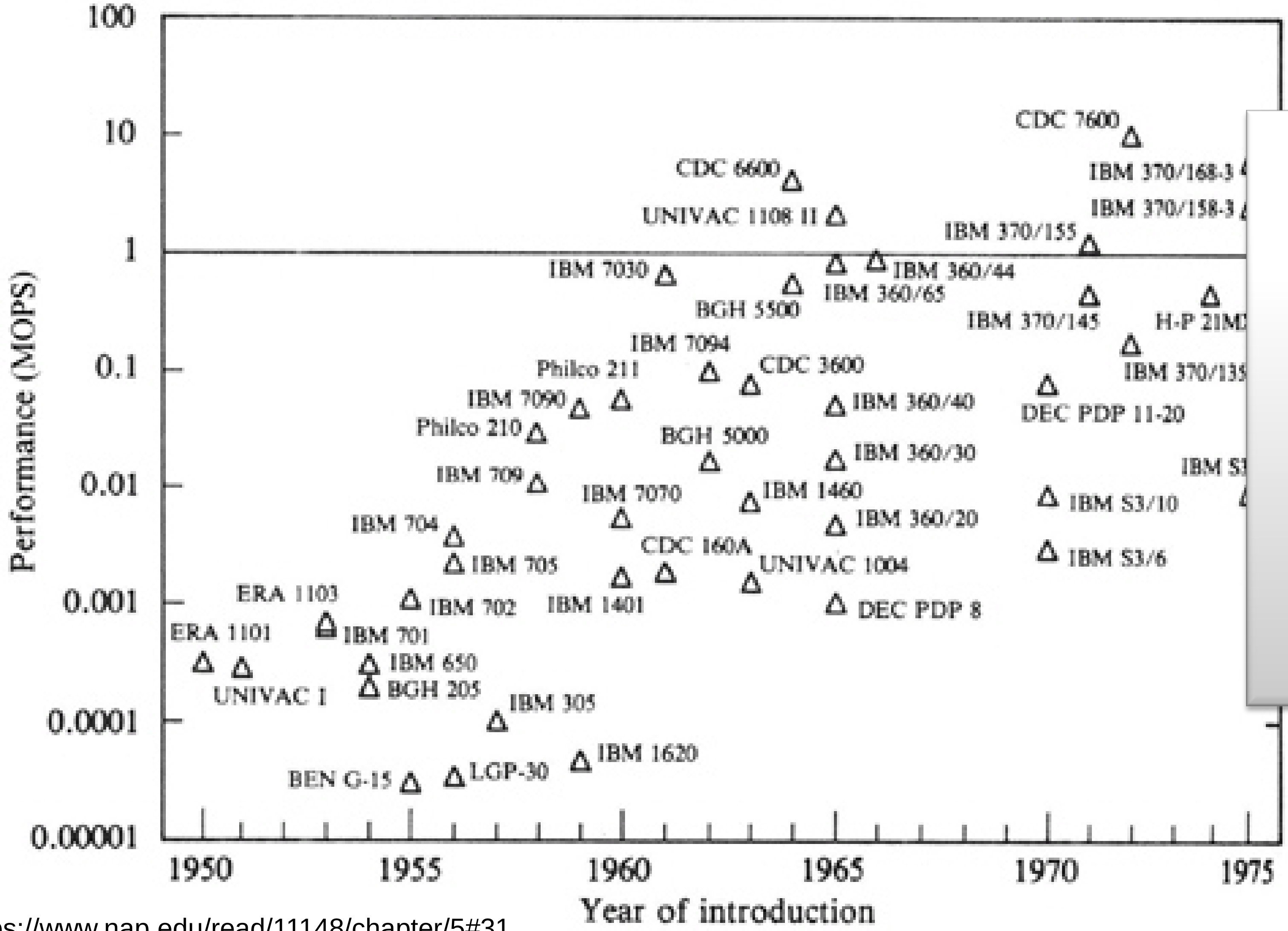
Temporal (timing issues)

Spatial (location issues)

Mechanistic (physics issues)

Topology (complexity issues)

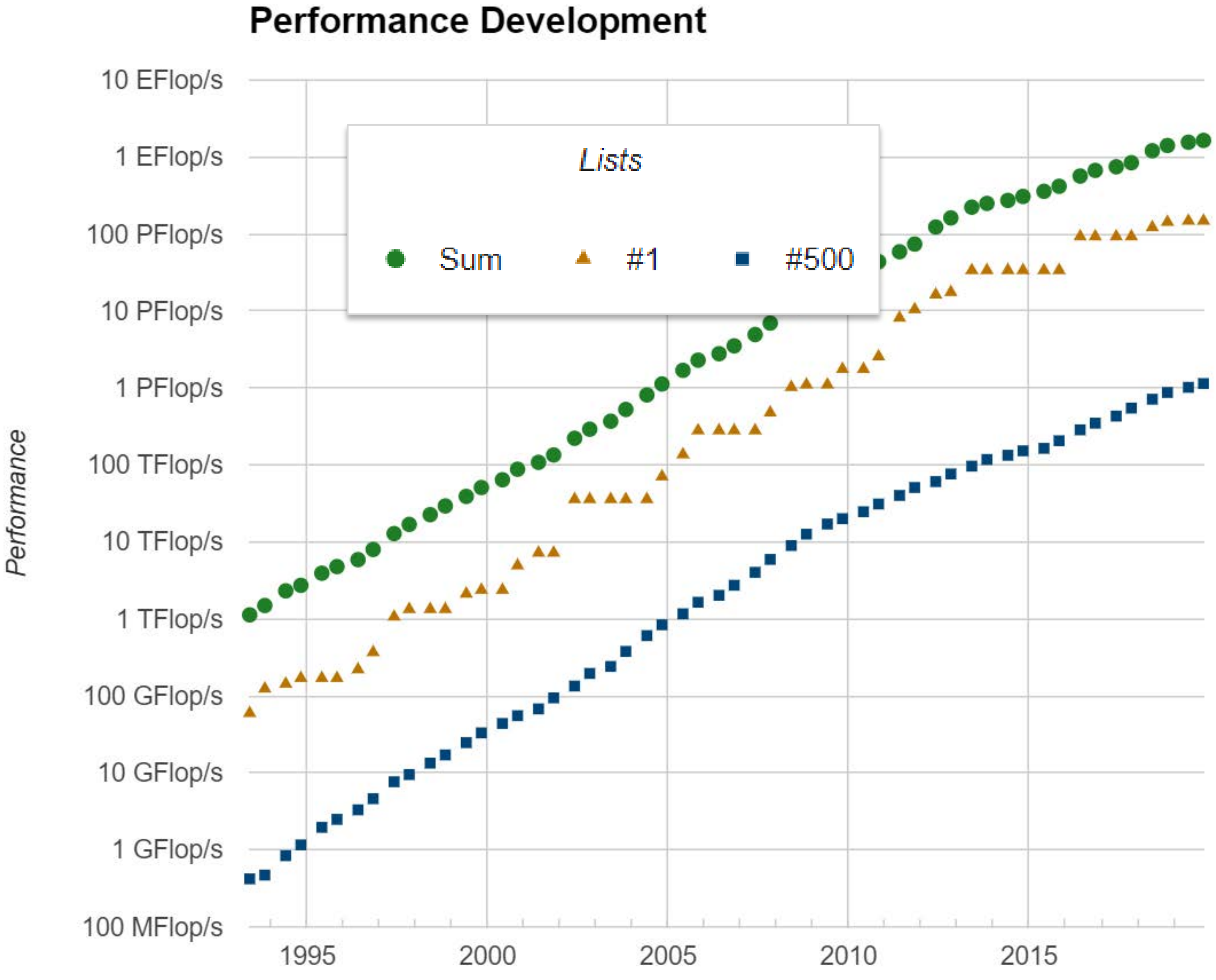
Computational performance @ dawn of risk and reliability analysis



