NHERI SimCenter

Center for Computational Modeling & Simulation

SimCenter Scientific Workflow Systems and connection to DesignSafe Infrastructure

Frank McKenna

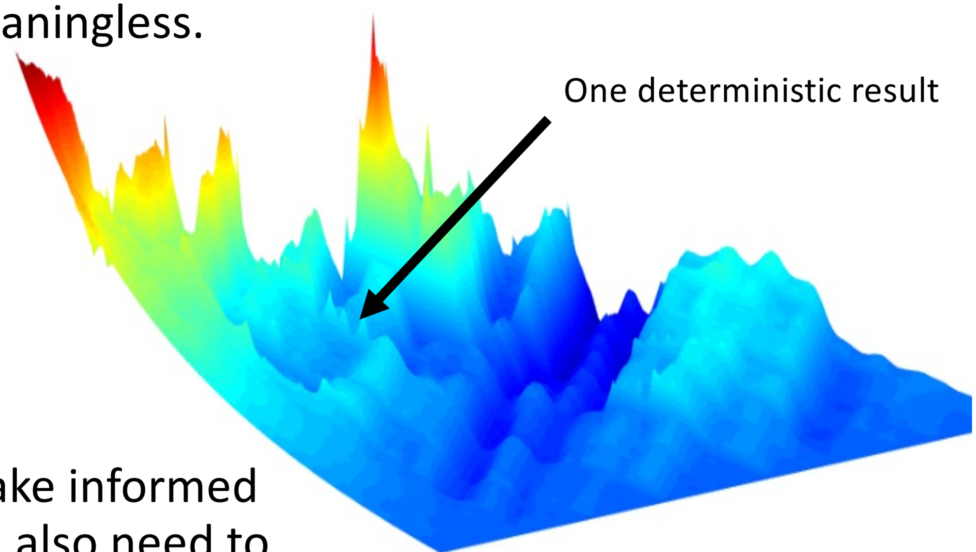
NSF award: CMMI 2131111 and 1612843

Start With a Quote

"An estimate without uncertainty is **no** estimate at all**."** (attributed to Sir Harold Jeffreys)

How this relates to OpenSees

- A single OpenSees analysis produces a single set of results, it is a **deterministic** result, it is just one of the many **possible** outcomes. By itself such a simulation is practically meaningless.



Surface Representing all Possible Outcom
(actual surface is N-dimensional)

- In order to make informed decisions, you also need to know how **probable** the outcome is.

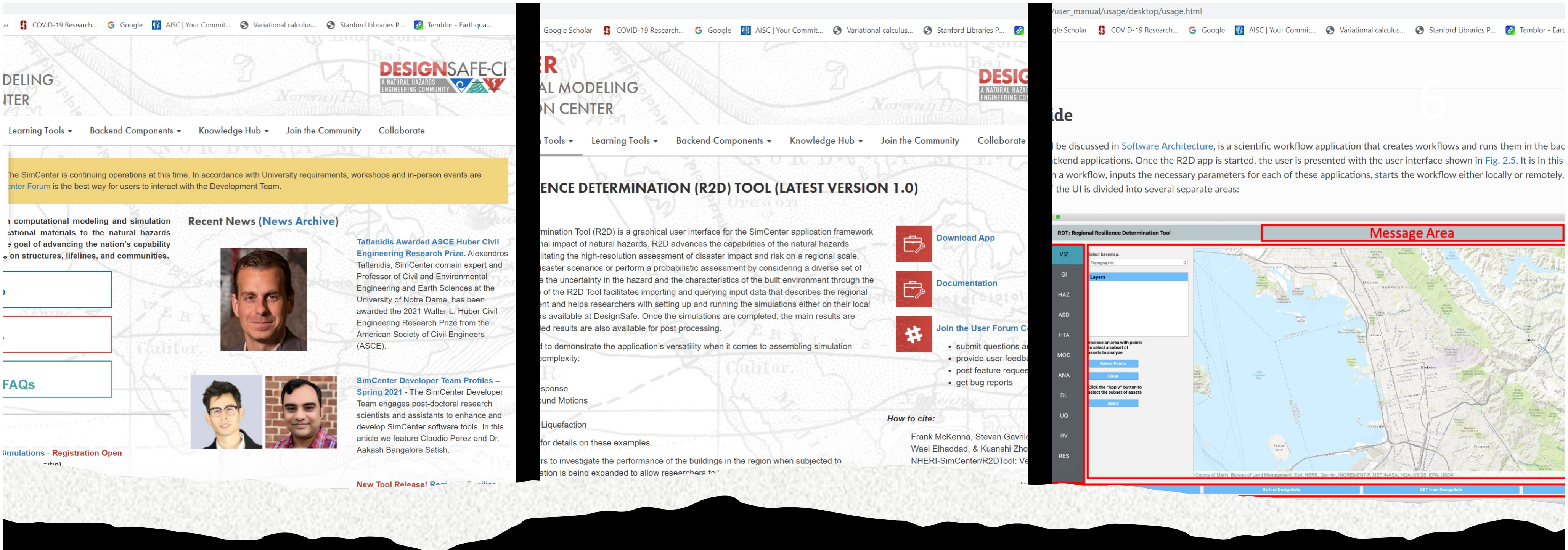
Conclusion

- ~~99%~~ 95% of OpenSees users do not **apply** it correctly!
- SimCenter Provides Applications to Fix this as **they force users to employ uncertainty quantification algorithms**.
- These SimCenter Applications (quoFEM, EE-UQ, WE-UQ, Hydro-UQ, PBE & R2D) provide features other than UQ which are incredibly useful.

NSF's Facilities/Programs

NHERI Natural Hazards Engineering Research Infrastructure

For more information, visit the
NHERI DesignSafe website: DesignSafe-ci.org



SimCenter Portal

- Software & Documentation
- Education and Training Webinars
- Forum & Other Communication

https://simcenter.designsafe-ci.org/

SimCenter Objectives

- Develop a **flexible, extensible, and scalable** **software framework** for creation of scientific workflow systems that support decision-making to enhance community resilience to natural hazards in the face of uncertainty;
- **Release open-source tools/applications built using this framework** that meet the computational needs of researchers in natural hazards engineering;
- **Provide an ecosystem** that fosters collaboration between scientists, engineers, urban planners, public officials, and others who seek to improve community resilience to natural hazards.

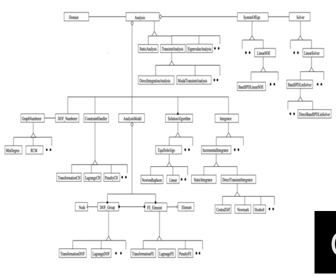
What is a Software Framework

Definition: A Software Framework is a collection of interfaces (abstract classes if C++) that define how components interact and a set of concrete components (instantiable C++ subclasses in C++) that allow you to build an example application from the framework.

OpenSees is an example of a Software framework (C++ Framework).

Applications Built using OpenSees Framework

~~G3~~ OpenSees
OpenSeesSP
OpenSeesMP
OpenSeesPy
all **SimCenter Tools**



Chapters 2 & 3

https://opensees.berkeley.edu/OpenSees/doc/fmkdiss.pdf

Fun(Depressing!) Fact

OpenSees

Intel has a Slogan

A SimCenter App Equivalent

Powered by OpenSees

OpenSees inside

and TACC and Dakota and ……

Scientific Workflow System?

Definition: a **Scientific Workflow System** is software that allows users to build, launch and monitor Scientific Workflows.

Definition: a **Scientific Workflow** is the **automation** of a process in which information is passed from **one application to the next.**

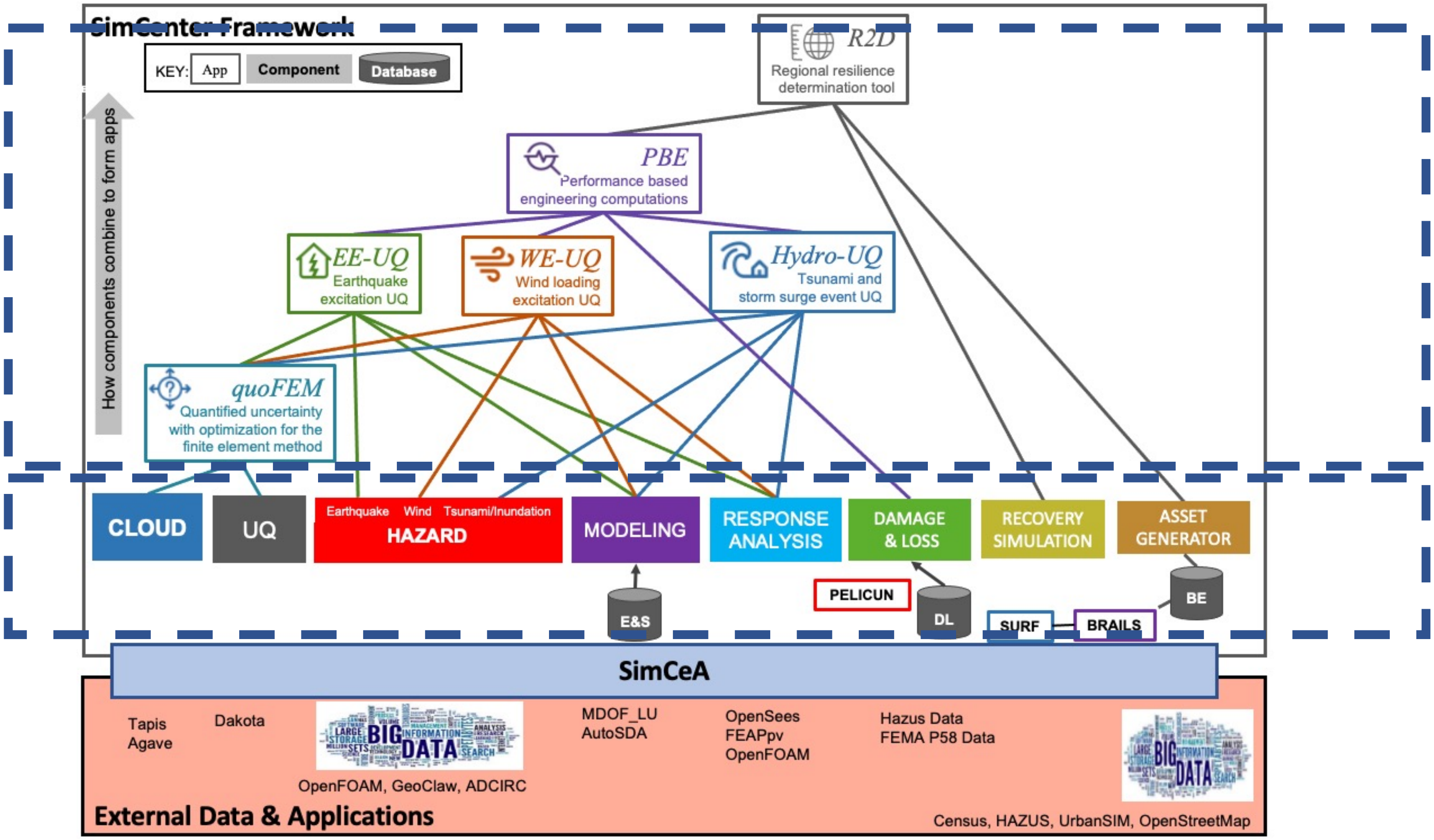
SimCenter Applications Framework

Applications

Interfaces

Components

(Powered By)



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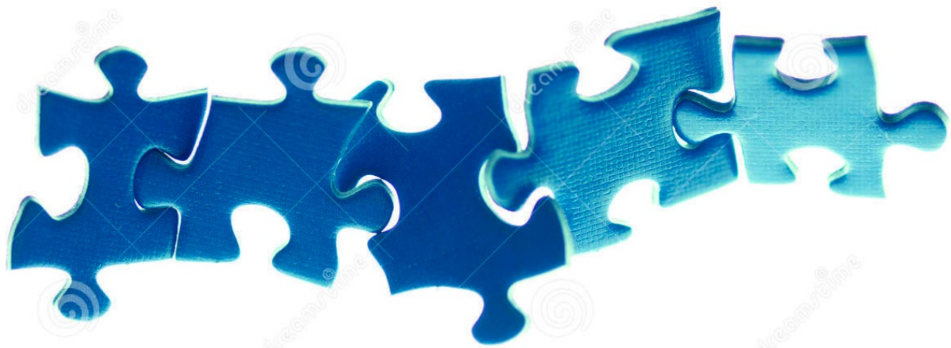
Existing Applications of course do not of Course work together



SimCenter defining interfaces they must meet!

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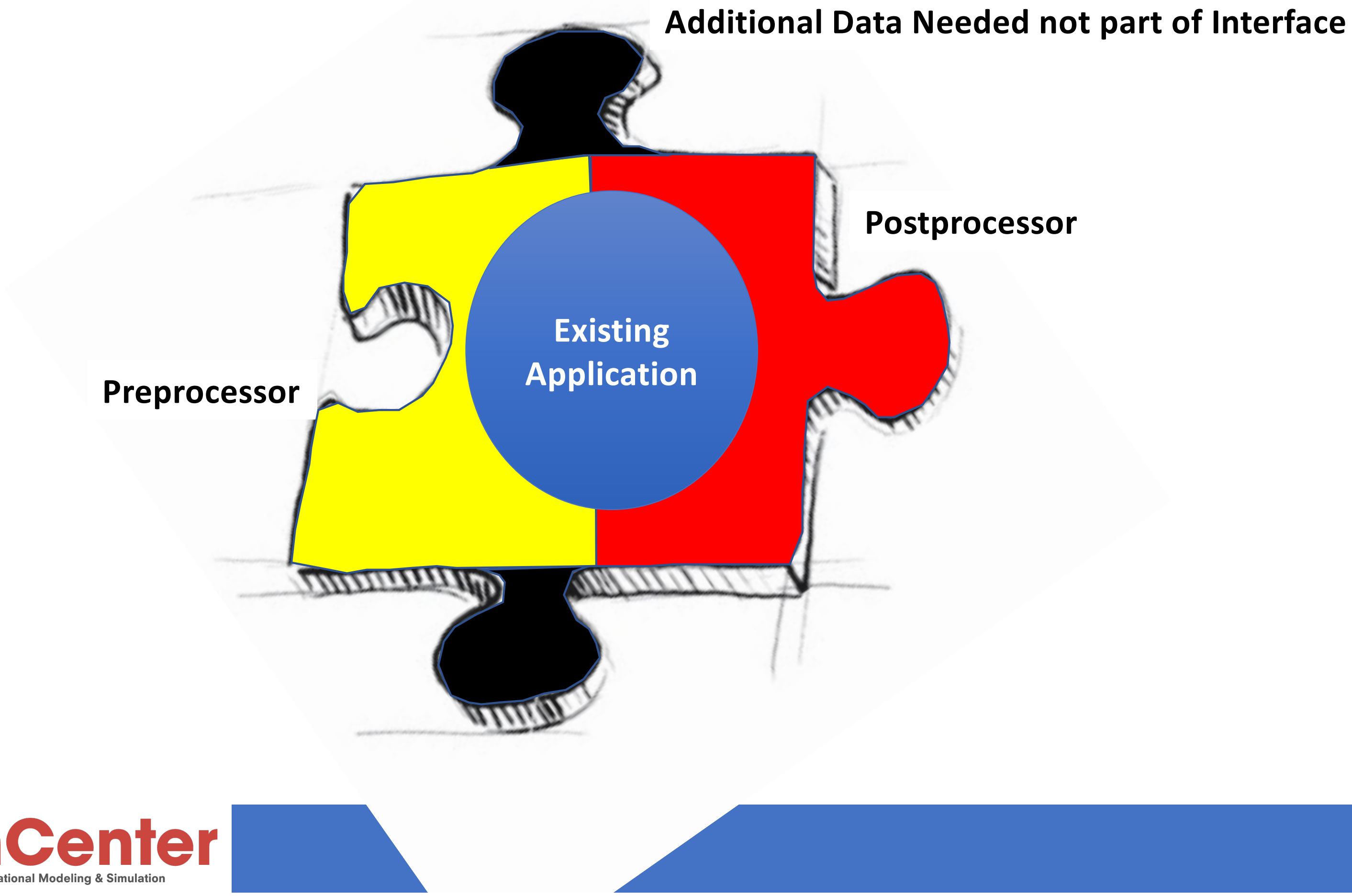
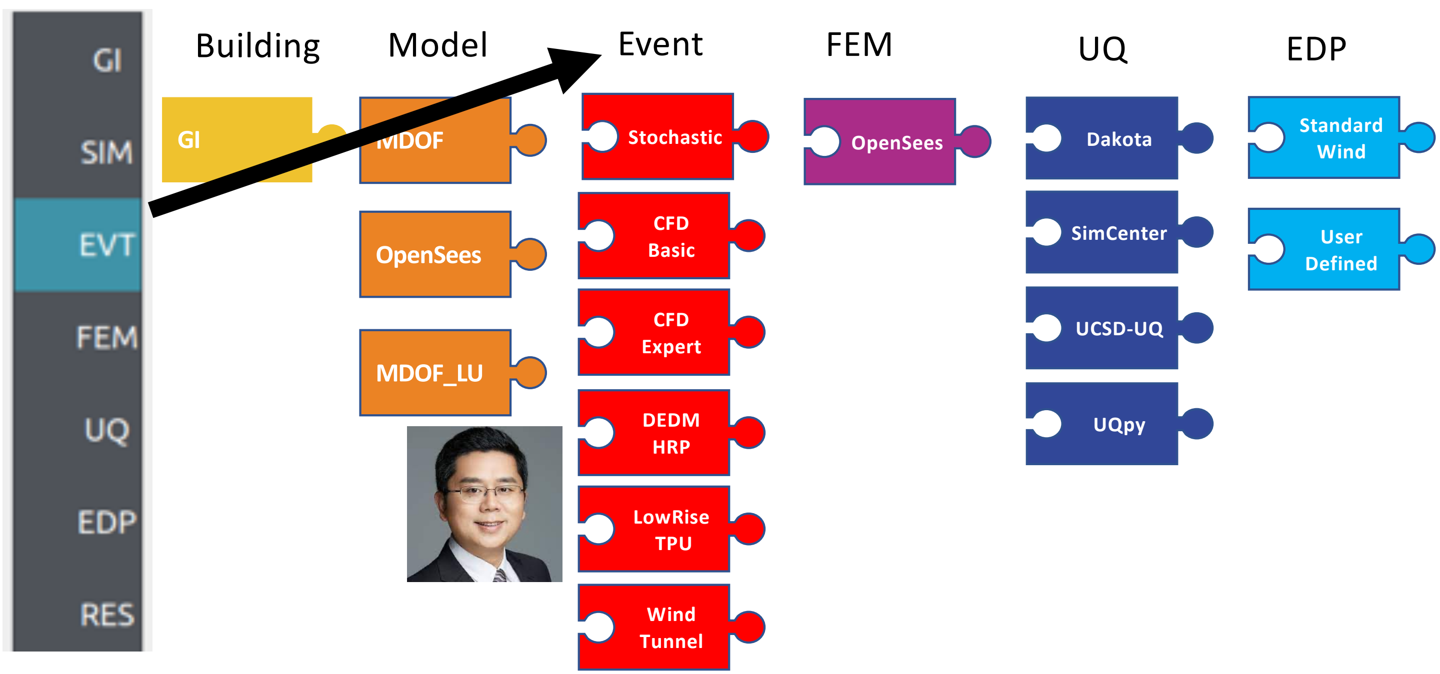
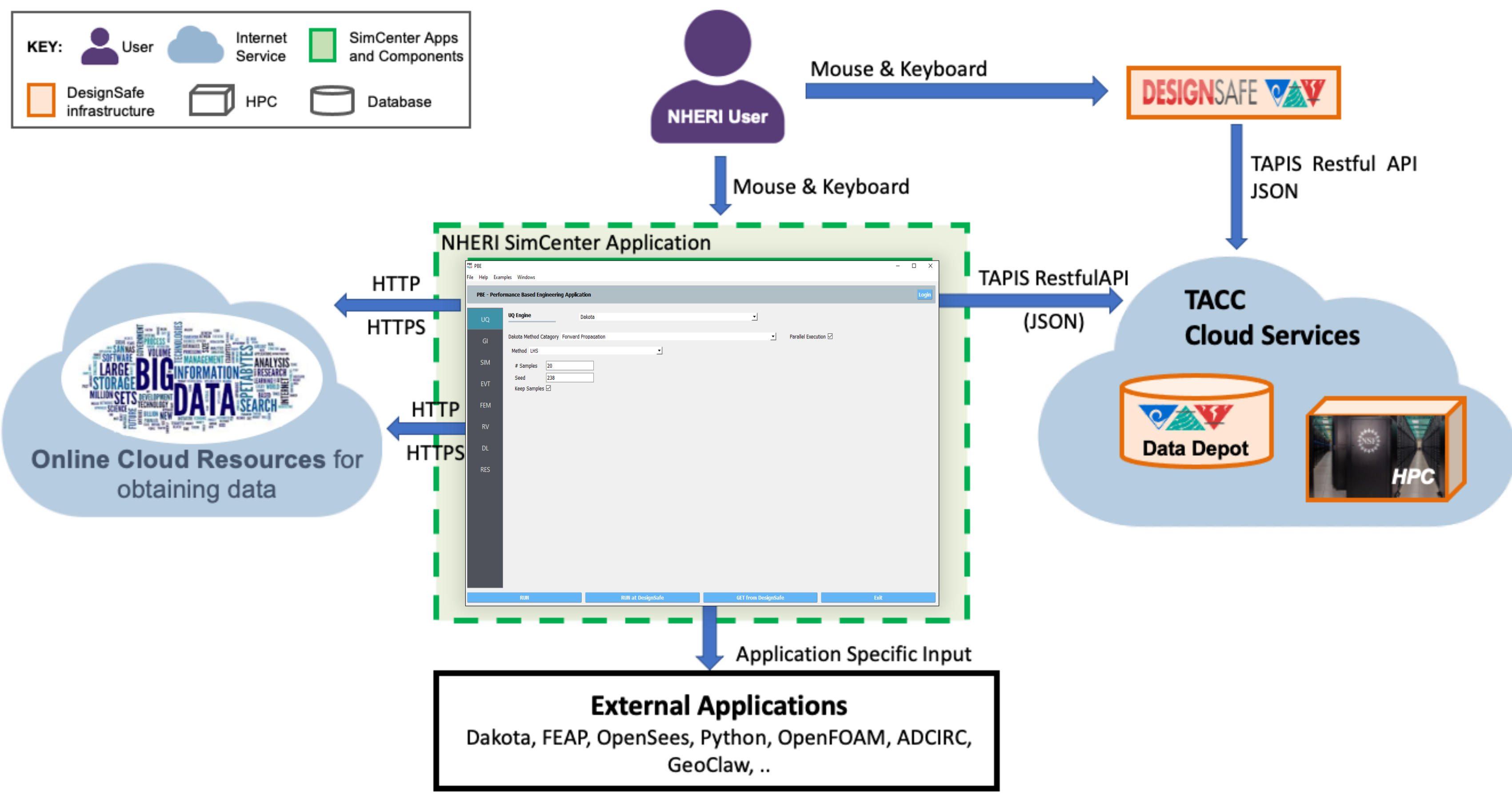
And Writing Code to incorporate Existing Applications into Workflow



