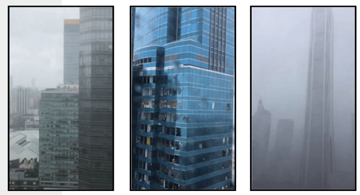
Experimental & Computational Simulation Of Wind Pressures & Forces on Buildings

Ahsan Kareem
Co-PI SimCenter

SimCenter

Glass Damage in Super Typhoon Mangkhut



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Wind vs. Earthquakes

- **Wind**
  - Loads: shape & profile dependent
  - Lacks transfer function from wind fluctuations to loads
  - Direction dependence
  - Response normally linear
  - Time history analysis requires an ensemble of surface pressure time histories
  - Response generally limited to lower modes
  - Near source events like downburst or tornado and far field ABL flows
- **Earthquakes**
  - Loads: mass distribution dependent
  - Loads dependent on mass and rel. ground acceleration
  - Direction dependence
  - Response can be nonlinear
  - Time history analysis uses available suite of ground motion time histories
  - Response requires often higher modes
  - Near source and far field ground motions

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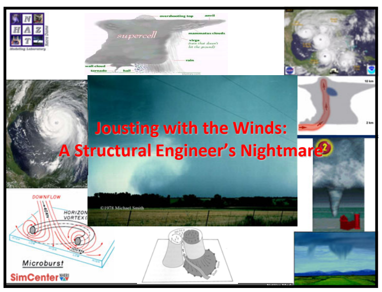
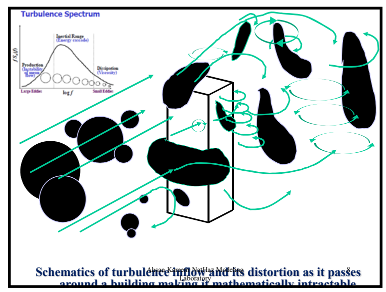
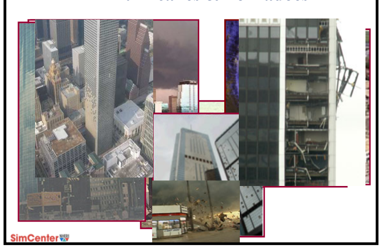


Communities wiped

SimCenter



Hurricanes & Tornadoes



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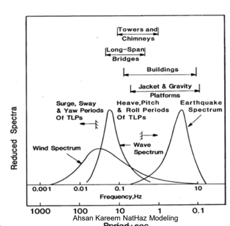
Environmental Loads



Kareem, 1978

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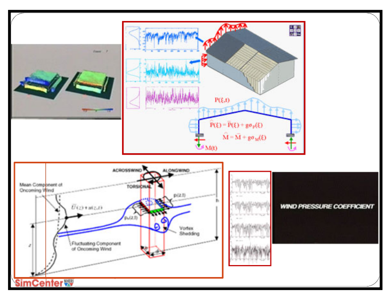
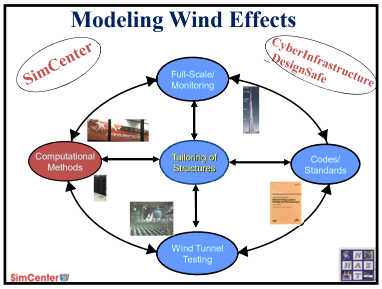
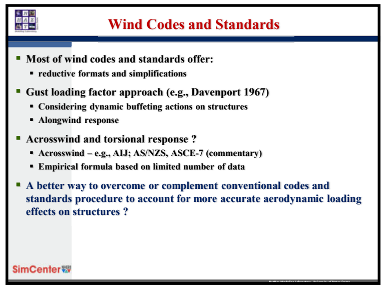



Modeling Wind Effects
SimCenter
CyberInfrastructure DesignSafe
Full-Scale/ Monitoring
Computational Methods
Tailoring of Structures
Codes/ Standards
Wind Tunnel Testing
SimCenter