MOPS = millions of operations per second

https://www.nap.edu/read/11148/chapter/5#31

Computational performance over time has steadily increased



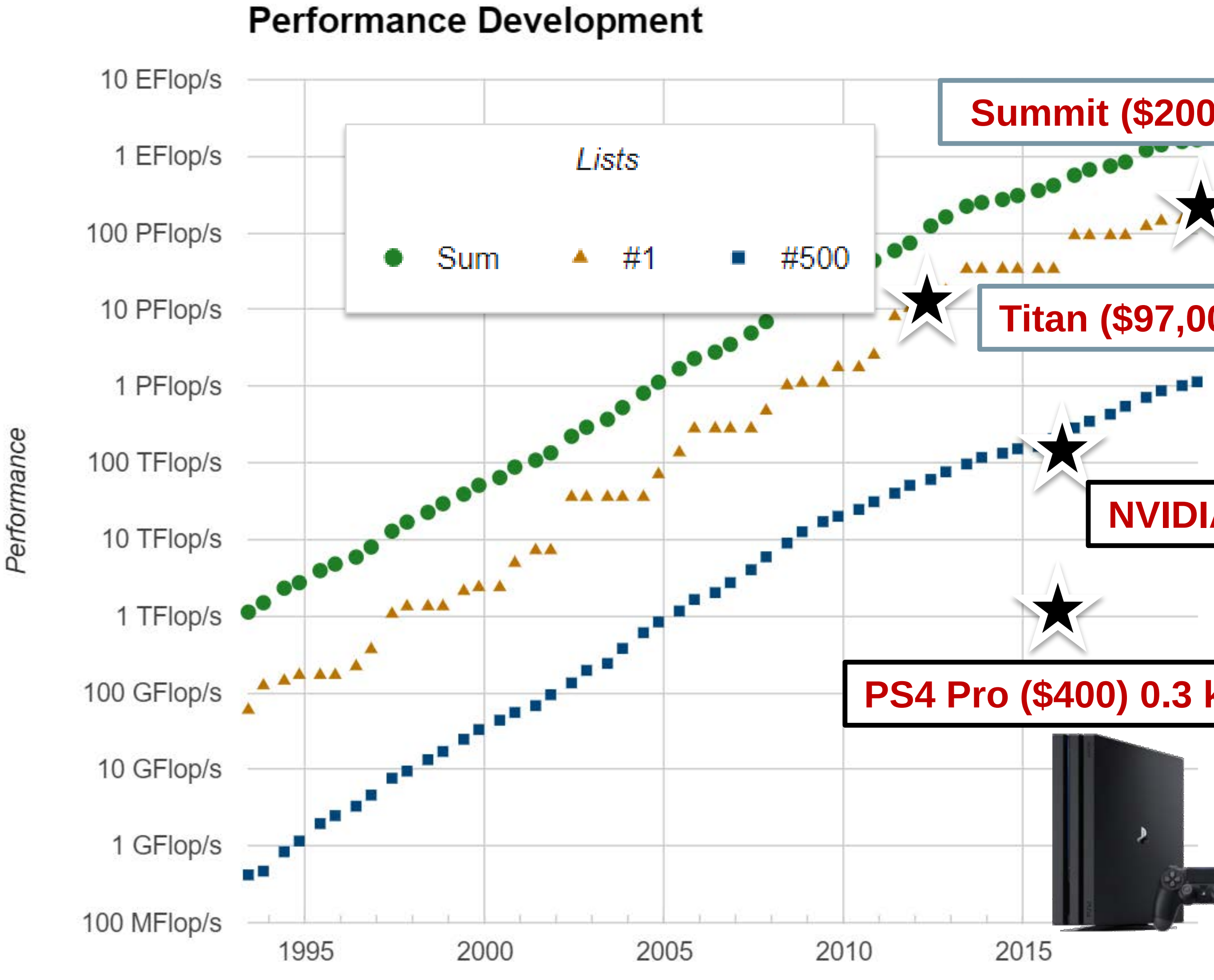
Notes:

1 EFlop/s = one exaFLOPS, or a billion billion calculations per second (10^{18})

1 MOPS does not even appear on this plot.

https://www.top500.org/statistics/perfdevel/

But how available is this "computational performance?"