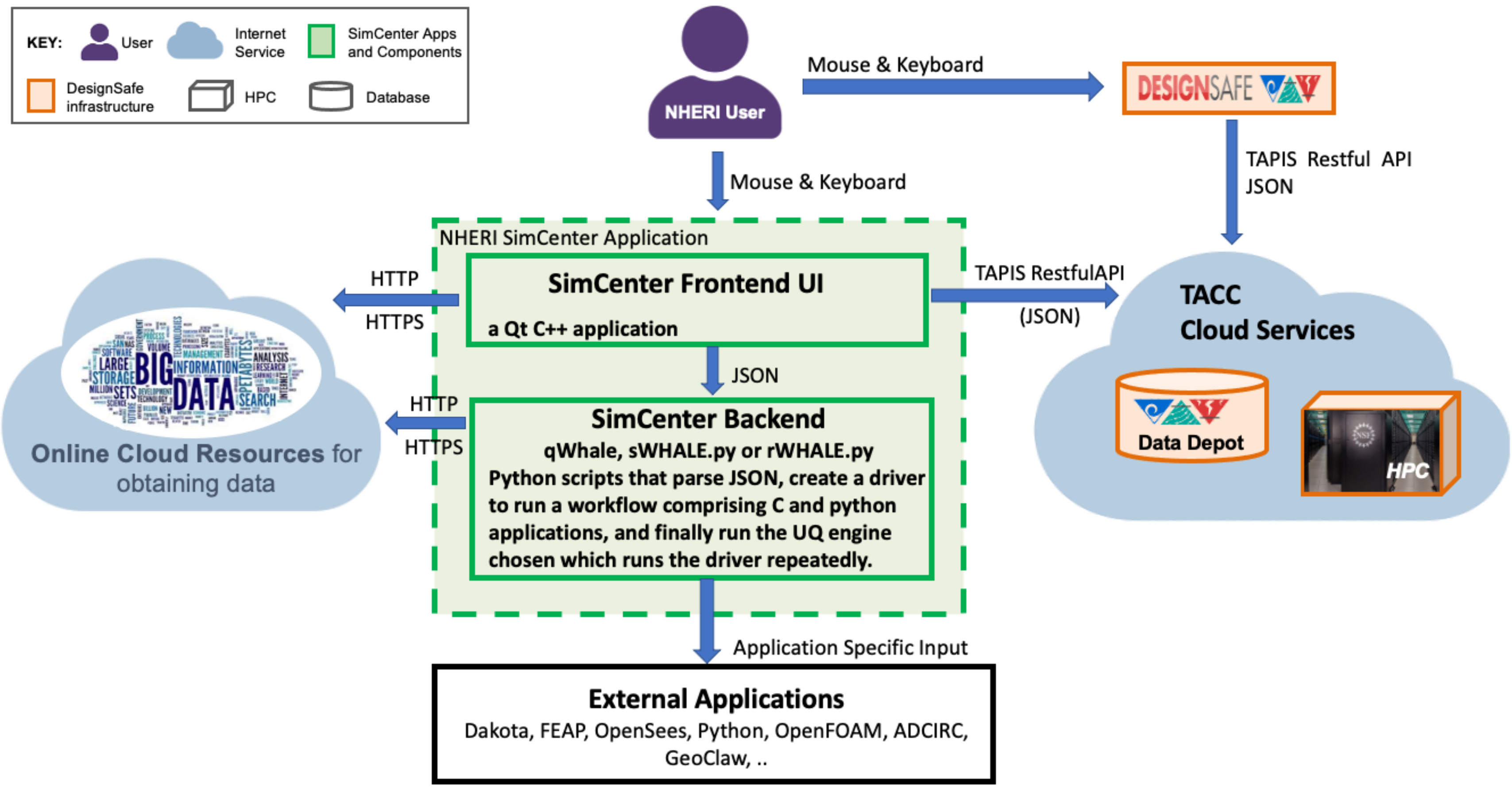
Putting workflow together in UI



UI Launches Scientific Workflows



UI Launches Scientific Workflows

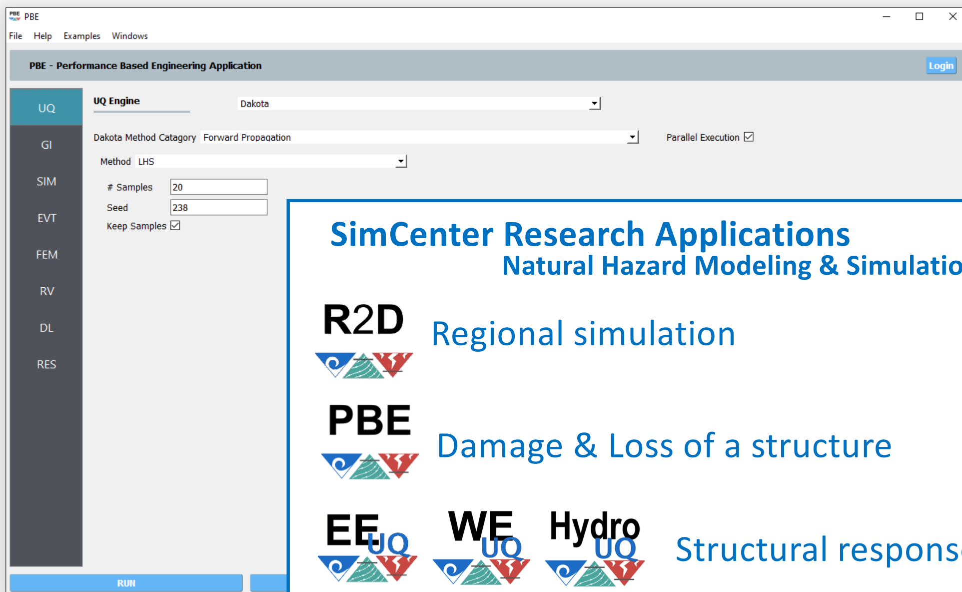


Overview

- SimCenter Objectives & Scientific Workflow Systems
- SimCenter Status
- ML use in SimCenter
- Why UQ
- quoFEM Demo

SimCenter Status

Released a number of open-source **software applications** that researchers in **Natural hazard engineering** are using, modifying and extending



Researchers
Industry
Government Agencies

SimCenter Research Applications
Natural Hazard Modeling & Simulation

- **R2D** — Regional simulation
- **PBE** — Damage & Loss of a structure
- **EE-UQ**, **WE-UQ**, **Hydro-UQ** — Structural response
- **quoFEM** — General UQ analysis

Workflow Application

UNCERTAINTY QUANTIFICATION
MODELING
RESPONSE ANALYSIS

quoFEM (v3.0)

Integrates Simulation Applications (**OpenSees, OpenSeesPy,…)** with UQ Applications

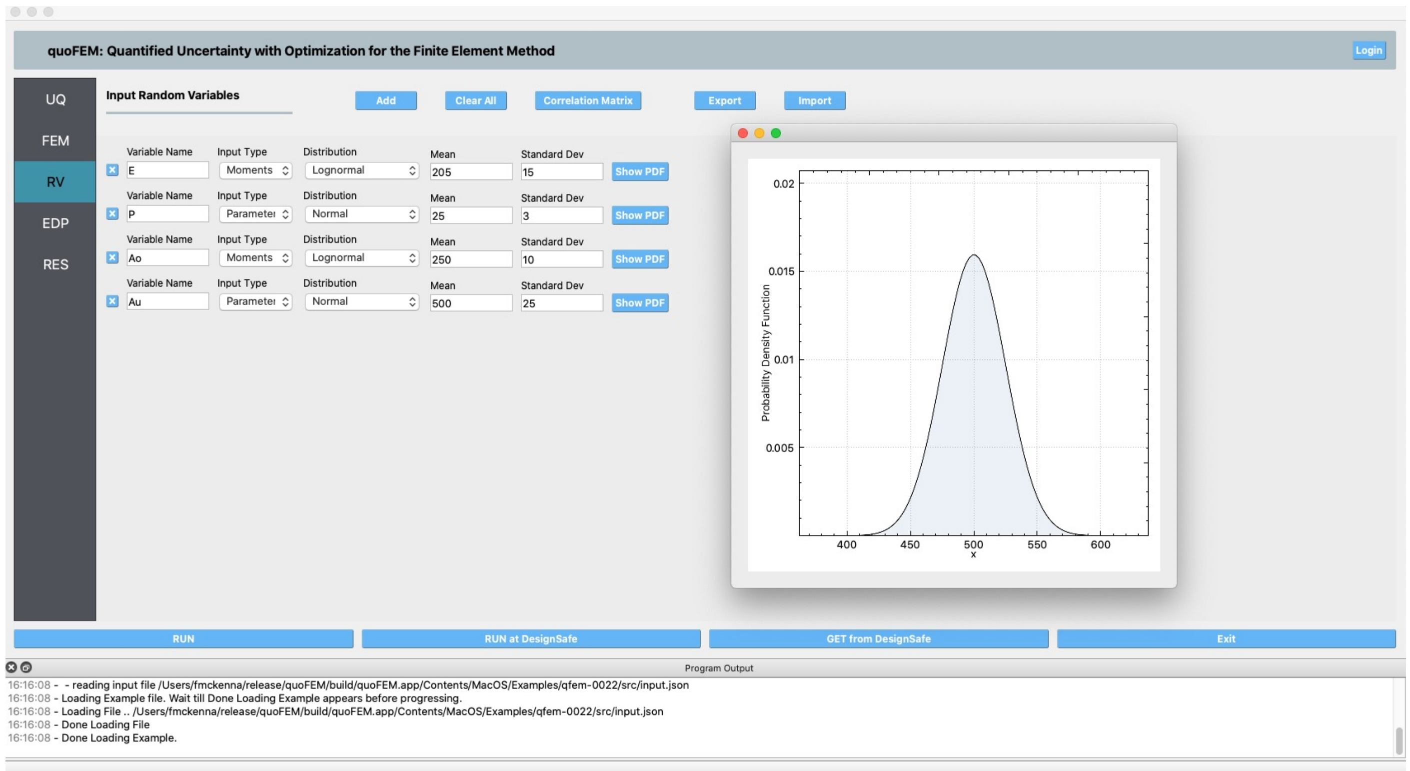
JQ Problem Types:

1. Forward Uncertainty

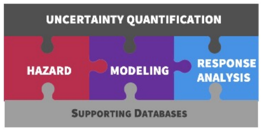
- Sampling
- Sensitivity
- Reliability
- Surrogate Modeling

2. Inverse Uncertainty

- Calibration
- Bayesian Calibration



Workflow Application



EE-UQ V3.0

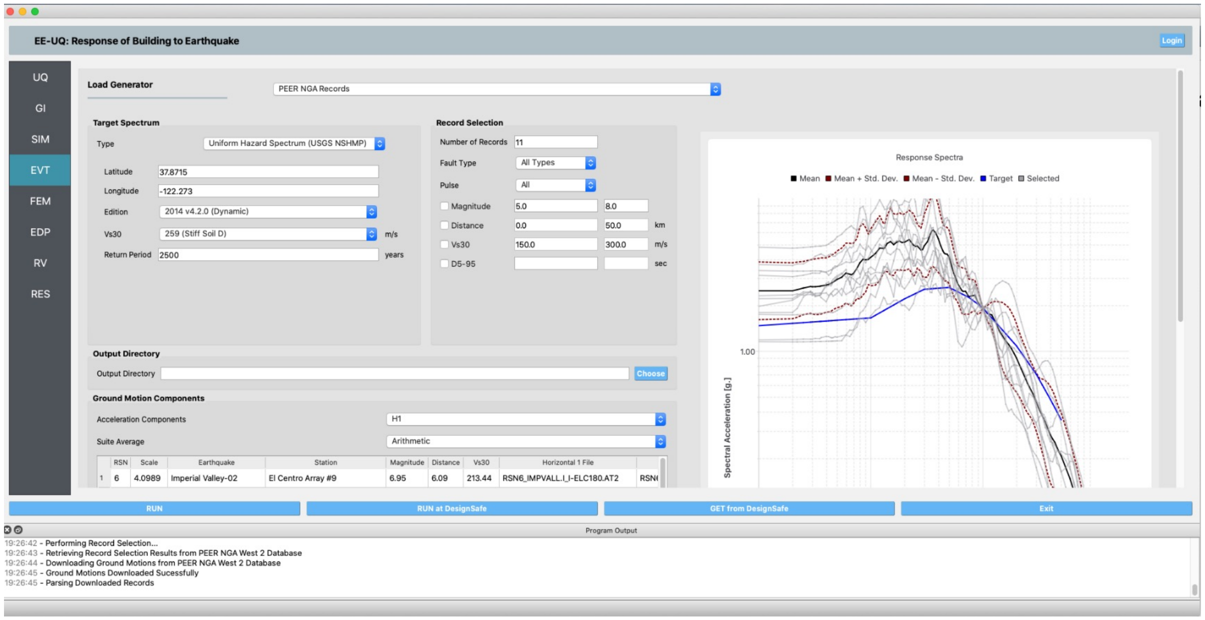
Integrates Forward UQ applications of quoFEM , Earthquake Loading Applications, Building Model Generators with analysis application to determine response of building to earthquake loading

Hazard (Earthquake):

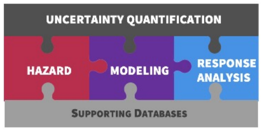
- Stochastic Motions
- PEER NGA Search with target spectrum
- Site Response with Random Fields

Modeling (Building):

- OpenSees
- Nonlinear Shear Spring (MDOF)
- Steel Building Design & Build (AutoSDA)
- Concrete Building Design & Build



Workflow Application



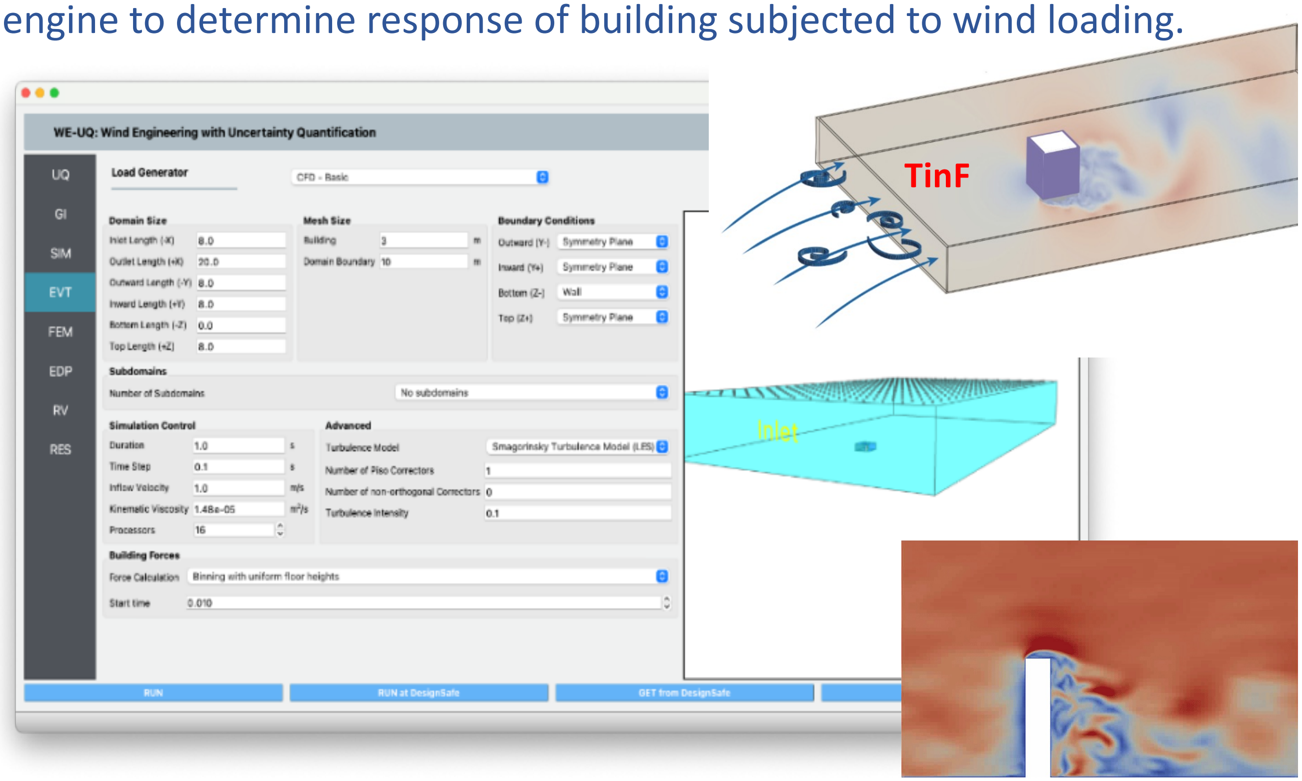
WE-UQ V2.2.0
Integrates quoFEM Forward UQ applications, Wind Loading Applications and Building Model Generators with analysis engine to determine response of building subjected to wind loading.