Wind Codes and Standards
Most of wind codes and standards offer:
reductive formats and simplifications
Gust loading factor approach (e.g., Davenport 1967)
Considering dynamic buffeting actions on structures
Alongwind response
Acrosswind and torsional response ?
Acrosswind – e.g., AIJ; AS/NZS, ASCE-7 (commentary)
Empirical formula based on limited number of data
A better way to overcome or complement conventional codes and standards procedure to account for more accurate aerodynamic loading effects on structures ?
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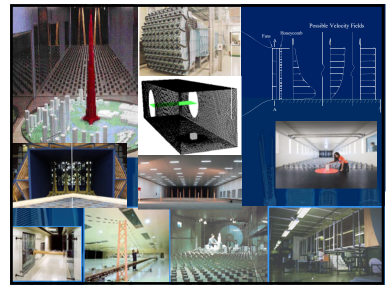
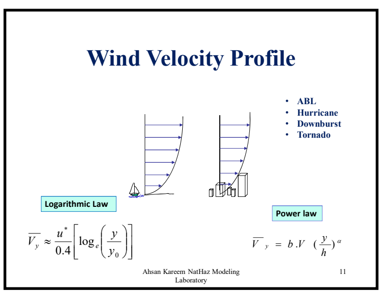

Possible Velocity Fields


Wind Velocity Profile
ABL
Hurricane
Downburst
Tornado
Logarithmic Law
Power law
$\overline{V}_y \approx \frac{u^*}{0.4}\left[\log_e\left(\frac{y}{y_0}\right)\right]$
$\overline{V}_y = b.V\left(\frac{y}{h}\right)^\alpha$
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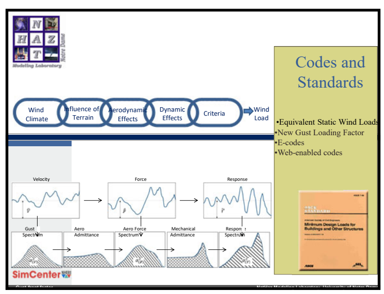
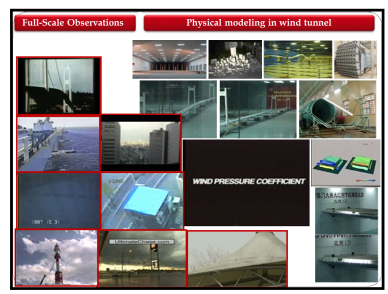
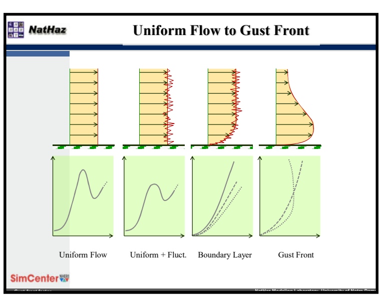

Codes and Standards
Wind Climate
Influence of Terrain
Aerodynamic Effects
Dynamic Effects
Criteria
Wind Load
•Equivalent Static Wind Loads
•New Gust Loading Factor
•E-codes
•Web-enabled codes
Velocity
Force
Response
SimCenter


Full-Scale Observations
Physical modeling in wind tunnel
WIND PRESSURE COEFFICIENT


NatHaz
Uniform Flow to Gust Front
Uniform Flow
Uniform + Fluct.
Boundary Layer
Gust Front
SimCenter