Summit ($200,000K) 10,096 kW

Titan ($97,000K) 8,200 kW

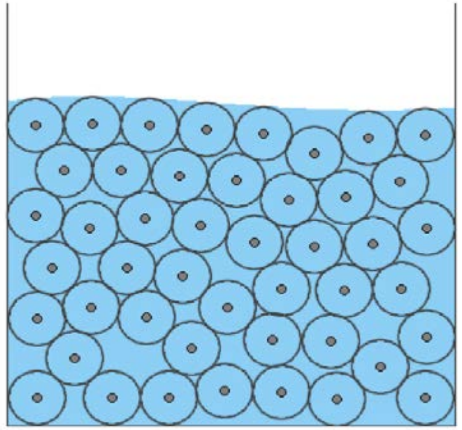
NVIDIA DGX-1 ($130K) 3.2 kW

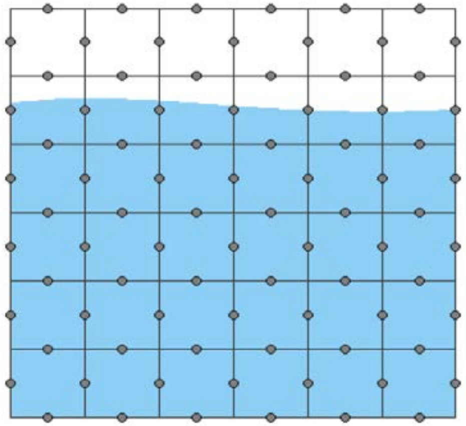
PS4 Pro ($400) 0.3 kW

https://www.top500.org/statistics/perfdevel/

Smoothed Particle Hydrodynamics

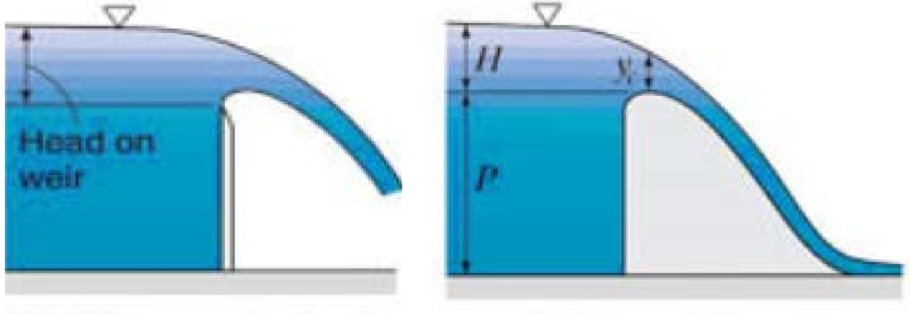
- **A way to simulate flooding scenarios is needed**
- **Smoothed Particle Hydrodynamics (SPH)**
  – Particle based method
  – Originally developed for astrophysics applications in 1977
  – Later extended for fluid dynamic applications
- **SPH allows for flooding scenarios to be simulated**
  – Does not confine fluid to meshes
  – Allows for a natural flow to be modeled
- **A reliable SPH code is needed**
  – Compare to experimental results

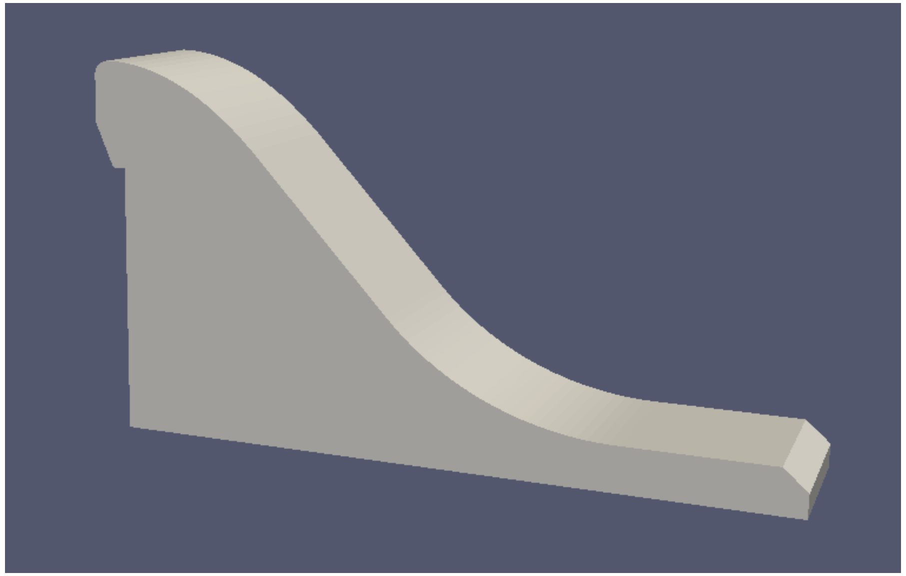




Ogee Spillway Comparison

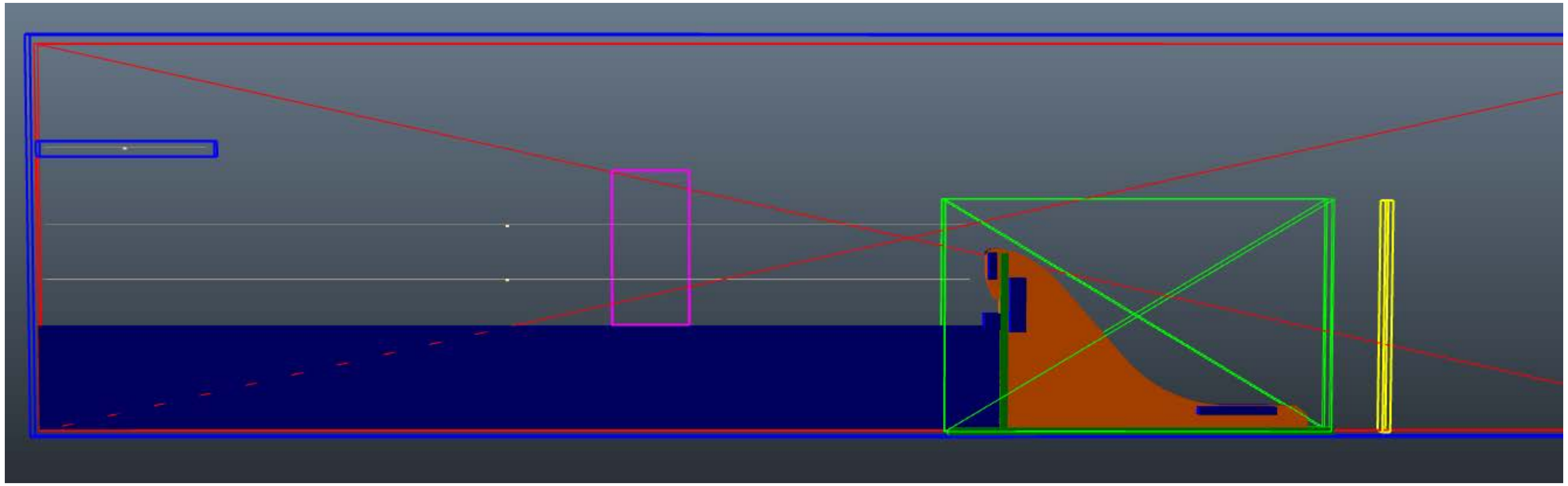
- **Comparison Model**
  - Ogee spillway with horizontal apron
  - Details of experiment provided in Flow over Ogee Spillway: Physical and Numerical Model Case Study by Bruce M. Savage and Michael C. Johnson
  - Experiment details (scaled model):
    - Measurements taken 2 m upstream
      - Flow Rate
      - Total Head
    - Ten different runs conducted
  - Prototype scale was used for the SPH comparison which required scaling the model scale up 30 times