Hazard (Wind):

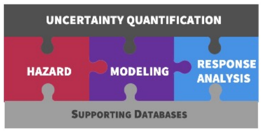
- Stochastic Wind
- Database-enabled utilizing Vortex-Winds
- TPU's low-rise wind tunnel datasets
- User-provided wind tunnel test data
- Uncoupled or **coupled** CFD simulations using OpenFOAM & incorporating TinF options for expert users

Modeling (Building)

- OpenSees
- Nonlinear Shear Spring (MDOF)



Hydro UQ Workflow Application



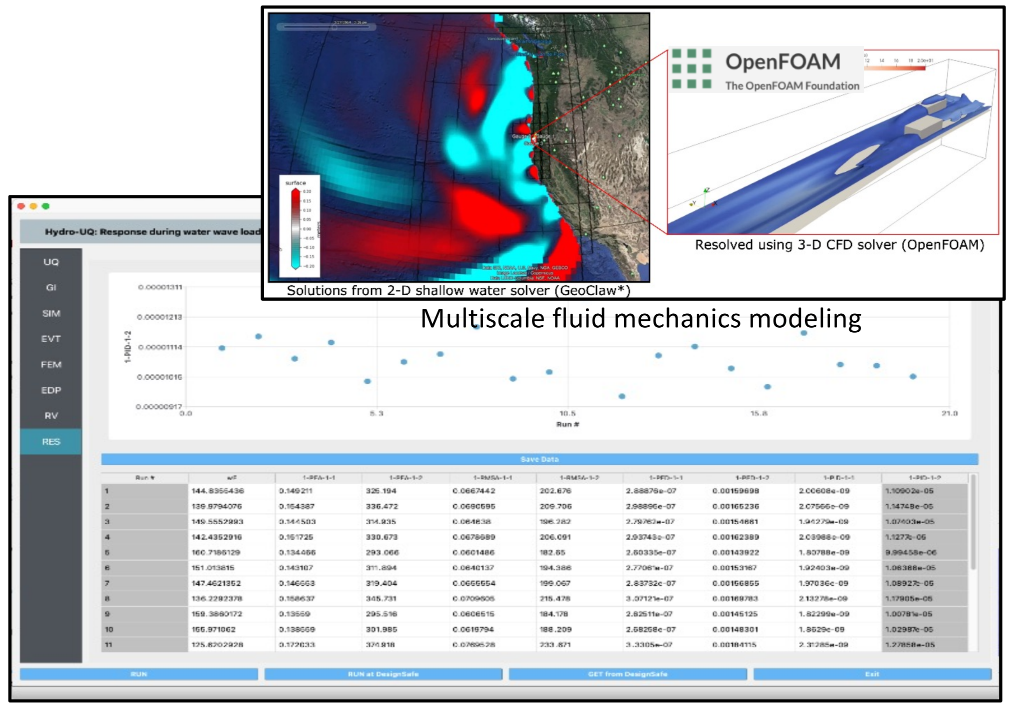
Hydro-UQ V1.0.0 –
Integrates Forward UQ applications, Tsunami & Storm Surge Loading Applications and Building Model Generators with Analysis engine to determine response of structure.

Hazard (Tsunami and storm surge):

- 2D Shallow-water → 3D CFD
- OSU wave flume digital twin
- Easy to use turbulence models for studying broken & unbroken wave behavior

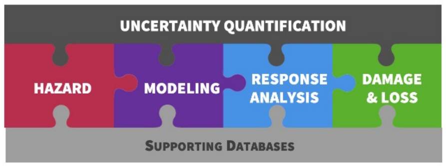
Modeling (Building)

- OpenSees
- Nonlinear Shear Spring (MDOF)



Probabilistic structural response

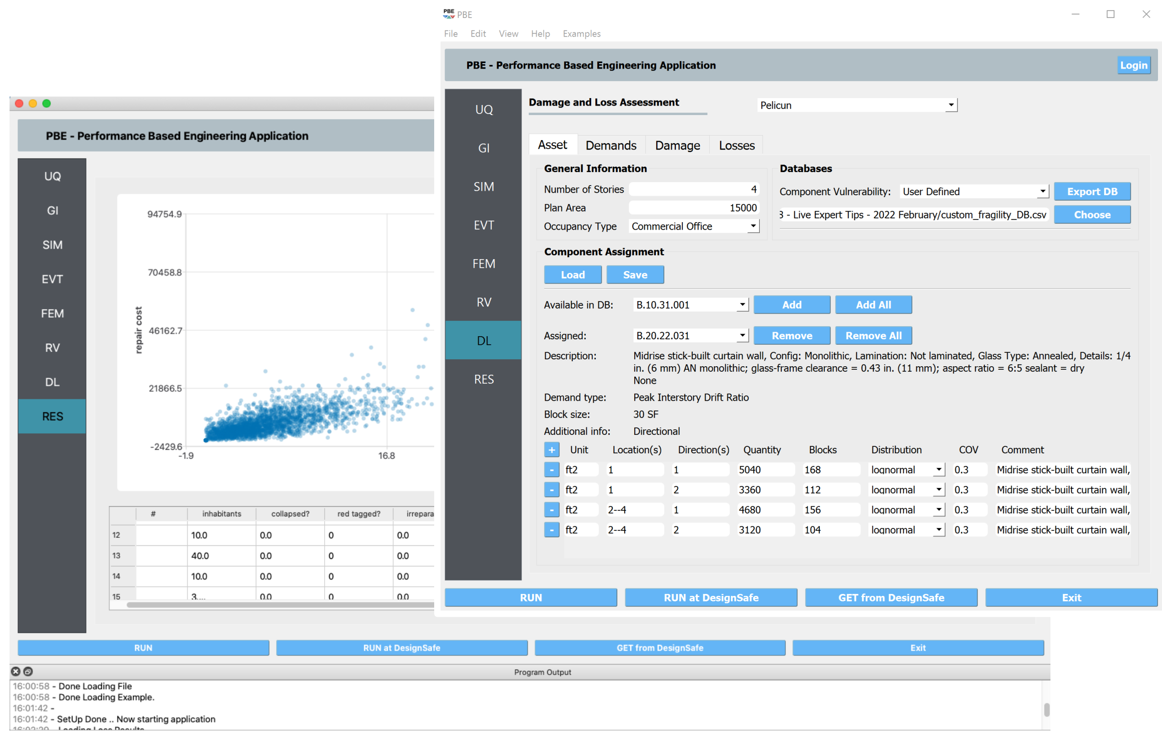
Workflow Application



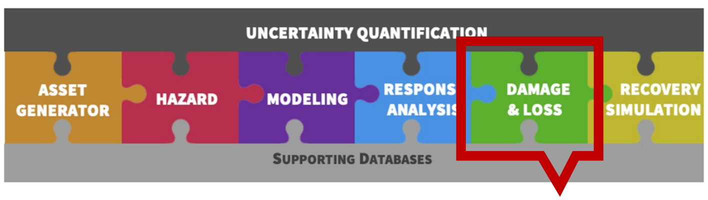
PBE v2.0 (3.0 coming this month!)–
Integrates UQ applications of quoFEM, Building Model Generators, Earthquake Loading, analysis engine and our PELICUN tool for damage and loss assessment.

Damage & Loss (using PELICUN):

- Building-level assessment (e.g., HAZUS)
- Component-level assessment (e.g., FEMA P58)
- Supports external response estimation
- Customizable fragility & consequence functions

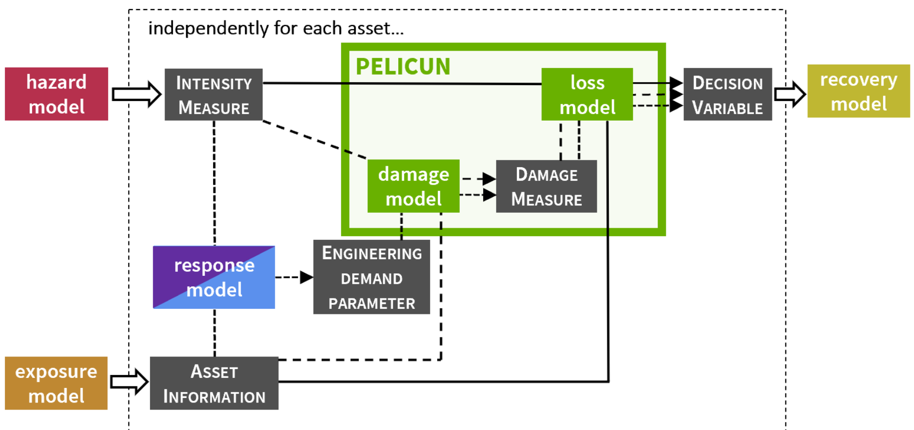


Pelicun: Performance Assessment

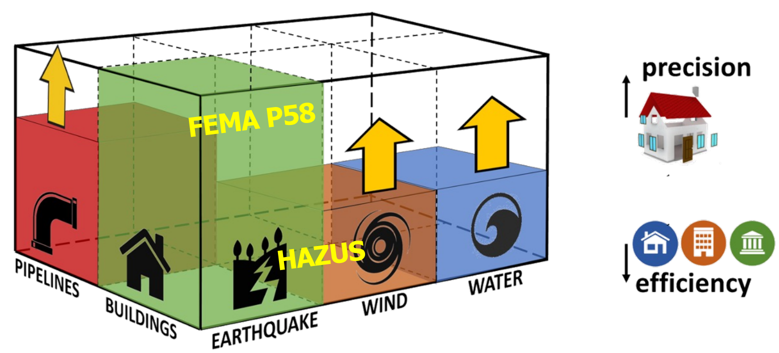


Newest Pelicun features:

- Standardized data schema that unifies performance model data across hazards, assets, and resolutions
- Cascading damages and damage processes
- Customizable damage – consequence mapping
- Portfolio and regional assessment
- Uncertainty in component assignments

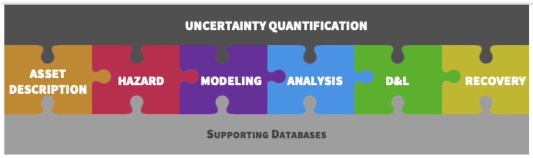


Multi-Fidelity Approach



Community-Driven Development of New Models & Data

R2D Workflow Application



R2D V2.1 –
Create complex workflows for regional hazard simulation to facilitate research in disaster risk management and recovery.

Asset definition

- csv files
- GIS files

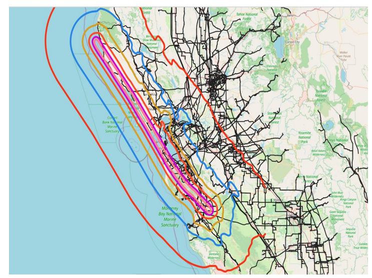
Hazard definition

- Regional Site Response
- User-supplied earthquake and hurricane grids
- Raster-defined earthquake, hurricane, and tsunami intensity fields
- Earthquake scenario simulation
- Hurricane wind field simulation

Damage and loss

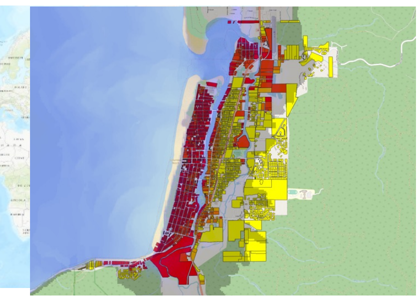
- HAZUS
- User-provided fragility functions

Multiple Hazards



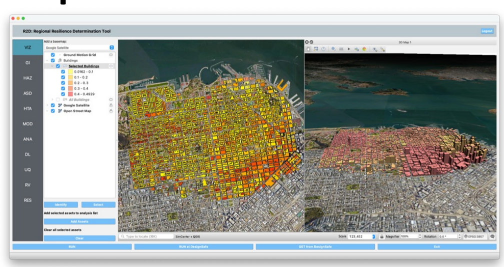
Earthquakes

Hurricanes

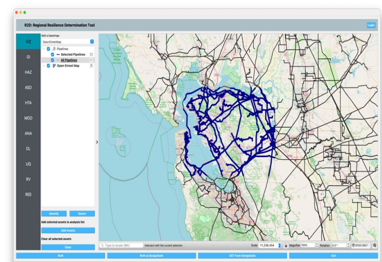


Tsunamis

Multiple Assets



Buildings



Lifelines

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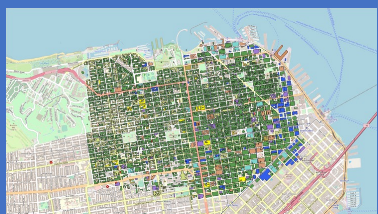
R2D

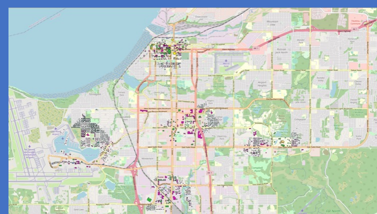
Regional Testbeds & Examples Available

Earthquake

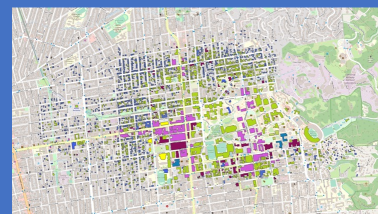
IM PGA



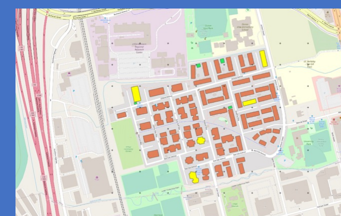
Recorded GMs

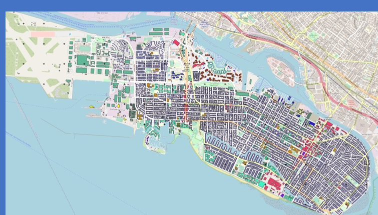


Physics-based GMs

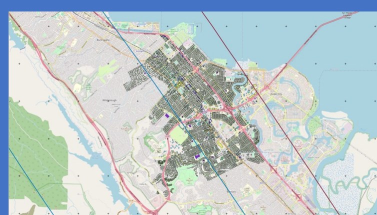


NGAWII GMs

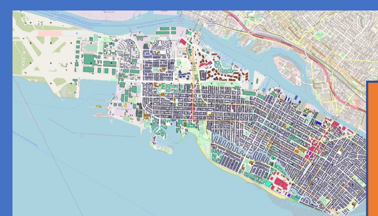




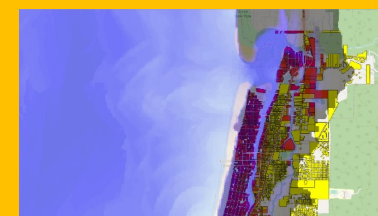
Liquefaction



USGS ShakeMap

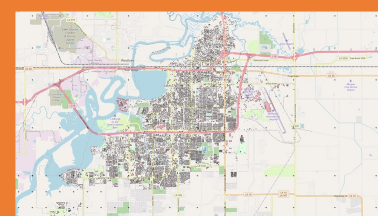


Site-response

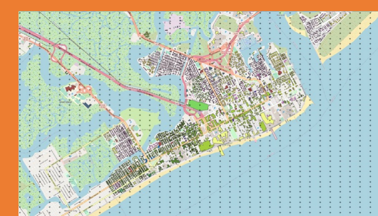


Tsunami

Hurricane:



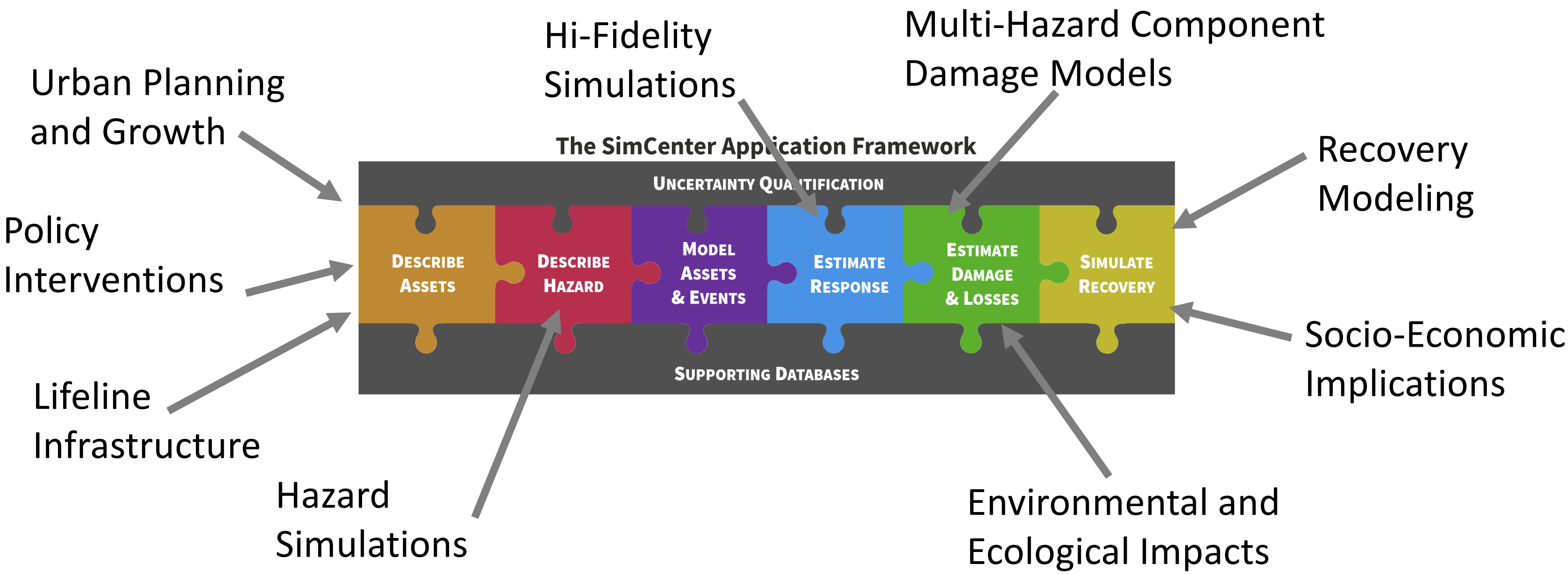
Wind



Wind/Water

Open Framework to Further NHE

Extensible computational workflow to develop and share models and data to simulate natural hazard effects and design communities to be more resilient