New York World Trade Center Wind Study
Investigators 1963
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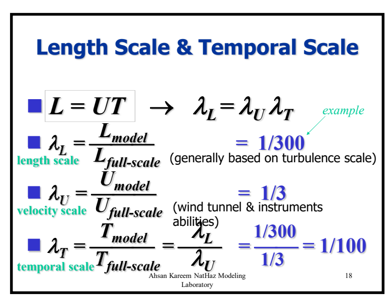
Length Scale & Temporal Scale
$L = UT \rightarrow \lambda_L = \lambda_U \lambda_T$
example
$\lambda_L = \frac{L_{model}}{L_{full\text{-}scale}} = 1/300$
length scale
(generally based on turbulence scale)
$\lambda_U = \frac{U_{model}}{U_{full\text{-}scale}} = 1/3$
velocity scale
(wind tunnel & instruments abilities)
$\lambda_T = \frac{T_{model}}{T_{full\text{-}scale}} = \frac{\lambda_L}{\lambda_U} = \frac{1/300}{1/3} = 1/100$
temporal scale
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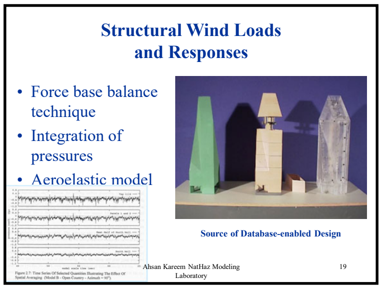
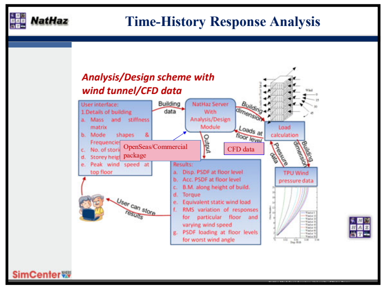
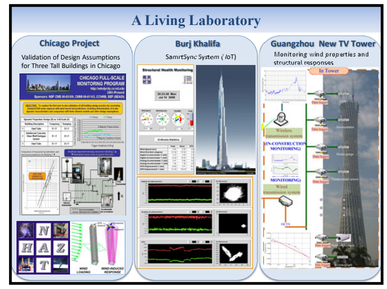
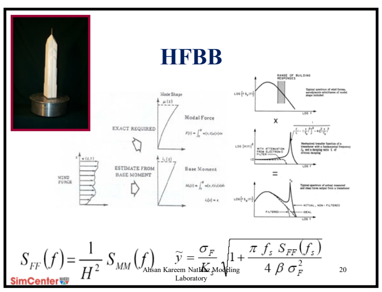
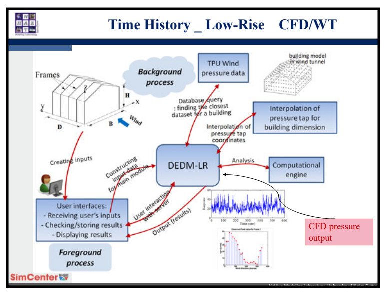
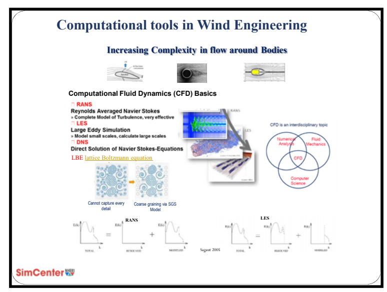