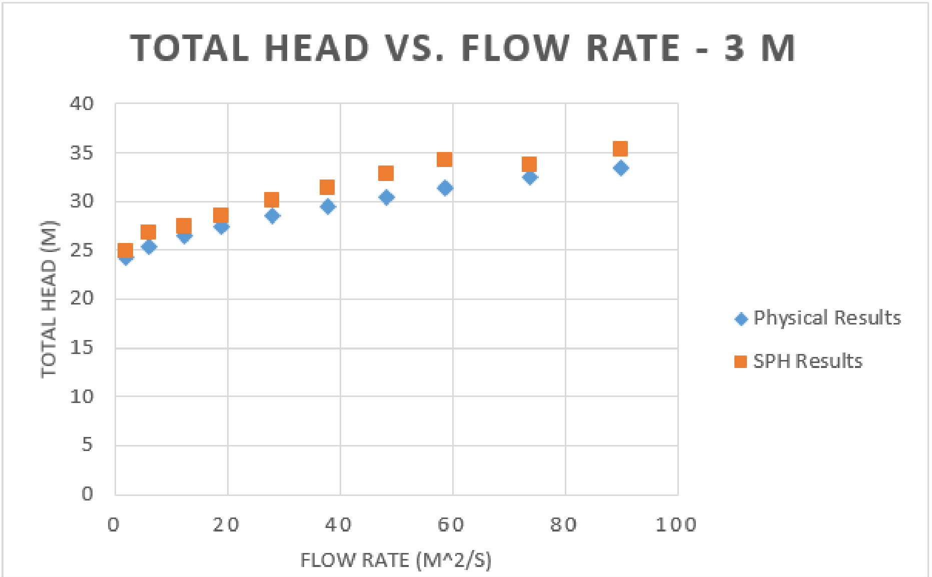
Neutrino Model

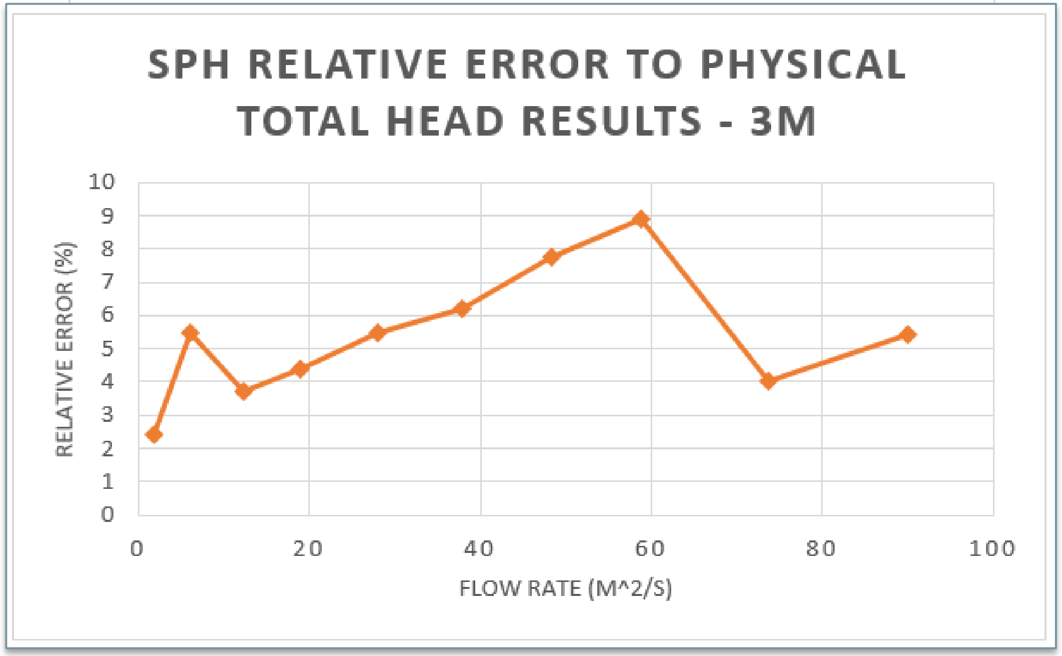
- **Developmental SPH code Neutrino was used to conduct the comparison**
- **Model construction process:**
  - Determine how to fill particles behind the spillway
  - Reduce leakage
  - Determine particle emitter location to set total head
  - Determine particle emitter location to set flow rate instead
  - Conduct parametric studies on model width and particle size
  - Reduce leakage again
  - Change particle emitter types