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Usage of AI/ML in SimCenter Workflows

1. Inventory Collection

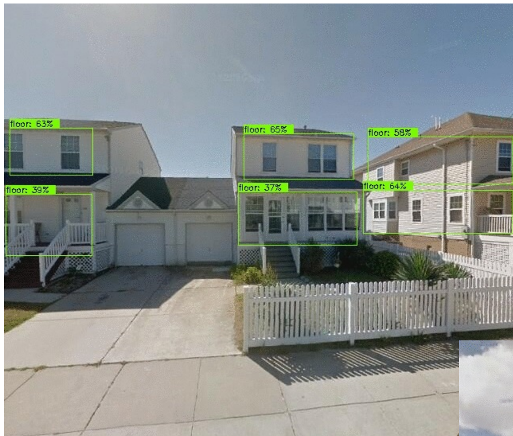
2. Reduction of Simulation Time

1. Inventory Generation

3 Categories of ML Methods Used:

1. Image Classification: to assign to an input image a single label from a fixed set of labels
2. Image Segmentation: to locate (detect) objects and object boundaries in an input image
3. Image Processing: using image segmentation combine object location with mathematics of pinhole cameras to determine information

BRAILS Workflow: Inventory



BRAILS creates regional-scale building inventories at building-level granularity using deep learning and computer vision techniques. BRAILS is capable of predicting:

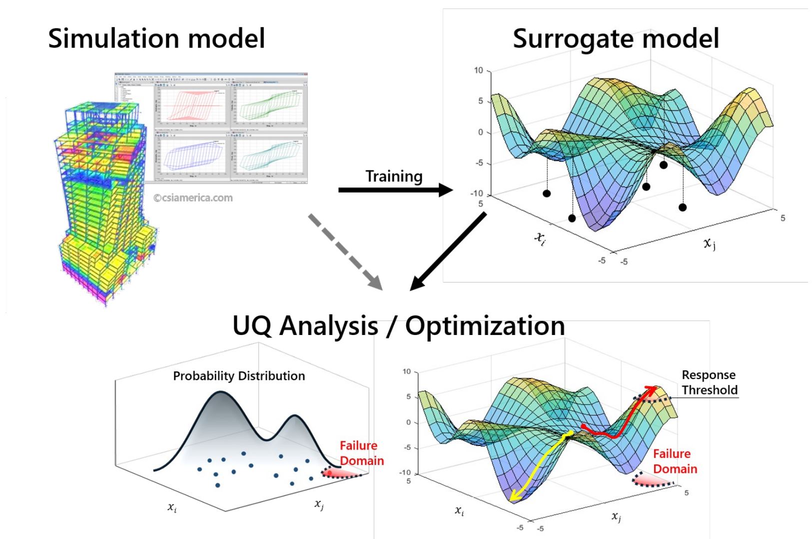
Classification
- Roof shape
- Roof cover type
- Occupancy type
- Era of construction

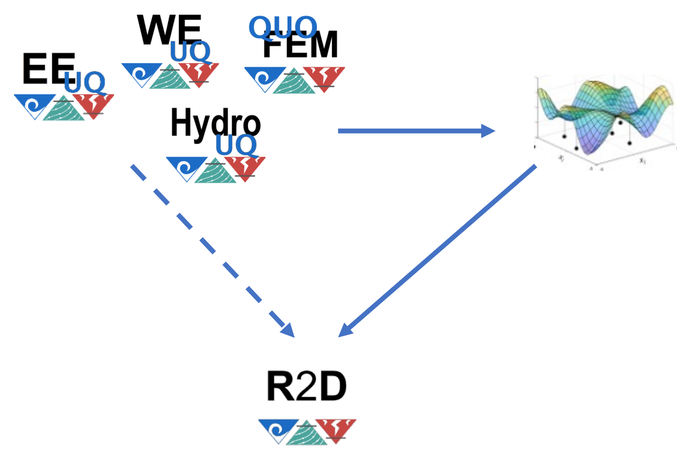
Object Detection
- Number of floors
- Existence of chimneys
- Existence of garages

Image Processing
- Building height
- Roof eave height
- Roof pitch angle
- Window area
- First floor height

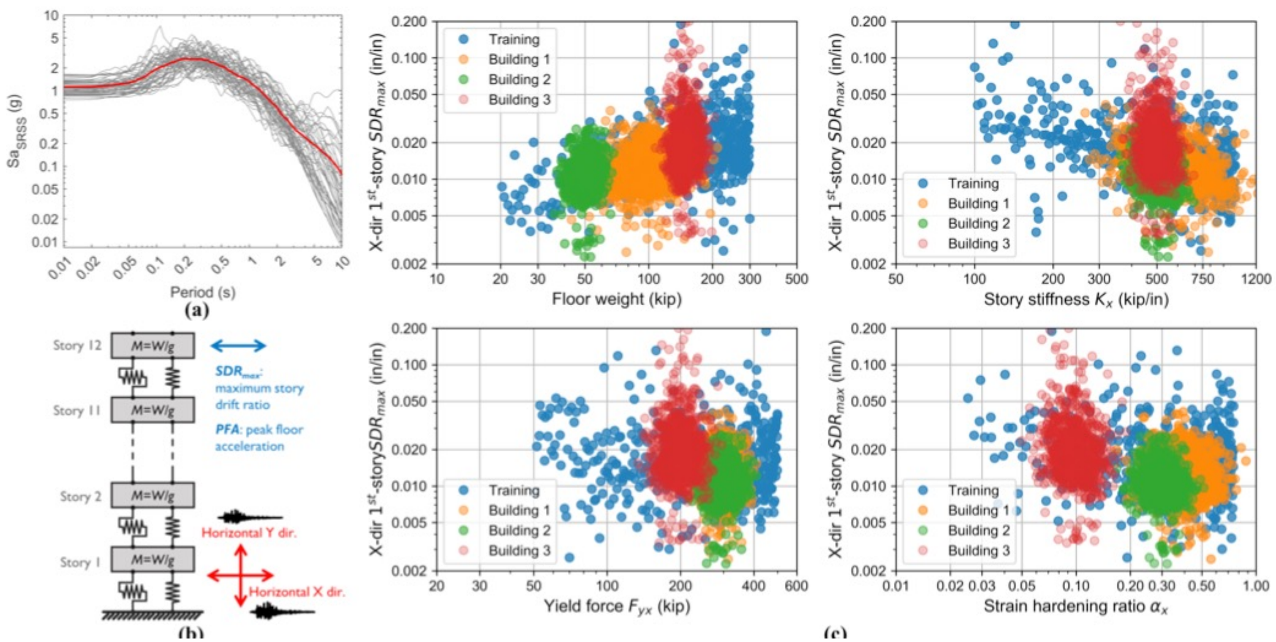
2. Reduction of Simulation Time

Use ML to generate Surrogates to replace Numerical Simulations in Workflow

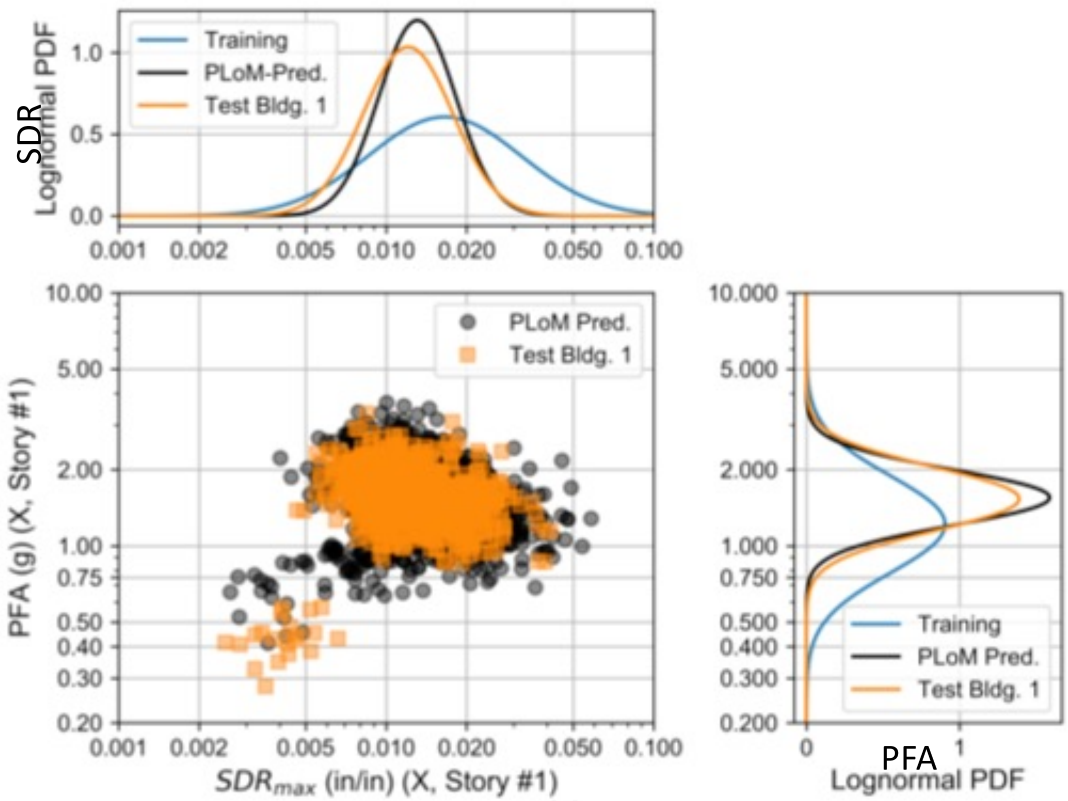


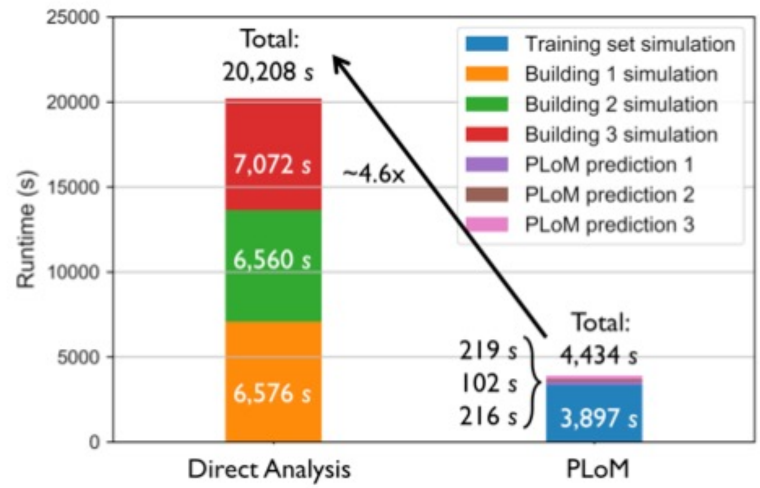


PLoM Example



PLoM Example





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That Quote Again!

"An estimate without uncertainty is **no** estimate at all." (attributed to Sir Harold Jeffreys)

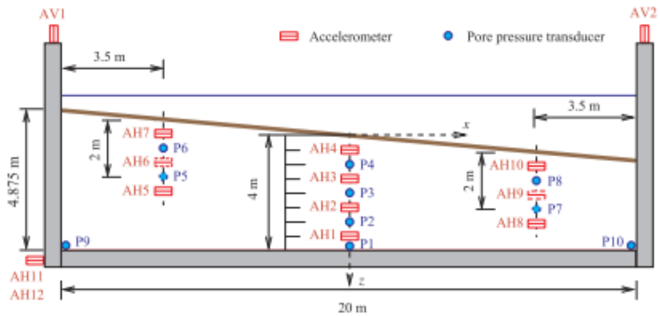
Thoughts from Prof. Graham Powell

PERFORM 3D

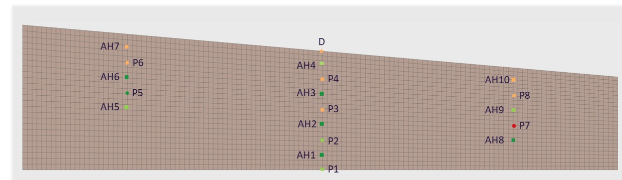
DRAIN2D, DRAIN3D

- *"Exact prediction of behavior is impossible, can't be done"* Performance Based Design, https://www.youtube.com/watch?v=HpnICZuoQdU
- *"While geotechnical Engineers cannot predict within 300% surface motion given a rock motion, structural engineers can predict within 10% the response of the structure given surface motion"* CE221 Nonlinear Structural Analysis Spring 1992.

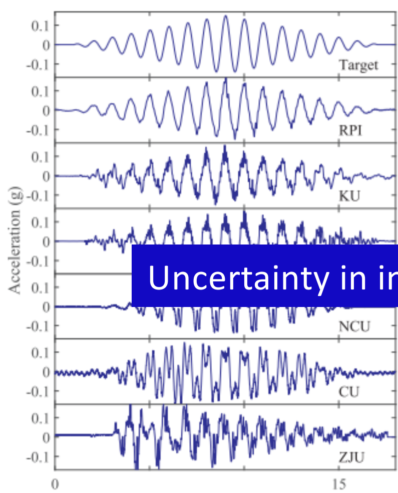
LEAP Projects 2019 ([Liquefaction Experiments and Analysis Projects)](#)



centrifuge



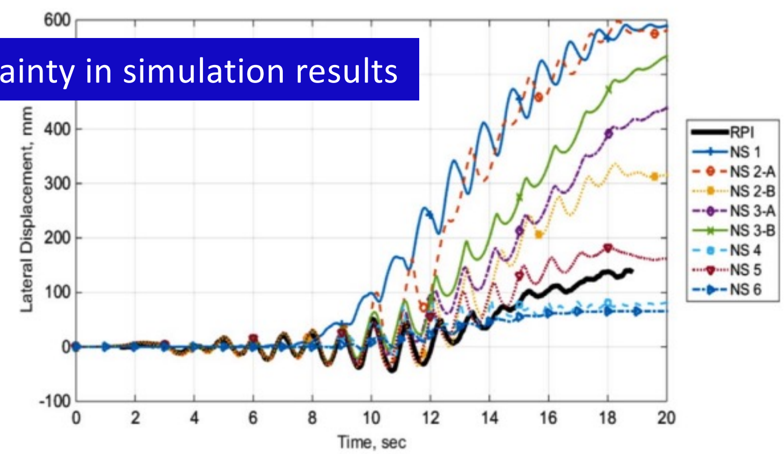
Simulations (OpenSees, PLAXIS, FLAC, Flip)



Uncertainty in input motion

Input acc

Uncertainty in simulation results

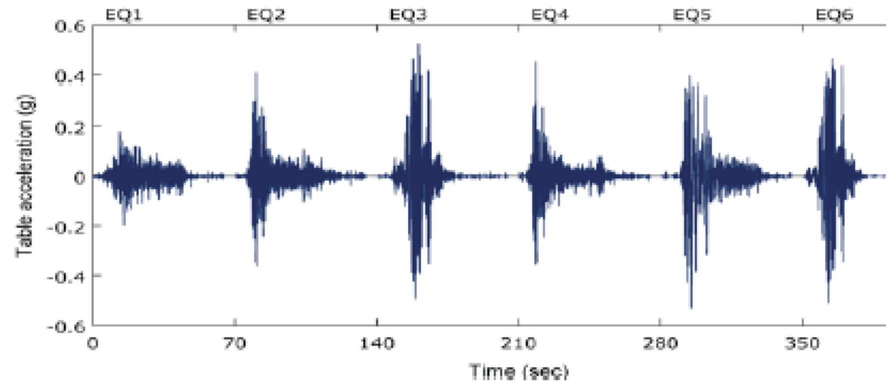


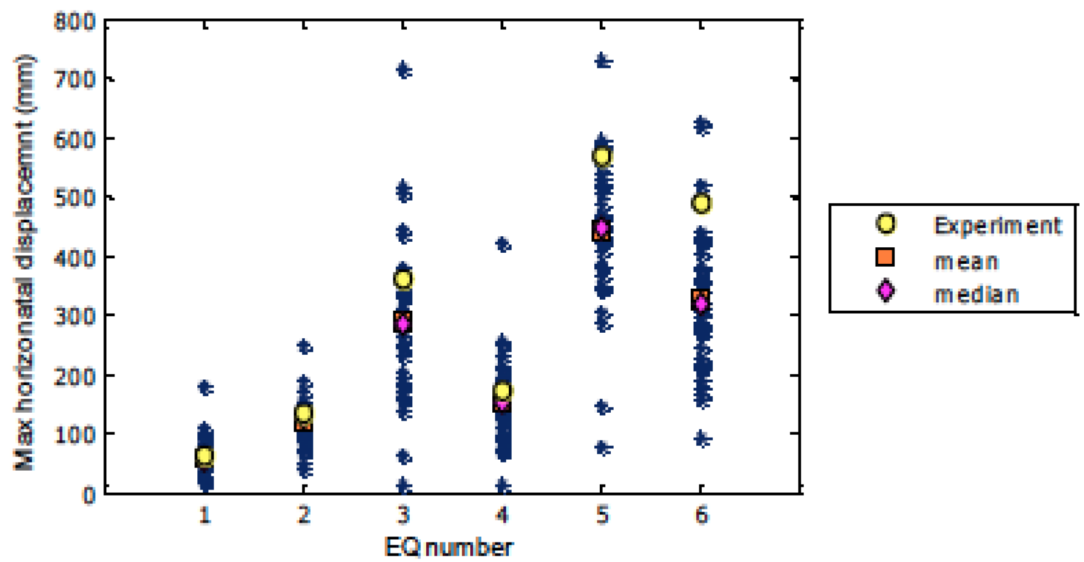
surface lateral deformation

Can Structural Engineers Do Better?

NO!