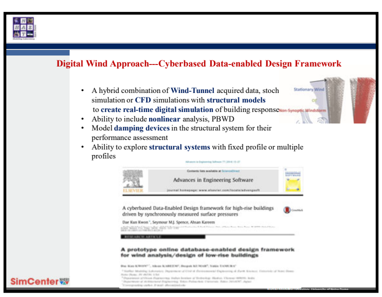


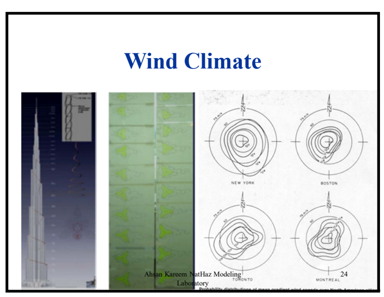




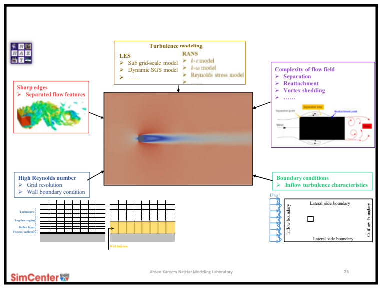


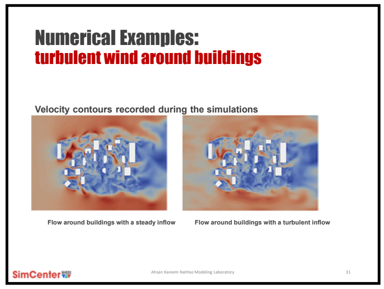


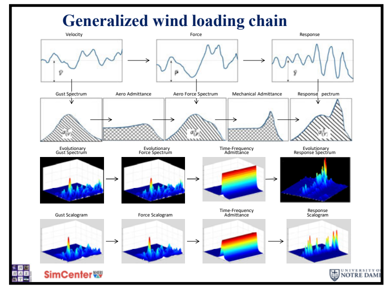


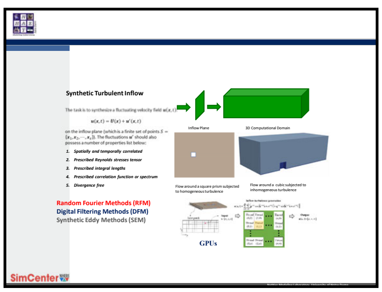


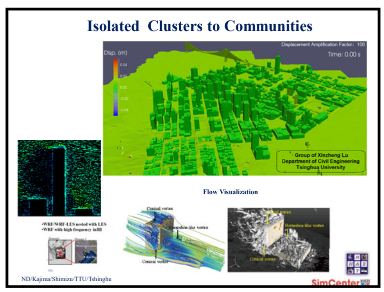
A theory (CFD !) is something nobody believes, except the person who made it. An experiment is something everybody believes, except the person who made it.
Albert Einstein
(Quoted in "The Advancement of Science and its Burdens, 1986")

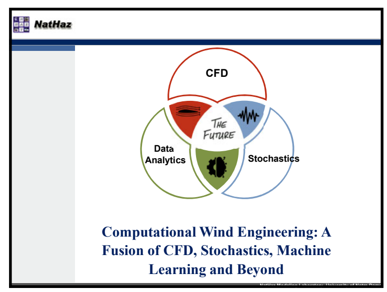

Turbulence modeling
LES
Sub grid-scale model
Dynamic SGS model
RANS
Complexity of flow field
Separation
Reattachment
Vortex shedding
Sharp edges
Separated flow features
High Reynolds number
Grid resolution
Wall boundary condition
Boundary conditions
Inflow turbulence characteristics
Lateral side boundary
SimCenter

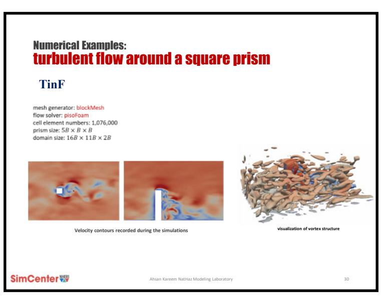

Numerical Examples:
turbulent wind around buildings
Velocity contours recorded during the simulations
Flow around buildings with a steady inflow
Flow around buildings with a turbulent inflow
SimCenter

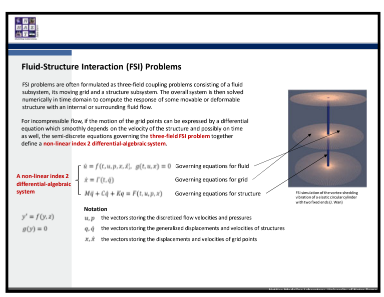

Generalized wind loading chain
Velocity
Force
Response
Gust Spectrum
Aero Admittance
Aero Force Spectrum
Mechanical Admittance
Response Spectrum
Evolutionary Gust Spectrum
Evolutionary Force Spectrum
Time-Frequency Admittance
Evolutionary Response Spectrum
Gust Scalogram
Force Scalogram
Time-Frequency Admittance
Response Scalogram
SimCenter
NOTRE DAME