Comparison Results

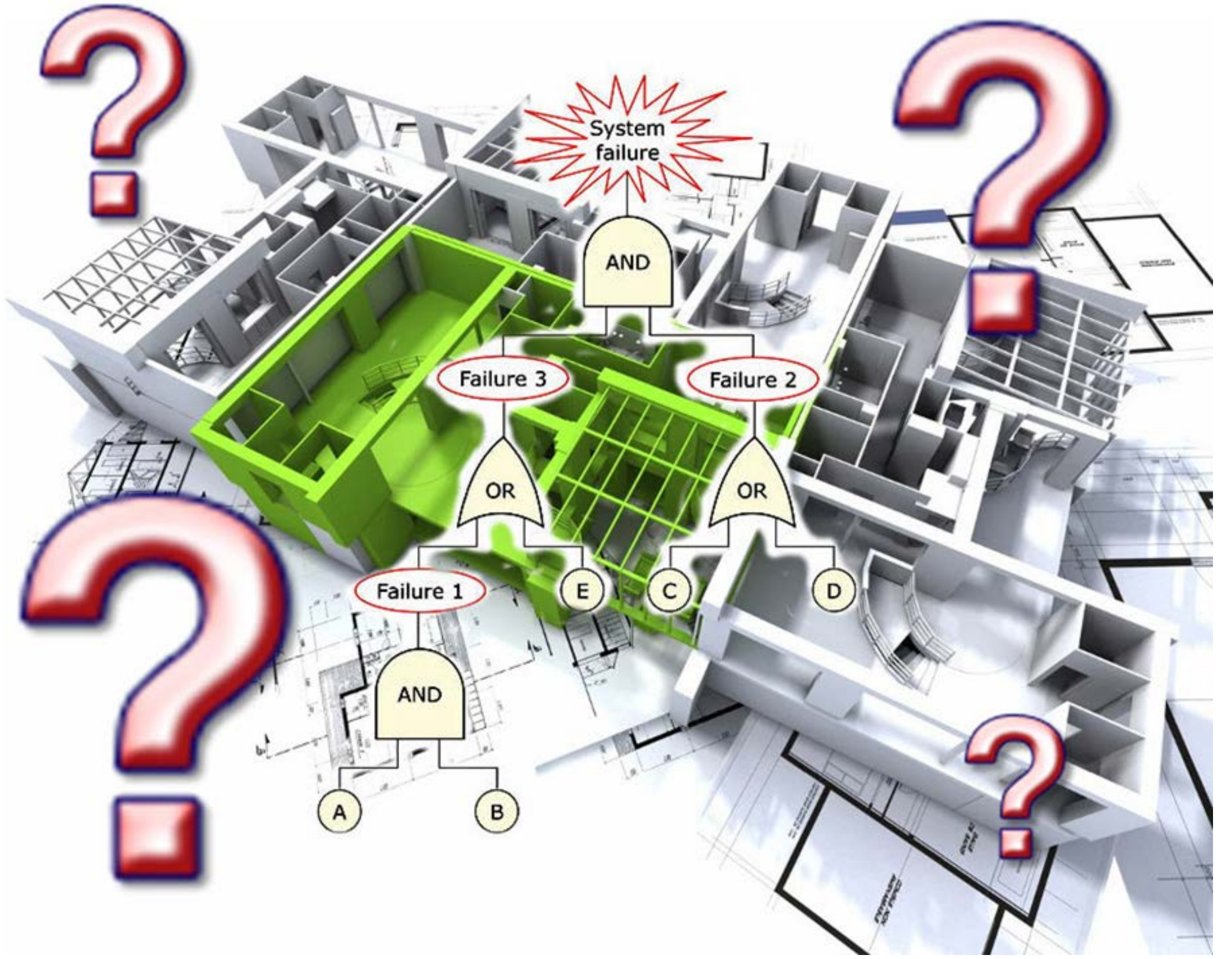
Run	Flow Rate	Physical Total Head Result	SPH Total Head Result	Relative Error
1	1.9 m^2/s ± 0.25%	24.3 m	24.9 m	2.4 %
2	6.0 m^2/s ± 0.25%	25.3 m	26.7 m	5.5 %
3	12.3 m^2/s ± 0.25%	26.5 m	27.5 m	3.7 %
4	19.0 m^2/s ± 0.25%	27.4 m	28.6 m	4.4 %
5	27.9 m^2/s ± 0.25%	28.5 m	30.0 m	5.5 %
6	37.8 m^2/s ± 0.25%	29.5 m	31.3 m	6.2 %
7	48.2 m^2/s ± 0.25%	30.4 m	32.8 m	7.7 %
8	58.9 m^2/s ± 0.25%	31.4 m	34.1 m	8.9 %
9	73.8 m^2/s ± 0.5%	32.4 m	33.7 m	4.0 %
10	89.9 m^2/s ± 0.5%	33.5 m	35.3 m	5.4 %





How to Join Physics Model & System Model

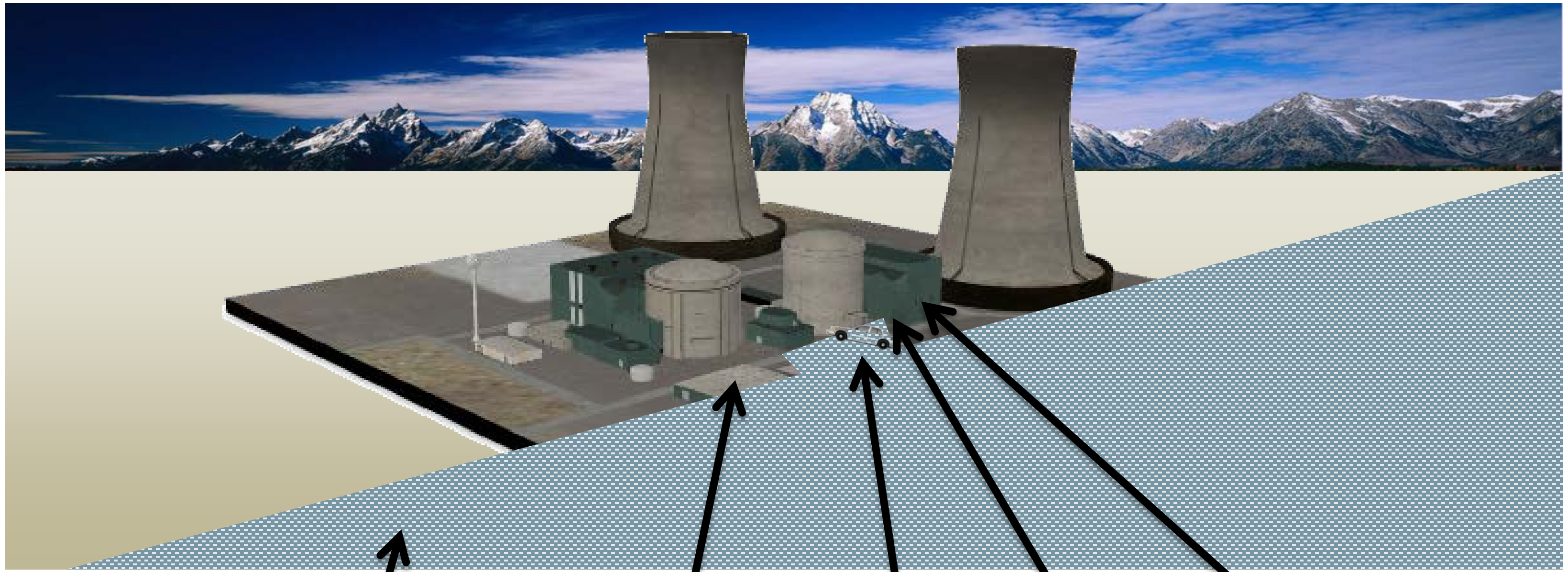
- **Good - Run repeated simulations and add the failure information into the existing static models**
- **Better – Dynamic PRA model that can interact with the simulation**
  - No corrections needed for time dependent calculations
  - Determine average or mean time of particular outcomes
  - Analyze time order of failures to determine early protection methods