RC Bridge Column, NEES@UCSD 2010

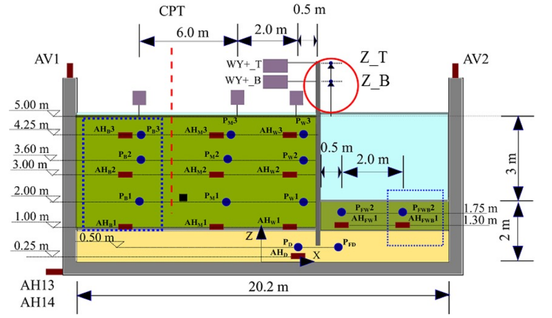




Probably Need Multi Model

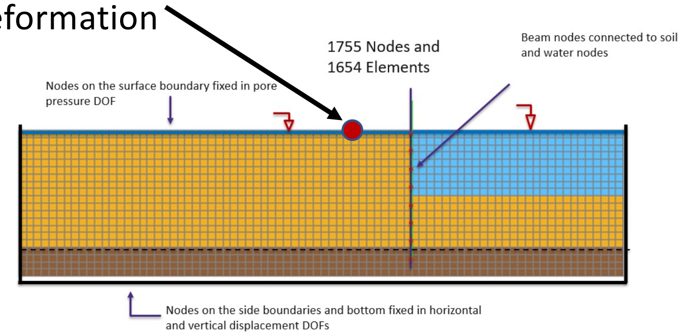
LEAP Projects 2022

Side View

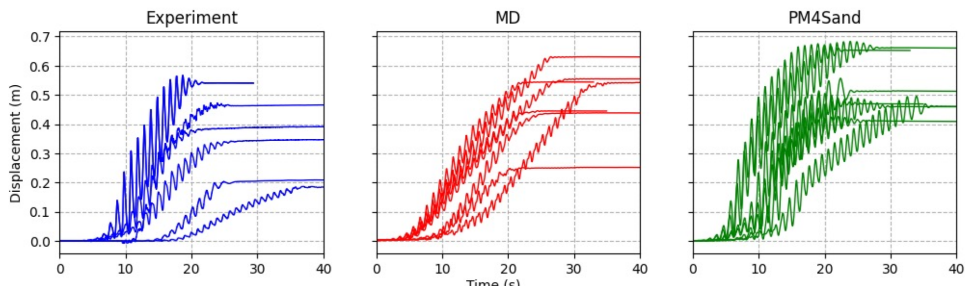


Centrifuge (UCD, RPI, CU, Ehime, KAIST)

Lateral deformation



Simulations (OpenSees, PLAXIS, FLAC, Flip)



Variability in experiments

Variability in simulations

"All models are wrong, but some are useful" – George E. P. Box

Authoritative Expert on the Subject .. ChatGPT!

FM

Should numerical simulations be performed without uncertainty quantification?

No, numerical simulations should not be performed without uncertainty quantification. Uncertainty quantification is the process of estimating the uncertainty in the results of numerical simulations. This is important because numerical simulations are often based on models that include assumptions and approximations, which can lead to errors in the results. By performing uncertainty quantification, one can estimate the range of possible results and determine how sensitive the results are to changes in the input data or model assumptions. This information can help in making decisions and drawing meaningful conclusions from the simulation results.

Good News … SimCenter Tools Produce UQ

YEAH!

BUT!

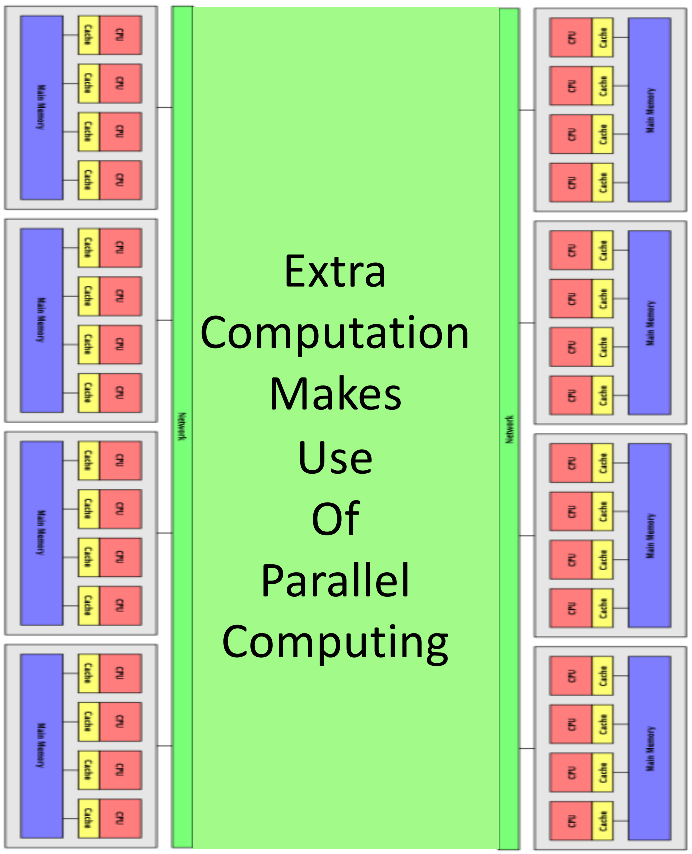
User Has More Work To Do

UQ Requires Extra Input From User

User has to identify certain parameters as being **Random Variables**

User then has to define the **Distribution** associated with these Random Variable

Computer Has More Work To Do



- SimCenter Applications can run these computations in parallel using the cores of your local computer;

- They also allow you to run the simulations through the Cloud on the HPC resources at TACC provided through DesignSafe-ci.

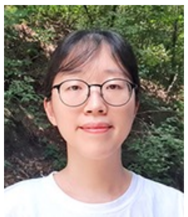
A Geotechnical Example of How to Apply OpenSees correctly!

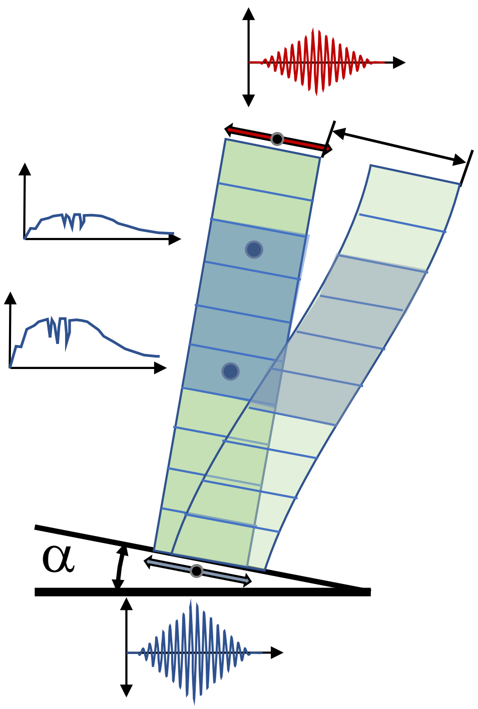
Using

QUOFEM

The PROBLEM:
Soil Liquefaction: Lateral Spreading

Sang-ri Yi, Aakash Bangalore Satish, Pedro Arduino





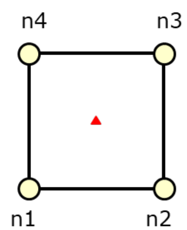
OpenSees

- OpenSees Model
  - Element: SSPQuad-UP
  - Const. Model: PM4Sand v3
    D_r, G_o, h_{p0}

Any Data?

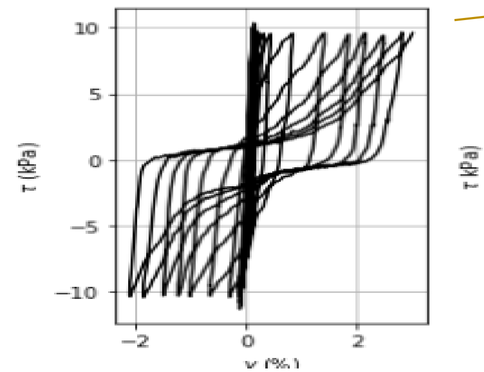
Soil Liquefaction: Experiments and Simulation

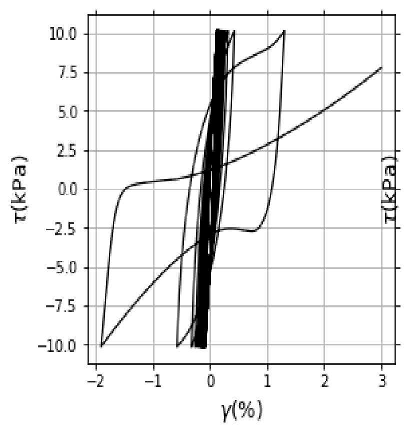
Sang-ri Yi, Aakash Bangalore Satish, Pedro Arduino

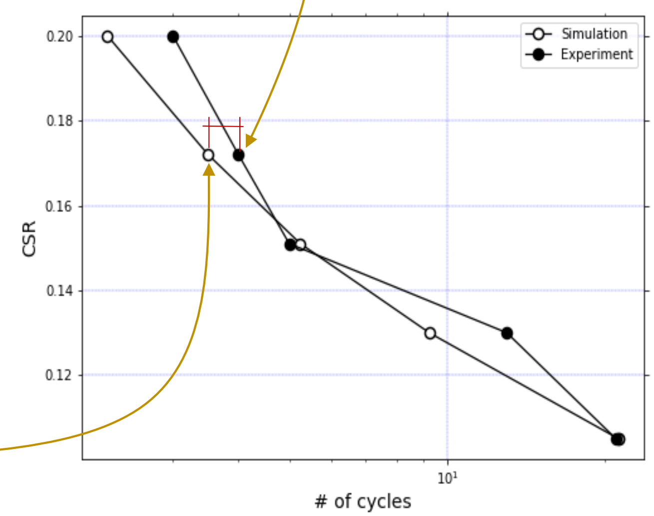


SSPquad (4 node)

OpenSees



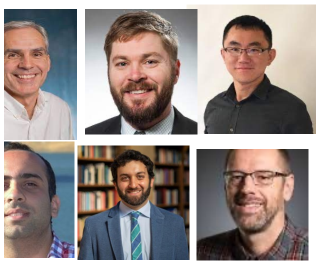




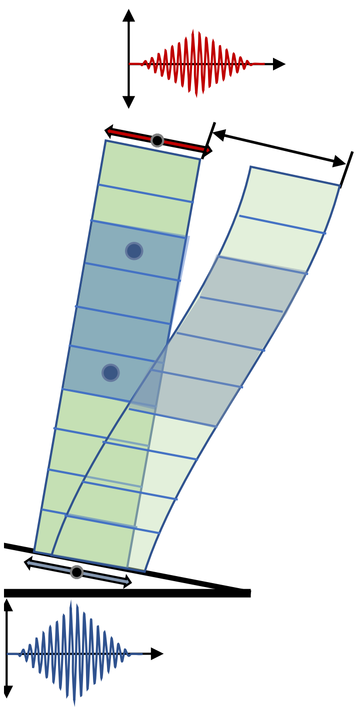
PM4Sand main parameter

Dr, G0, hpo

ep 1:Build a Model (Multiple Models if Possible)



Pedro,
Chris,
Long,
Alborz,
Andrew,
& Peter



ıSees Model

```
# Material parameters
pset Dr 0.61
pset G0 255
pset hpo 0.14
set grade 3.0
set layerT 3.0
# ---SOIL GEOMETRY
set numLayers       3
set layerThick(3)  2.0
set layerThick(2)  $layerT
set layerThick(1)  1.0
set waterTable     2.0
# mesh geometry
set nElemX  1
set nNodeX  [expr $nElemX + 1]
set sElemX  0.25
set nElemY(3)  8
set nElemY(2)  [expr int($layerT
set nElemY(1)  4
# define grade of slope (%)
set g -9.81
# material param
set N160 10.0
set Cd   46.0
set Gs 2.67
set emax 0.8
set emin 0.5
set void [expr $emax - $Dr * ($e
set por [expr $void / (1 + $void
set rho_d [expr $Gs / (1 + $void
set rho_s [expr $rho_d *(1.0+$vo
set K0 0.5
set nu [expr $K0 / (1 + $K0)]
# define properties of the under
set rockVS        182.0
set rockDen       $rho_s

# calculate the thickness of soi
set soilThick 0.0
for {set i 1} {$i <= $numLayers}
      set soilThick [expr $soi
}
# total number of elements in ve
set nElemT      0
set layerBound(1) 0
for {set i 1} {$i <= $numLayers}
    incr nElemT    [expr $nElem
    set  sElemY($i) [expr $layer
    set  layerBound([expr $i+1])
}
set layerBound(1) 1
# number of nodes in vertical di
set nNodeT 0
for {set k 1} {$k < $numLayers}
```

```
model BasicBuilder -ndm 2 -ndf 3

set yCoord  0.0
set count   0
set gwt     1
set waterHeight [expr $soilThick-$waterTable]
set nodesInfo [open nodesInfo.dat w]
# loop over layers
for {set k 1} {$k <= $numLayers} {incr k 1} {
        # loop over nodes
        for {set j 1} {$j <= $nNodeL($k)} {incr j $nNodeX} {
                for {set i 1} {$i <= $nNodeX} {incr i} {
                        node  [expr $j+$count+$i-1]    [expr ($i-1)*$sElemX]     $yCoord
                        # designate nodes above water table
                        if {$yCoord>=$waterHeight} {
                                set dryNode($gwt) [expr $j+$count+$i-1]
                                set gwt [expr $gwt+1]
                        }
                }

                set yCoord  [expr $yCoord + $sElemY($k)]
        }
        set count  [expr $count + $nNodeL($k)]
}
# define fixities for pore pressure nodes at base of soil column
for {set i 1} {$i <= $nNodeX} {incr i} {
        fix $i  0 1 0
        # puts "fix $i  0 1 0"
        if {$i > 1} {
                equalDOF 1 $i 1
        }
}
# define equal degrees of freedom for pore pre
for {set j [expr $nNodeX + 1]} {$j < $nNodeT}
        for {set i $j} {$i < [expr $j + $nNode
                equalDOF $j [expr $i+1] 1 2
        }
}
# define pore pressure boundaries for nodes ab
for {set i 1} {$i < $gwt} {incr i 1} {
     fix $dryNode($i)  0 0 1
}
set slope [expr atan($grade/100.0)]
nDMaterial PM4Sand 3 $Dr $G0 $hpo $rho_d 101.3
nDMaterial PM4Sand 2 $Dr $G0 $hpo $rho_s 101.3
nDMaterial ElasticIsotropic 1 $E 0.3 $rho_s
set elemInfo [open elementInfo.dat w]
set count 0
for {set i 1} {$i <= $numLayers} {incr i 1} {
        for {set j 1} {$j <= $nElemY($i)} {inc
```

```
#------------------------------------------------------------------------------------------
#  6. LYSMER DASHPOT
#------------------------------------------------------------------------------------------
model BasicBuilder -ndm 2 -ndf 2

# define dashpot nodes
set dashF [expr $nNodeT+1]
set dashS [expr $nNodeT+2]

node $dashF  0.0 0.0
node $dashS  0.0 0.0

# define fixities for dashpot nodes
fix $dashF  1 1
fix $dashS  0 1

# define equal DOF for dashpot and base soil node
equalDOF 1 $dashS  1
puts "Finished creating dashpot nodes and boundary conditions..."

# define dashpot material
set colArea       [expr $sElemX*$thick(1)]
set dashpotCoeff  [expr $rockVS*$rockDen]
```

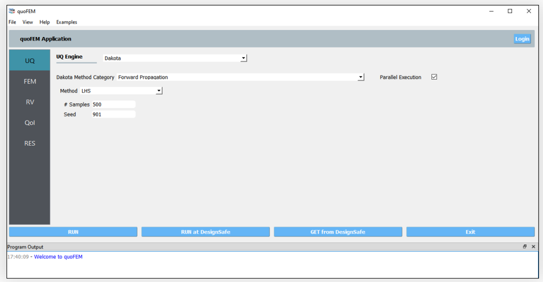
Step 2: Sensitivity Study

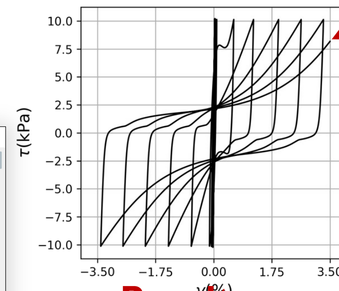
Sang-ri Yi, Aakash Bangalore Satish, Pedro Arduino

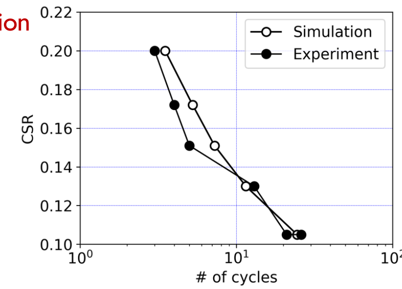
- Identify influential and redundant input parameters
- Inputs: PM4Sand material model parameters (Dr, Go, hpo)
- Outputs: Number of cycles to onset of liquefaction at given CSR values, parameters of power law model fit to cyclic strength curve

1. Global Sensitivity Analysis

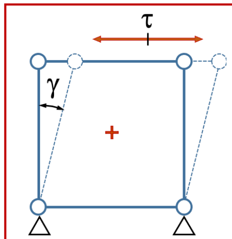
Dr, G0, hpo







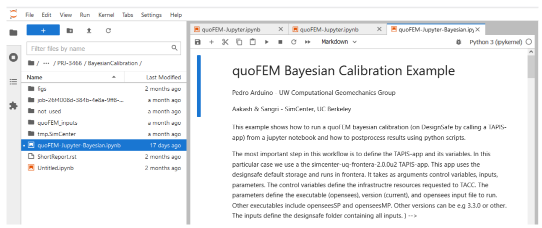
Computational model



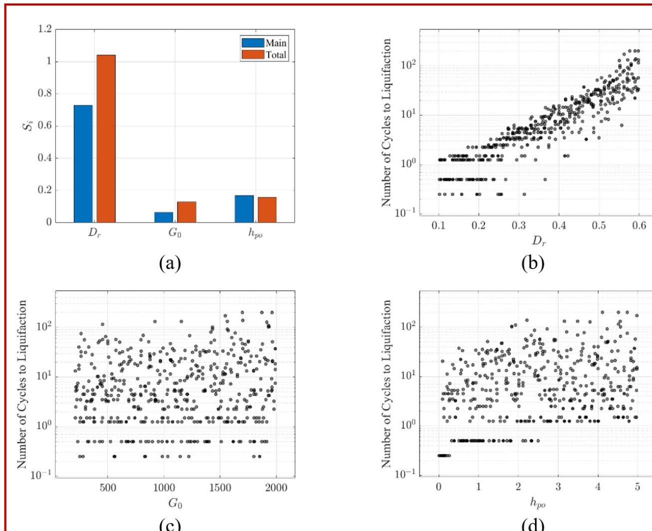
OpenSees

PM4Sand

Single element simulation



Results



Main effect and Total effect Sobol Indices

(a) Sensitivity analysis results for the critical number of cycles given CSR= 0.172; (b)-(d) Individual input-output scatter plots

Global Sensitivity Analysis with quoFEM: https://youtu.be/JC8xN5LAo84

Boulanger RW, Ziotopoulou K (2017) PM4Sand (Version 3.1): "A sand plasticity model for earthquake engineering applications", Dept. of Civil and Env. Eng., Univ. of California, Davis, Davis, CA, Rep. UCD/CGM-17/01

Chen L, Arduino P (2021) "Implementation, verification, and validation of the PM4Sand model in OpenSees", Pacific Earthquake Engineering Research (PEER) Center, University of California, Berkeley, Berkeley, USA, Rep. 2021/02

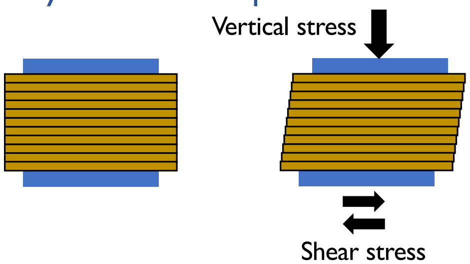
Nair AS *et al.* (2021) "Research Experience for Undergraduates (REU), NHERI 2021: Uncertainty Analysis of Seismic Soil Liquefaction using quoFEM." DesignSafe-CI. [link]