Risk Analysis Steps for Scenario Generation

Enabling Conditions → Flood → Plant SSC Response to Initiator → SSC Failures & Successes → Scenario Simulation

3D Models for the Facility including Systems, Structures, & Component (SSC)

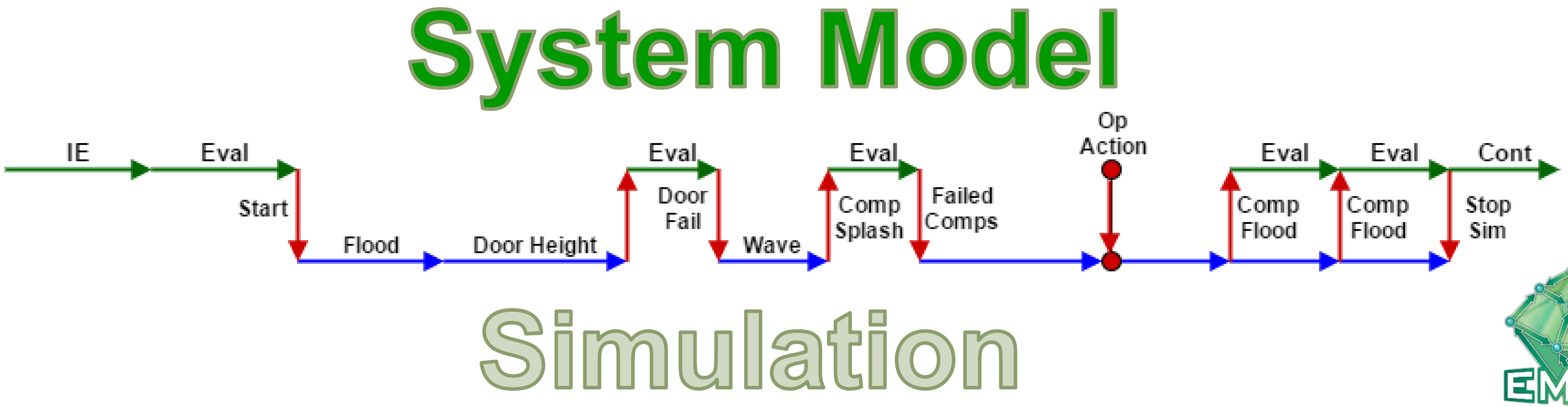


Computational Layers Used for the Analysis

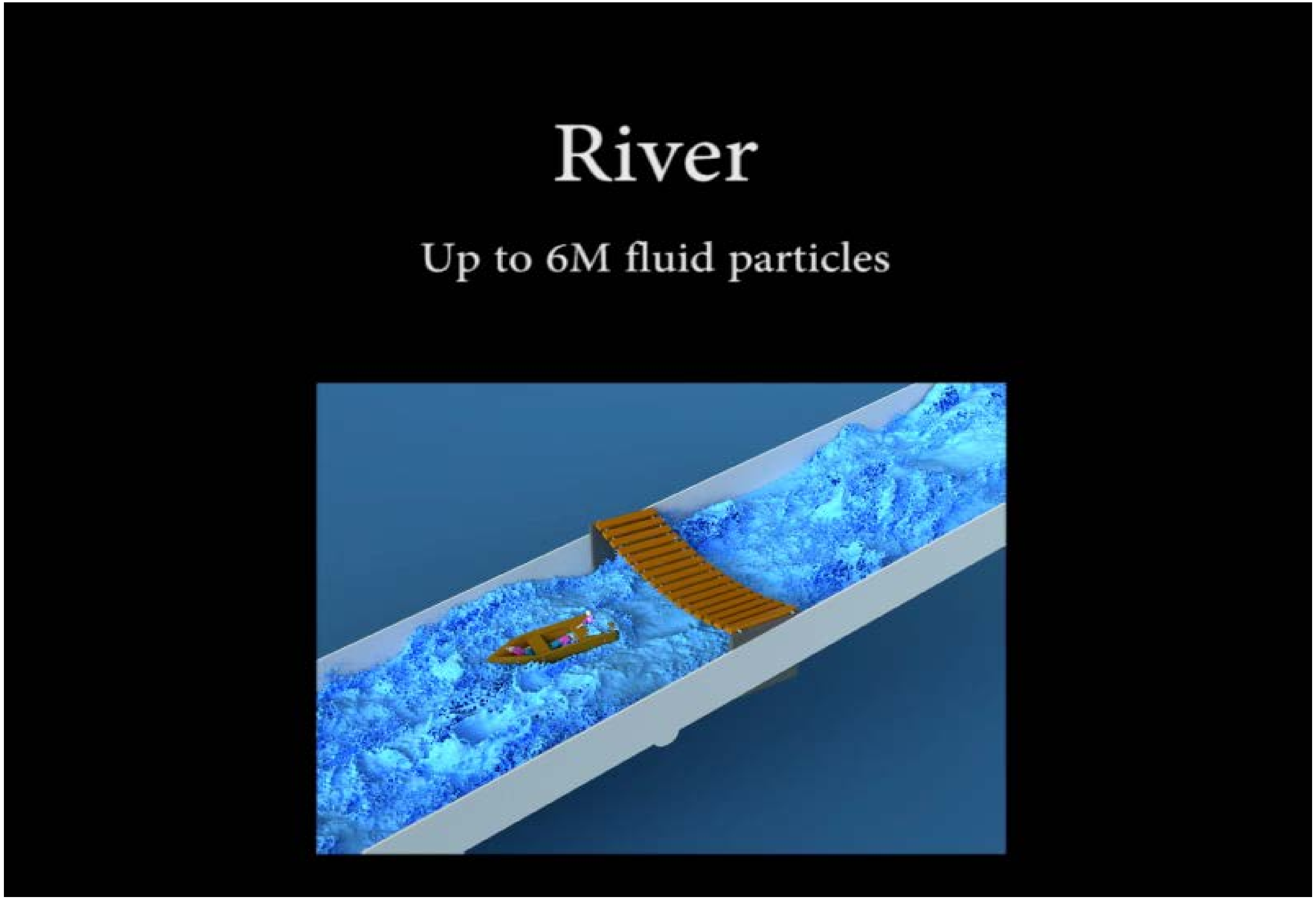
- Probabilistic events
- Seismic
- Flooding: Hazard Freq. | Static/Dynamic Loads | Debris | Water Migration | Fragilities
- . . .
- Thermal-hydraulics

Timing is Everything

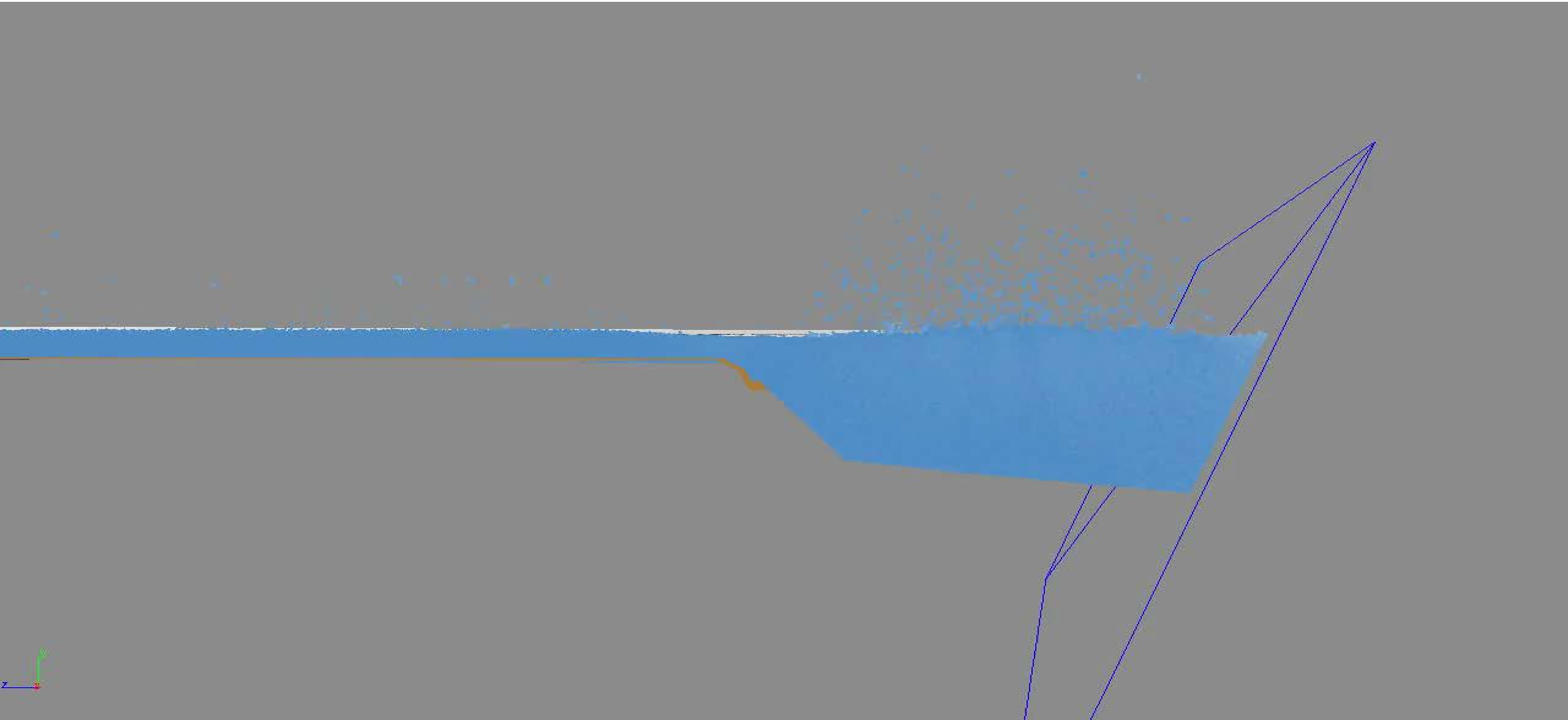
- Physics simulation are dynamic and time dependent
- Control logic is not always available in simulations
- Need to modify the behavior of the simulation at during execution.