Step 3: Bayesian Calibration

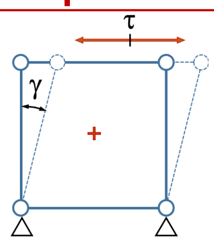
Sang-ri Yi, Aakash Bangalore Satish, Pedro Arduino

Experimental data

Cyclic direct simple shear test



Computational model

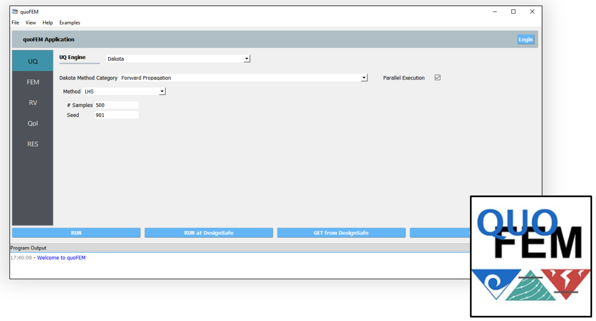


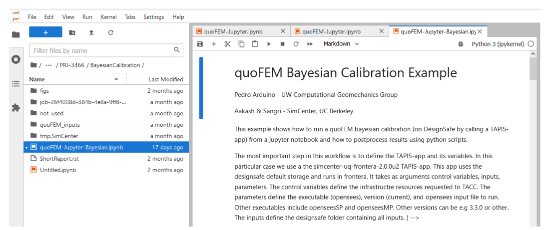
OpenSees

PM4Sand

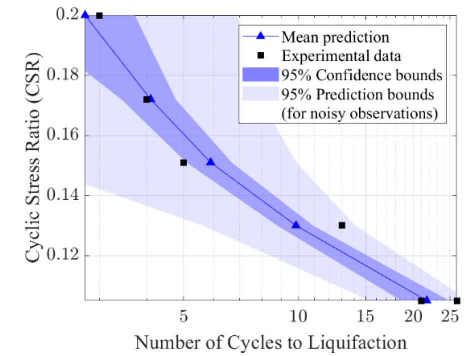
Single element simulation

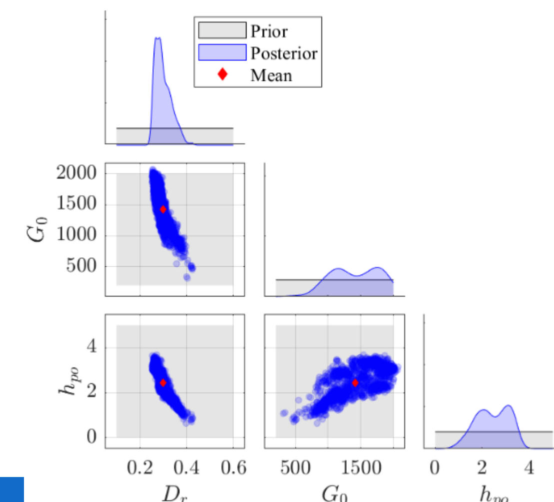
2. Bayesian Parameter Calibration





Results





Bayesian Calibration with quoFEM: https://youtu.be/hLBB6nGld2M

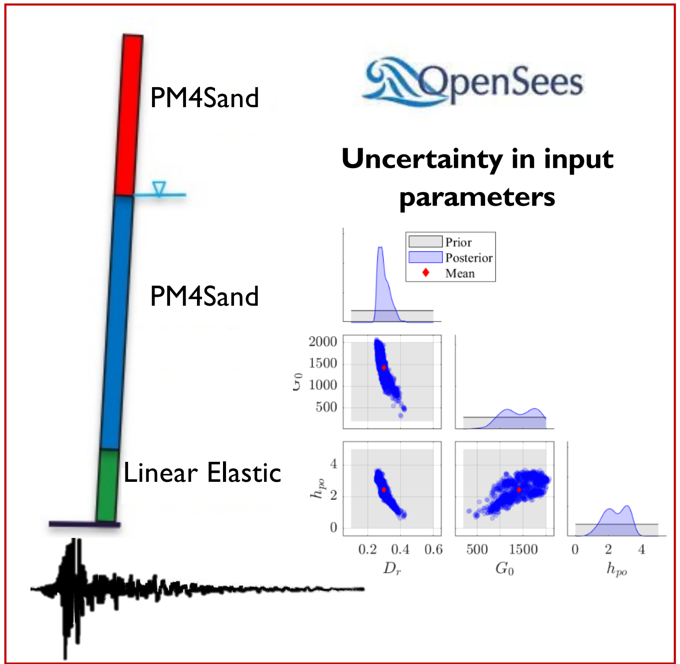
Morales B et al. (2021) "Data from: Cyclic Direct Simple Shear Testing of Ottawa F50 and F65 Sands." Distributed by DesignSafe-CI Data Depot. doi: 10.17603/ds2-eahz-9466

Ziotopoulou K et al. (2018) "Cyclic Strength of Ottawa F-65 sand: laboratory testing and constitutive model calibration." *Geotechnical Earthquake Engineering and Soil Dynamics*, vol 293, pp. 180-189

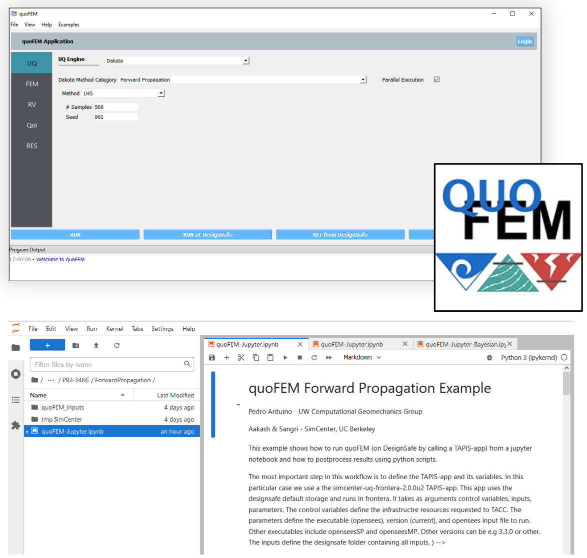
Step 4: Forward Propagation

Sang-ri Yi, Aakash Bangalore Satish, Pedro Arduino

Computational model

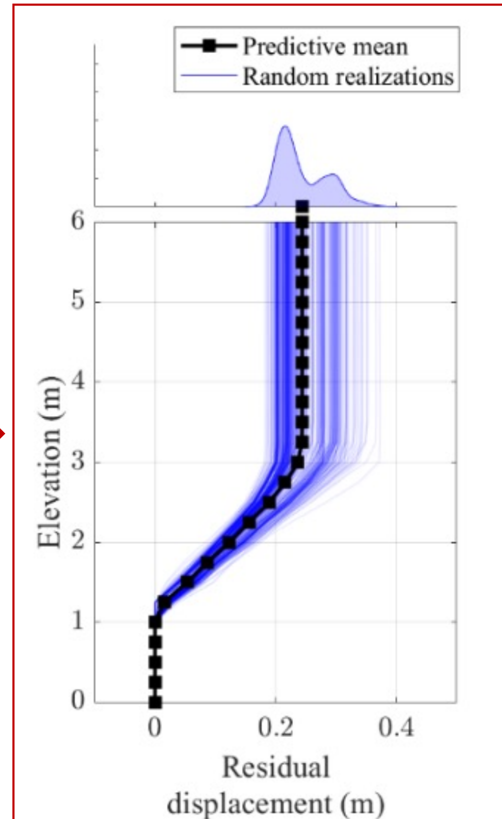


3. Forward Uncertainty Propagation



Uncertainty in response

Results



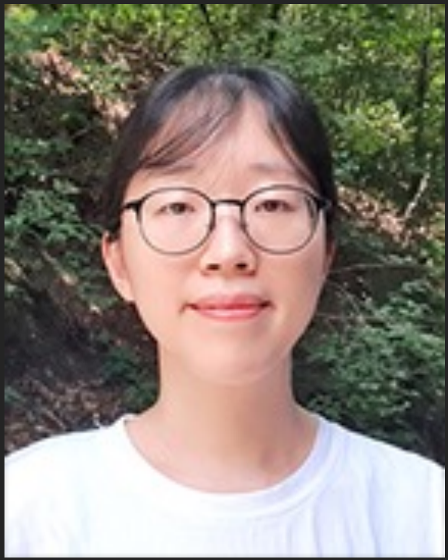
Nair AS *et al.* (2021) "Research Experience for Undergraduates (REU), NHERI 2021: Uncertainty Analysis of Seismic Soil Liquefaction using quoFEM." DesignSafe-CI. [link]

Demo Using

QUO FEM

EXTRA SLIDES ON UQ

What follows are Extra slides from Aakash and Sang-ri.



Types of UQ

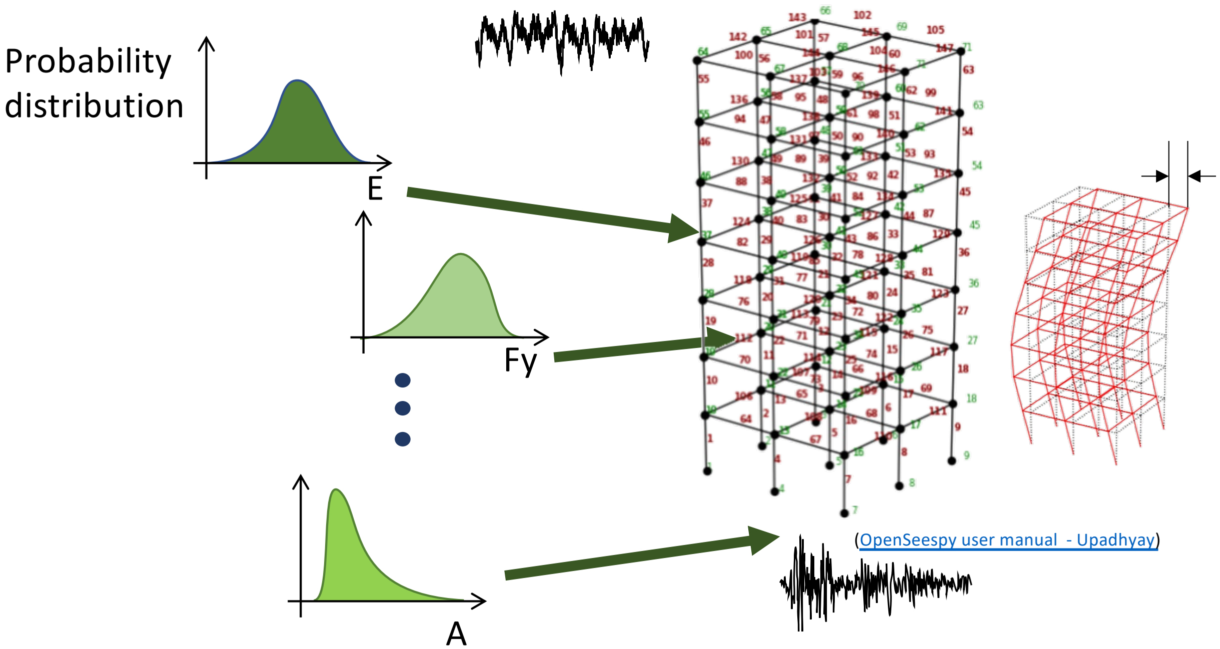
Forward Uncertainty Quantification

Inverse Uncertainty Quantification

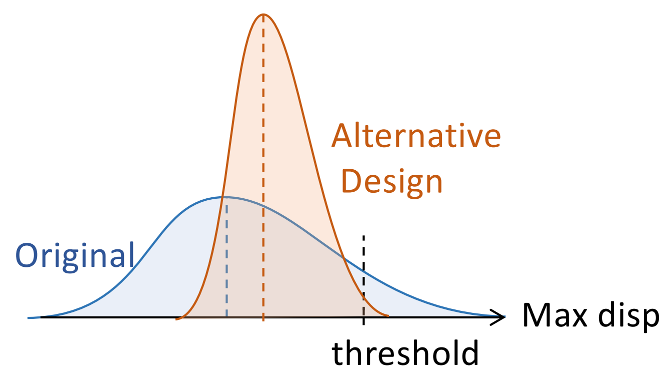
Forward UQ

- Propagation of uncertainty from inputs to outputs

Simulation Model



(OpenSeespy user manual - Upadhyay)

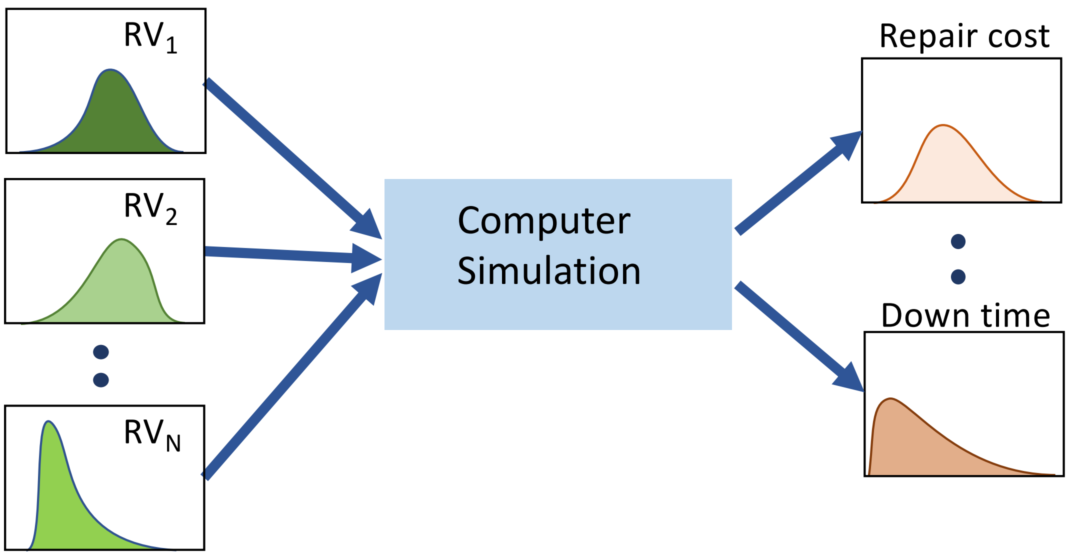


Which design would you select?

→ Uncertainty quantification is essential in making decisions

Forward UQ

- Based on assumptions on inputs, predict the uncertainty in outputs



Mean expected down time
Standard deviation of repair cost

Forward sampling

Probability of significant damage

Reliability analysis

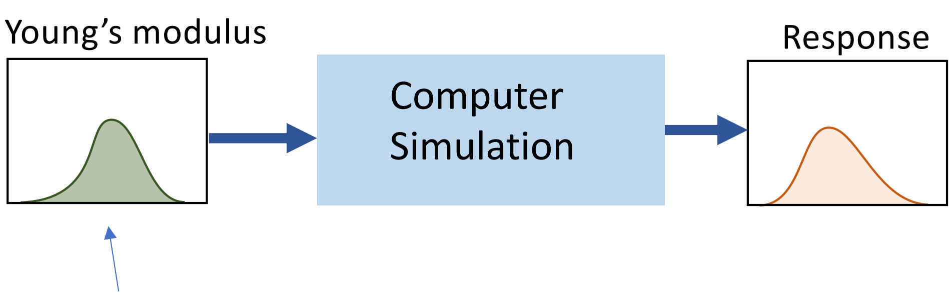
Importance of each parameter

…

Global sensitivity analysis

Forward UQ

- Let us first consider single RV / Response



How do we get the input distribution?

Mean expected down time
Standard deviation of repair cost

Forward sampling

Probability of significant damage

Reliability analysis

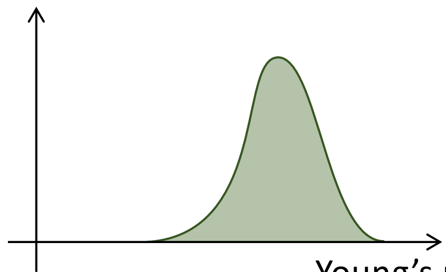
Importance of each parameter

…

Global sensitivity analysis

Probability distribution of RV

- Everything is **possible** but not everything is **probable**



Engineering Judgement + Observation

- Based on underlying physics of quantity
- Select a simple distribution and apply reasonable limits

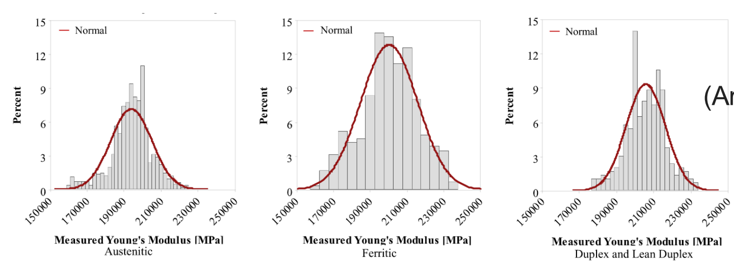
- Bayesian updating
  →inverse UQ

Examples

Known range of interest - Uniform distribution

Assumption - Gaussian with 10% variation

From reference

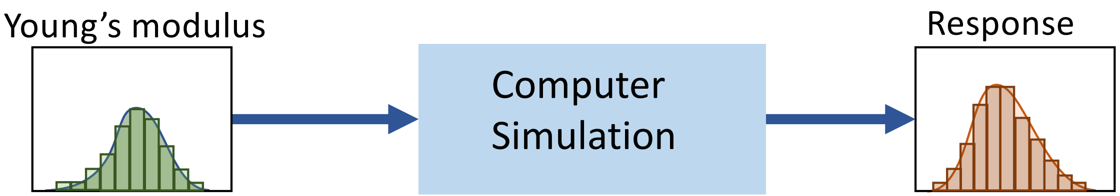


(Arrayago et al. 2020)

NHERI SimCenter
Center for Computational Modeling & Simulation

Forward Propagation

- Based on assumptions on inputs, predict the uncertainty in outputs

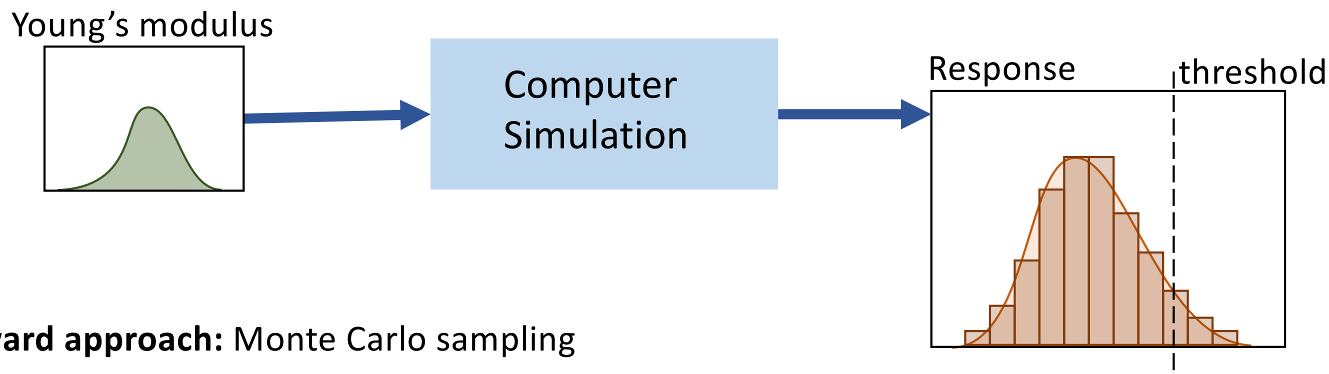


Mean
Standard deviation
Probability distribution

- **A straightforward approach** Monte Carlo sampling
- **Is the model numerically expensive?** Few simulations as much as possible
  - **- Better UQ algorithms**
    e.g. Latin hyper cube sampling
  - **- Approximation methods**
    e.g. Surrogate modeling
  - **- Combination of both**
    e.g. Multi-fidelity modeling