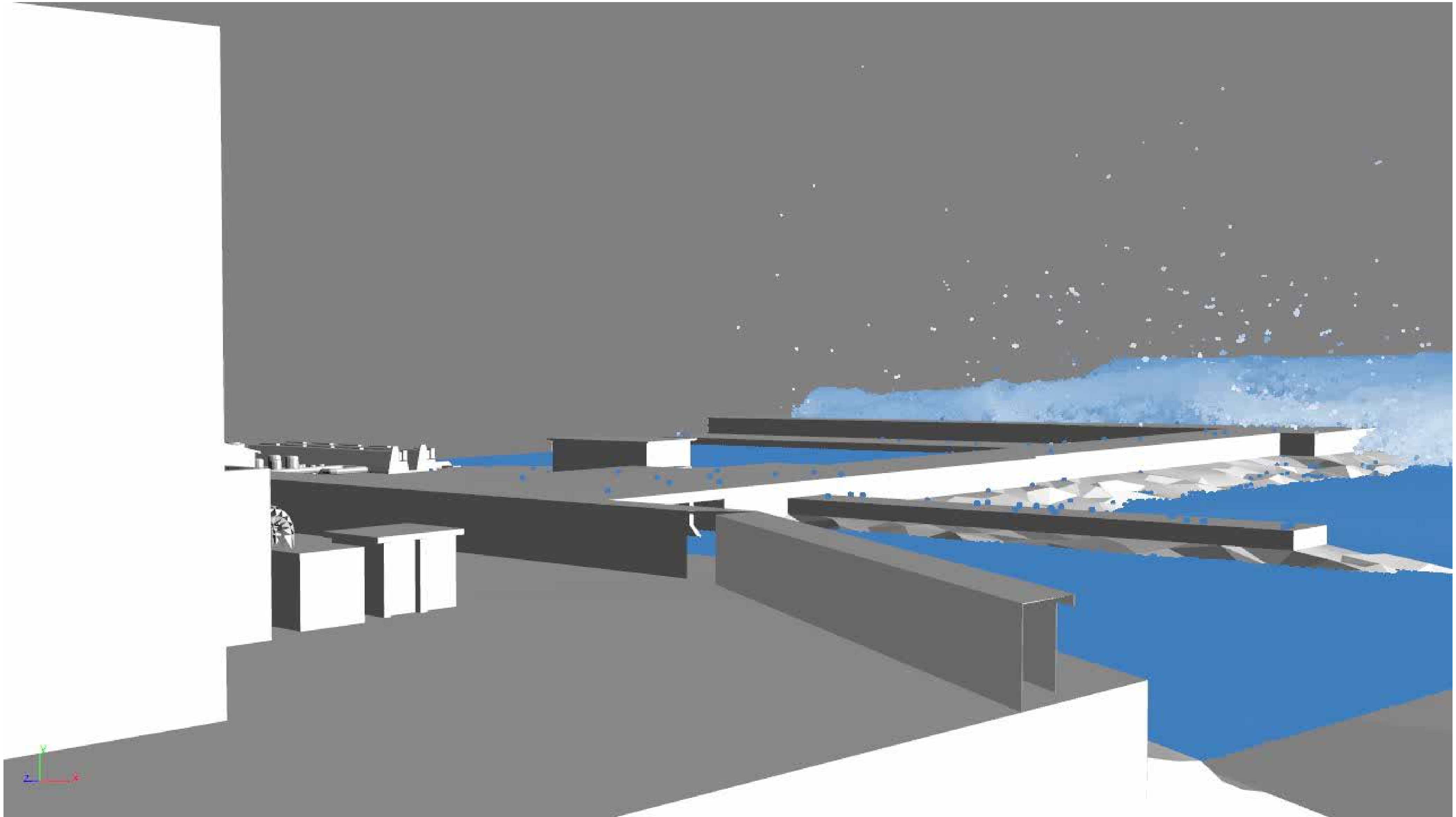
Example of a fluid solver (physics representation)



Making a wave CRA style (water physics)

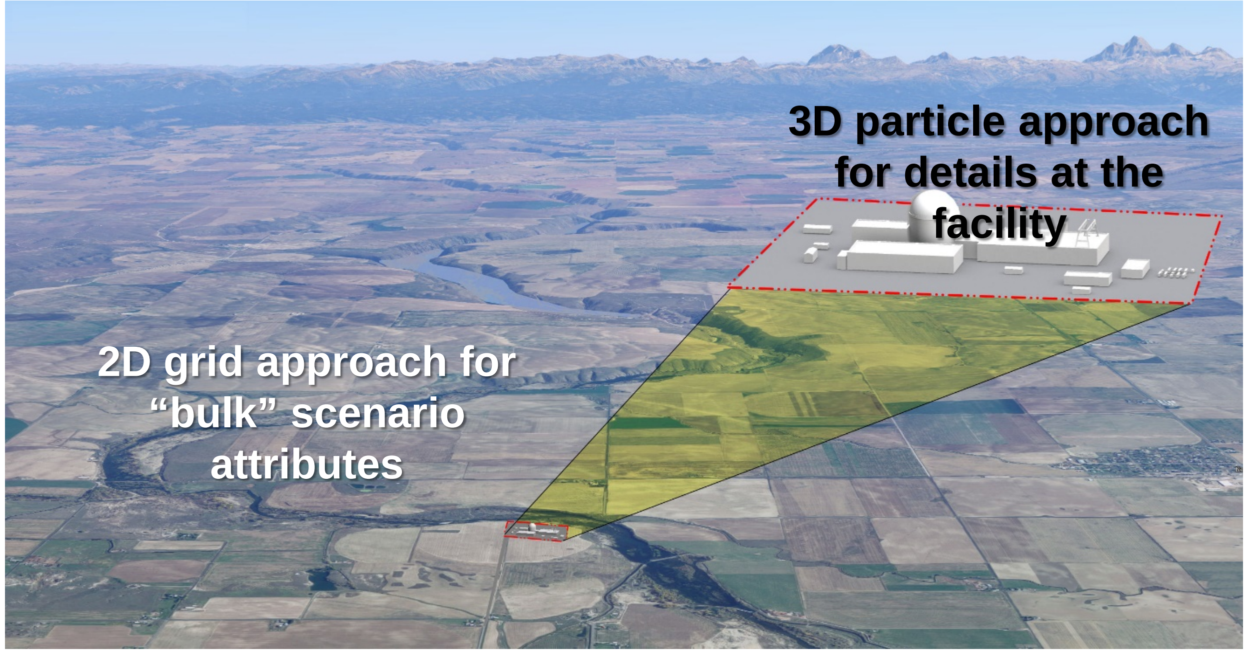


Physics (water) + facility model + probabilistic failures = CRA



River flood modeling

- **INL/EXT-15-37091, Flooding Capability for River-based Scenarios**
- **Evaluated two different types of potential river-based flooding tools**
  - 1D/2D grid based (GeoClaw, EPA's SWMM code, and Army Corps HEC)
  - 3D particle based
  - Both the 2D and 3D methods have positives and negatives
- **Combination of both seems to be best approach moving forward**



Dam break and subsequent river flood

by

Steve Prescott (INL)
Ram Sampath (Centroid Lab)
Donna Calhoun (BSU)

Conclusions

- The Idaho National Laboratory is demonstrating a next-generation uncertainty and risk-assessment approach that supports PRA and decision-making
- Combines mechanistic physics-based models with probabilistic analysis (CRA)
- Provides new opportunities for the next generation of scientists/engineers to attract talent

- Uncertainty analysis can be built upon and supported for next-generation methods and tools
  - Provides an opportunity to greatly enhance the realism in our risk models
    - Can provide solution to "what's next" in modeling (e.g., synthetic data for machine learning, digital twin framework)

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Thank you!