Reliability Analysis

- Probability of the response exceeding a threshold level
- Important for design decision



- **A straightforward approach:** Monte Carlo sampling
- **When the model is expensive & when failure probability is low**
  It is desirable to reduce the number of simulations

  P_f = 10% requires 1000 simulations
  P_f = 0.001% requires 1000000 simulations

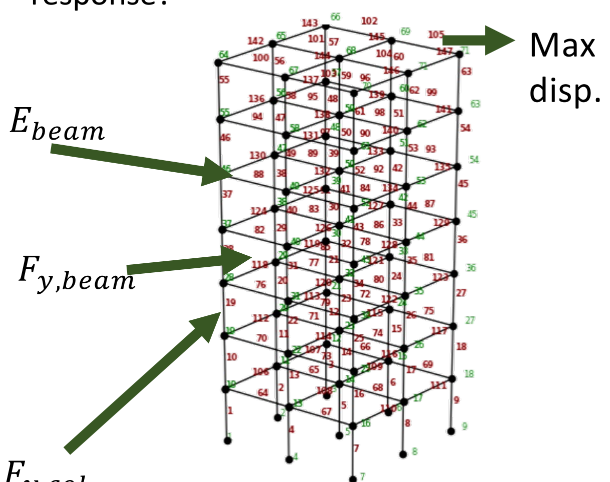
$$c.o.v = \sqrt{\frac{NP_f}{1-P_f}} < 0.1$$

To reduce the number of simulations

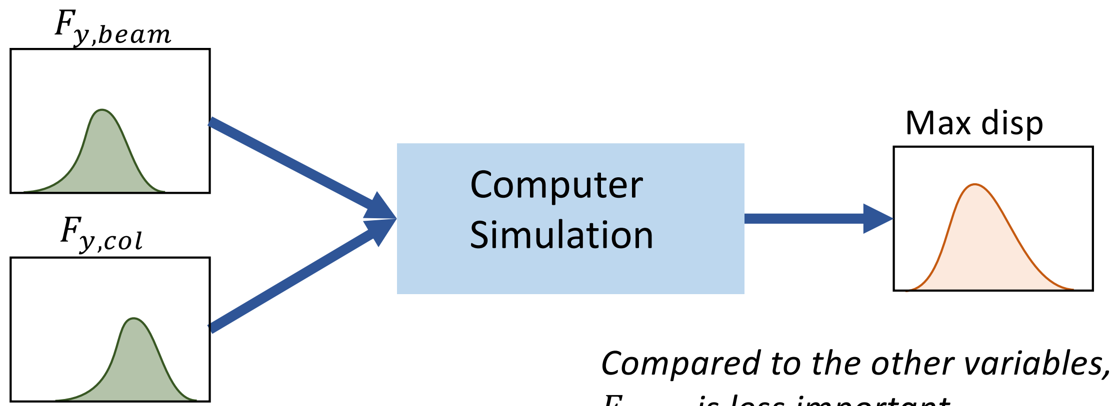
- **Better UQ algorithms**
  Importance sampling, subset simulation
- **Approximation methods**
  Surrogate modeling, First-order approximations
- **Combination of both**

Global Sensitivity Analysis

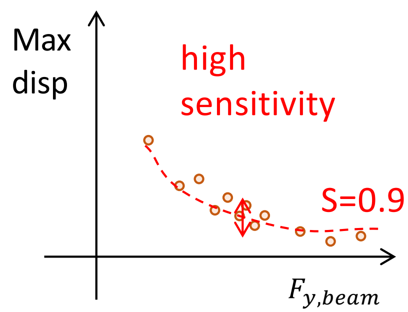
Are all the parameters equally impacting the response?

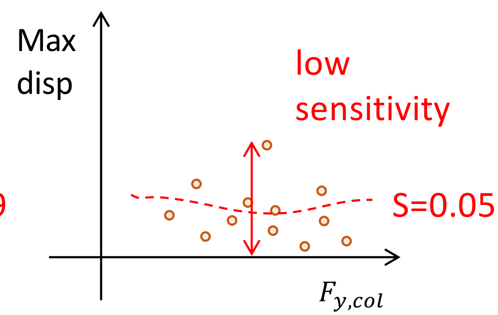


Probably not.
Then what are the variables that are **actually** influential?



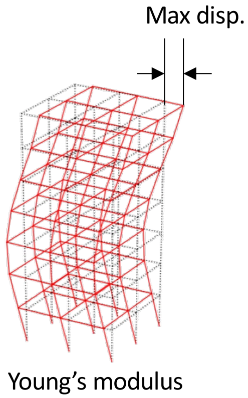
Compared to the other variables,
$F_{y,col}$ *is less important.*
→ *You might want to let* $F_{y,col}$ *be deterministic*



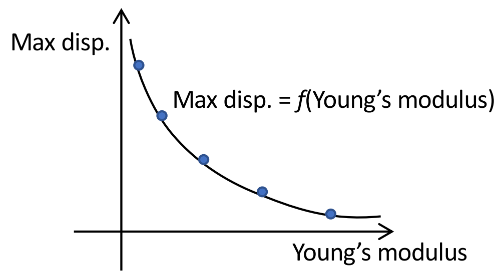


Surrogate modeling

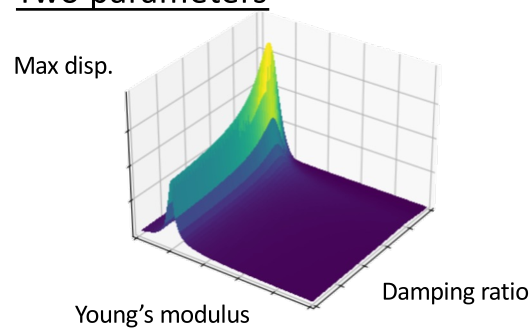
- Response surface representation



One parameter



Two parameters



- Usually the curve (surface) is very flexible & general
  Neural networks, Gaussian process model, polynomial chaos…

- **Design of experiments** are used to reduce the number of simulations

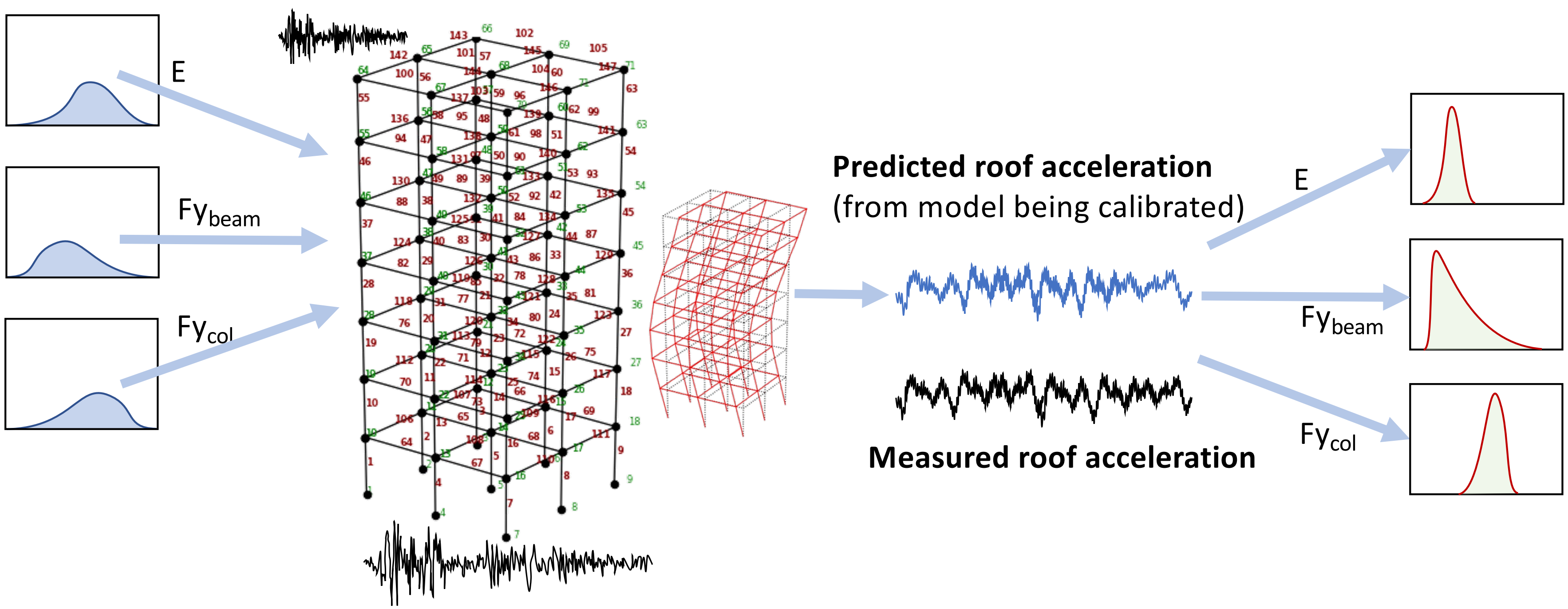
Types of UQ

Forward Uncertainty Quantification

Inverse Uncertainty Quantification

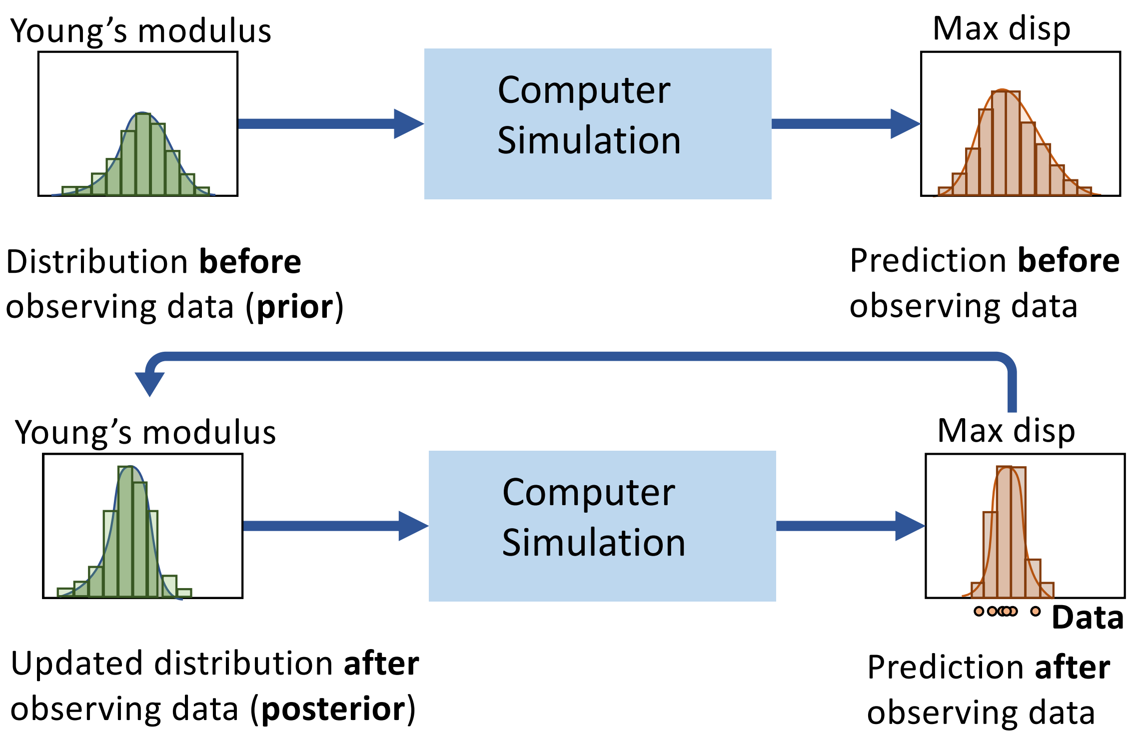
Inverse UQ

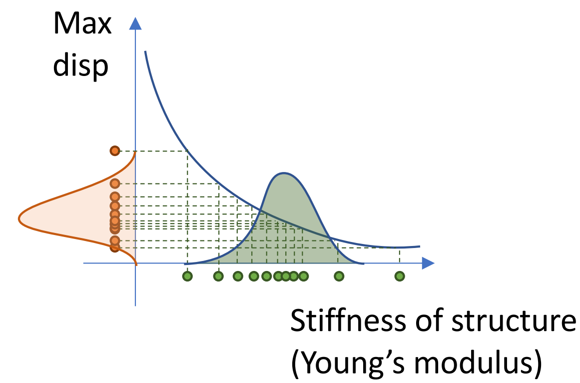
- Based on observed data, update the assumptions about the inputs and/or the model



Inverse UQ Methods – Bayesian calibration

- Based on observed data, update the distribution of the inputs to be consistent with the observations

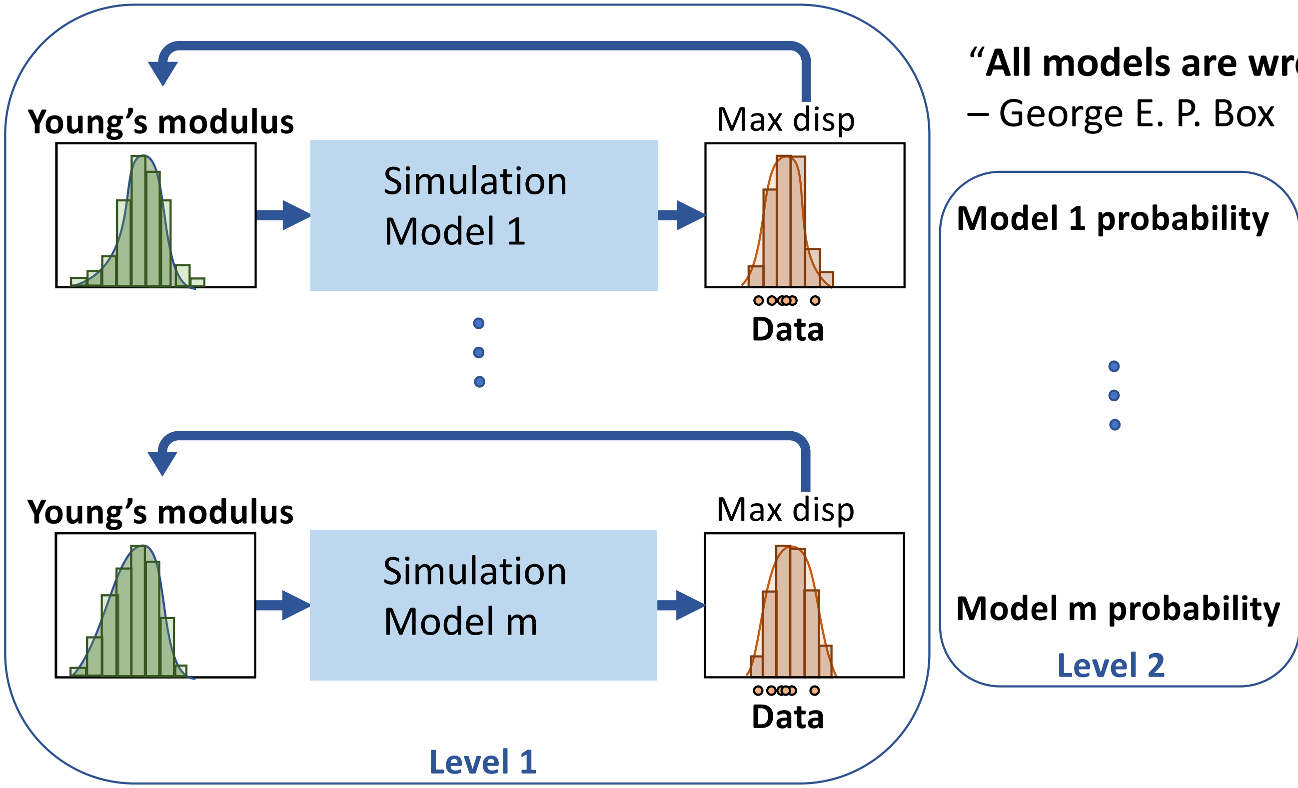




- Calibration of material model
- Calibration of reduced order model
- Post-event damage diagnosis and prognosis
- Digital twin of structure – real time updating
- Reliability updating

Inverse UQ Methods – Model Class Selection / Averaging

- Based on observed data, update the probability of a set of plausible models

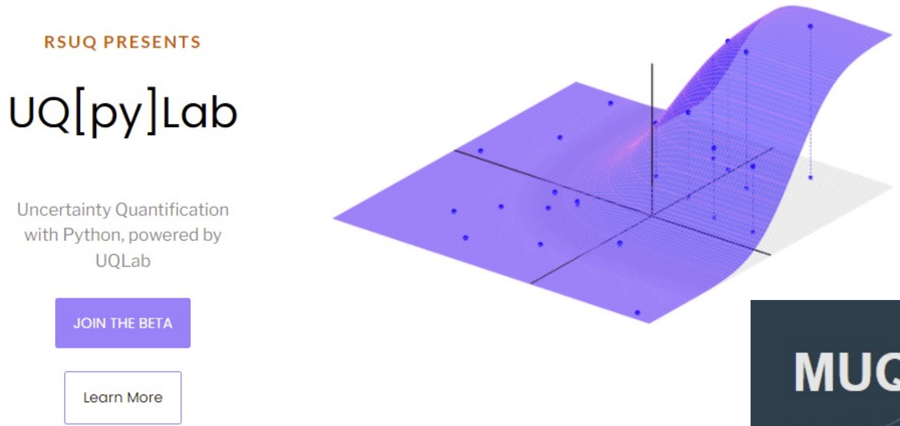


"**All models are wrong, but some are useful**"
– George E. P. Box

- **Model parsimony:** if two models fit the data equally well, the simpler model is assigned higher probability
- **Model class selection** – select the best model from the set and use for prediction
- **Model class averaging** – select all or the best few models, take weighted average of predictions from these models

Running UQ

- Toolbox/software packages for UQ analysis



UQpy

MUQ
The MIT Uncertainty Quantification Library

QUOFEM

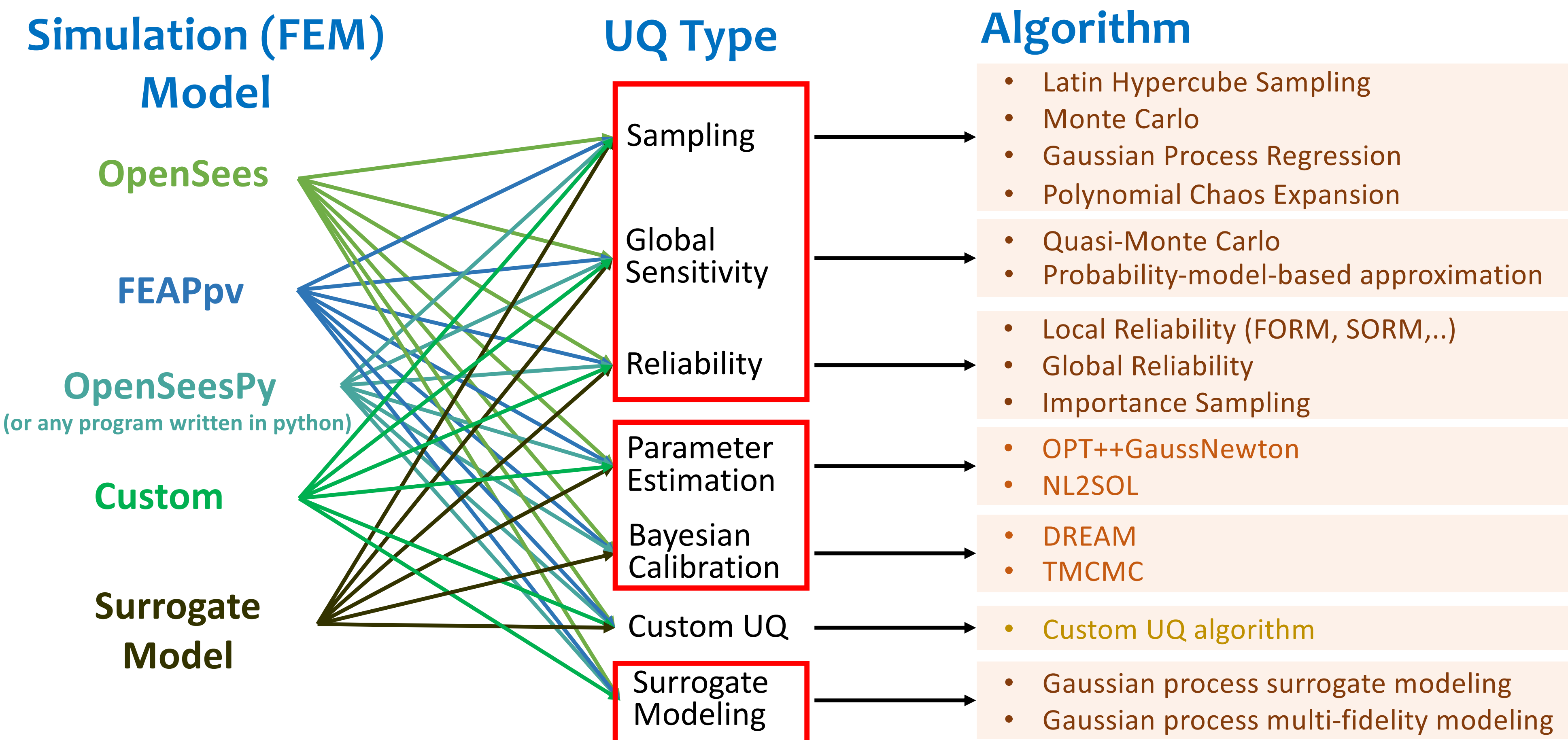
quoFEM

- A software tool with a user interface developed in SimCenter

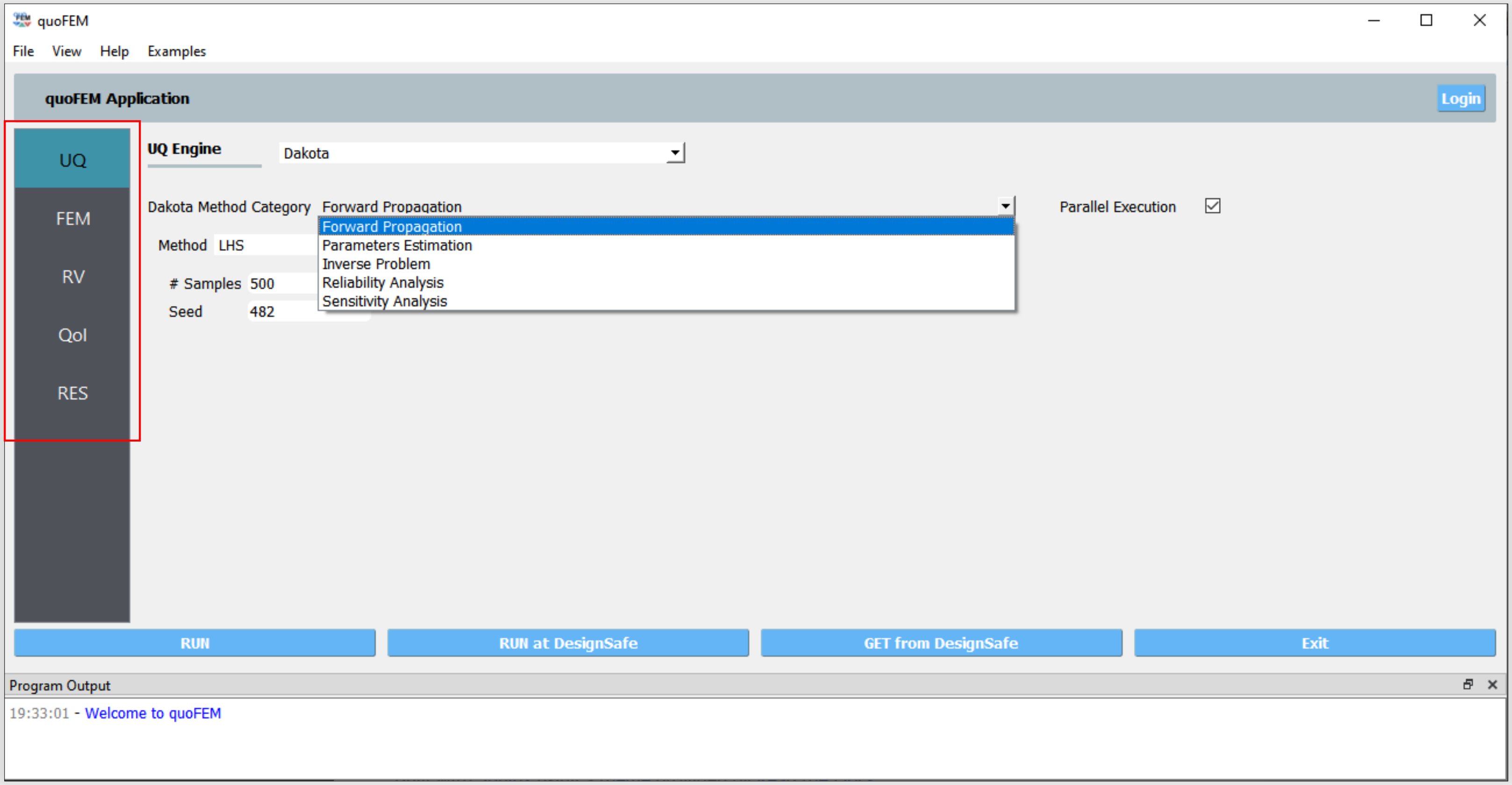
"You bring the FEM model, we do the rest"

- Need more than what we have?
  - **Build your own quoFEM**
    Github page: https://github.com/NHERI-SimCenter/quoFEM
  - **Tell us what you need**
    SimCenter Forum: http://simcenter-messageboard.designsafe-ci.org/smf/index.php

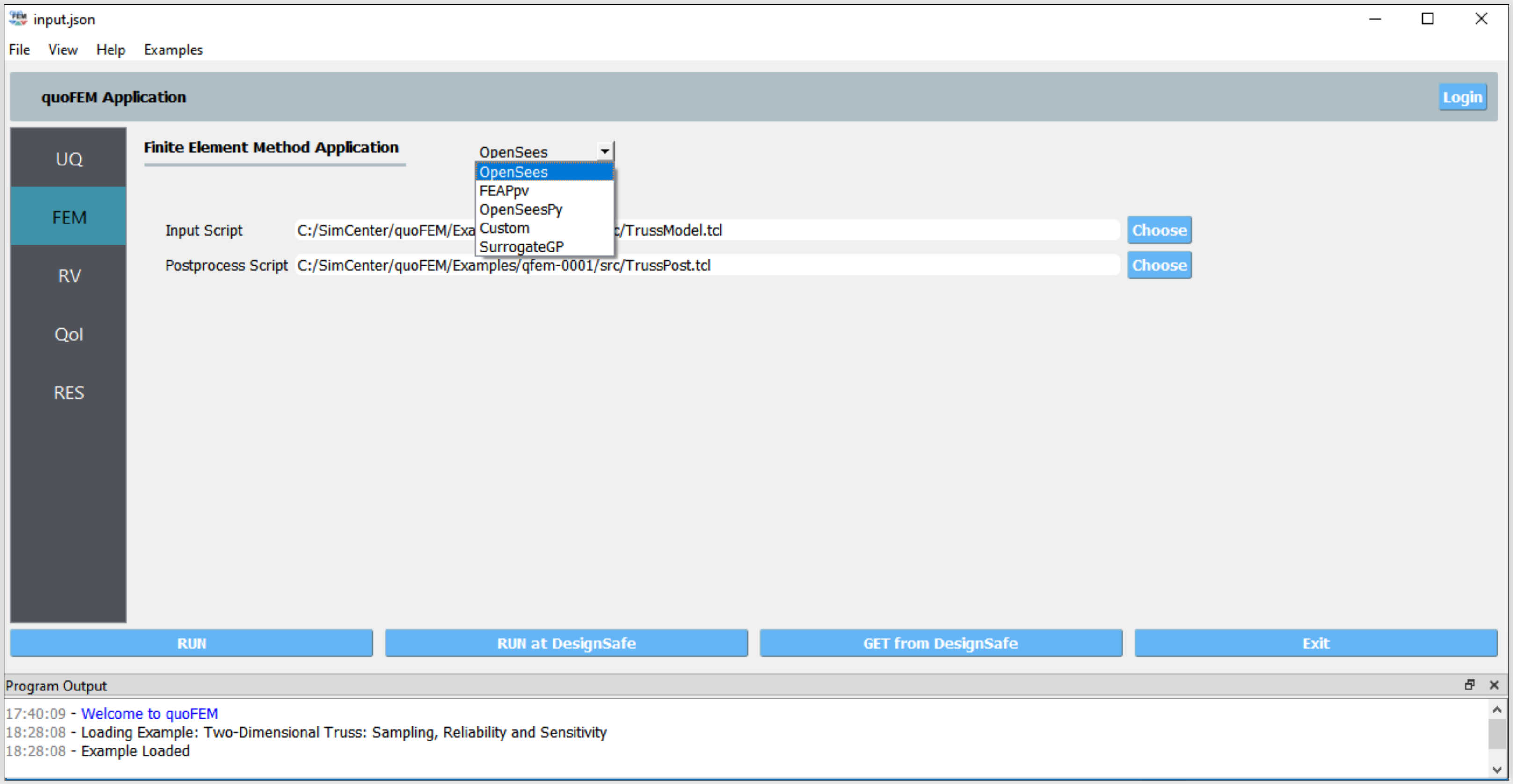
quoFEM (v.2.4)


Simulation (FEM) Model
UQ Type
Algorithm
OpenSees
FEAPpv
OpenSeesPy
(or any program written in python)
Custom
Surrogate Model
Sampling
Global Sensitivity
Reliability
Parameter Estimation
Bayesian Calibration
Custom UQ
Surrogate Modeling
• Latin Hypercube Sampling
• Monte Carlo
• Gaussian Process Regression
• Polynomial Chaos Expansion
• Quasi-Monte Carlo
• Probability-model-based approximation
• Local Reliability (FORM, SORM,..)
• Global Reliability
• Importance Sampling
• OPT++GaussNewton
• NL2SOL
• DREAM
• TMCMC
• Custom UQ algorithm
• Gaussian process surrogate modeling
• Gaussian process multi-fidelity modeling

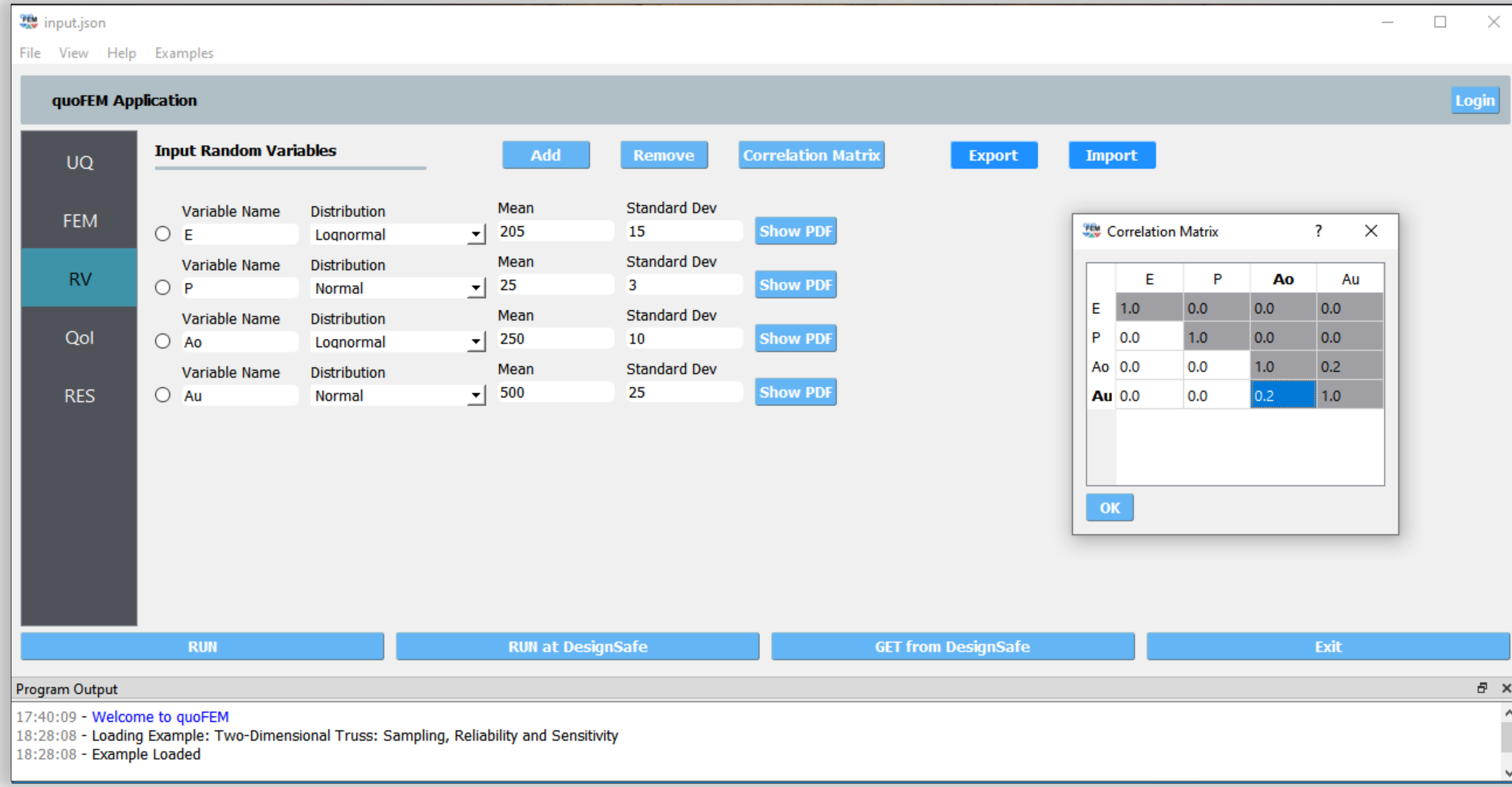
quoFEM User Interface



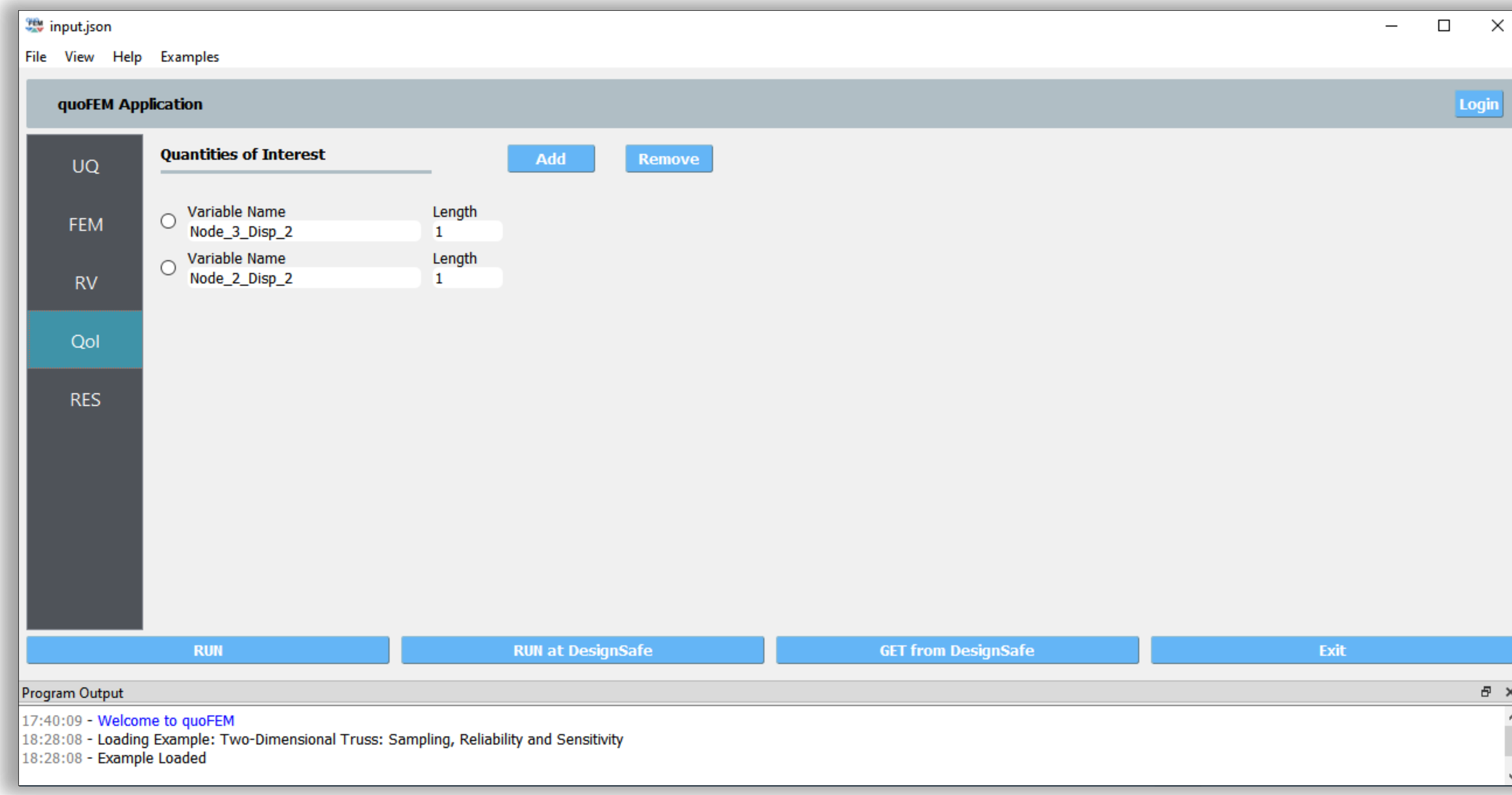
quoFEM User Interface



quoFEM User Interface



quoFEM User Interface



quoFEM User Interface