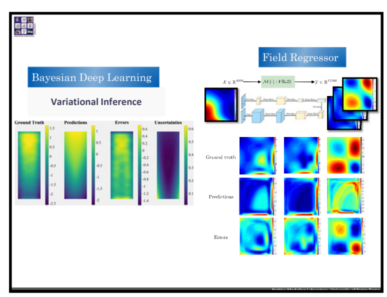

Synthetic Turbulent Inflow
Random Fourier Methods (RFM)
Digital Filtering Methods (DFM)
Synthetic Eddy Methods (SEM)
GPUs
SimCenter

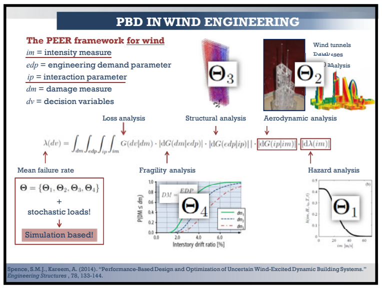

Isolated Clusters to Communities
Group of Xinzheng Lu
Department of Civil Engineering
Tsinghua University
Flow Visualization
ND/Kajima/Shimizu/TTU/Tsinghu
SimCenter

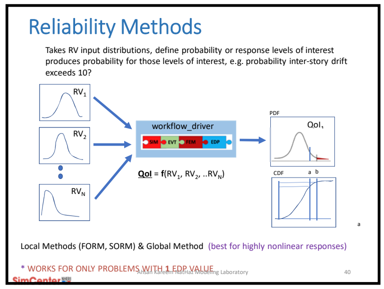

NatHaz
CFD
Data Analytics
Stochastics
The Future
Computational Wind Engineering: A Fusion of CFD, Stochastics, Machine Learning and Beyond

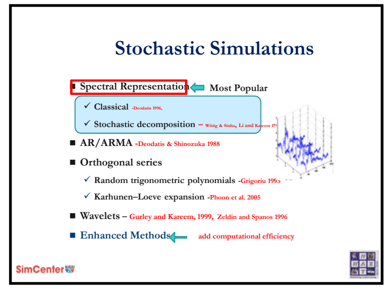

Numerical Examples:
turbulent flow around a square prism
TinF
mesh generator: blockMesh
flow solver: pisoFoam
cell element numbers: 1,076,000
Velocity contours recorded during the simulations
visualization of vortex structure
SimCenter

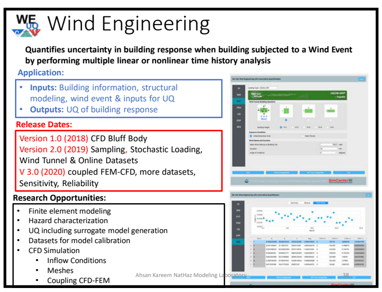

Fluid-Structure Interaction (FSI) Problems
A non-linear index 2 differential-algebraic system
Governing equations for fluid
Governing equations for grid
Governing equations for structure
Notation

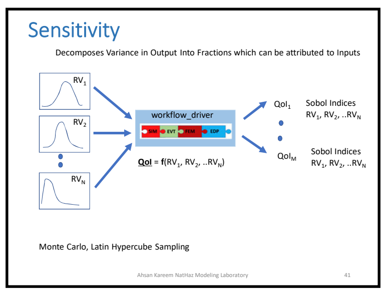

Field Regressor
Bayesian Deep Learning
Variational Inference
Ground Truth
Predictions
Errors
Uncertainties


PBD IN WIND ENGINEERING
The PEER framework for wind
im = intensity measure
edp = engineering demand parameter
ip = interaction parameter
dm = damage measure
dv = decision variables
Wind tunnels
Loss analysis
Structural analysis
Aerodynamic analysis
Mean failure rate
Fragility analysis
Hazard analysis
stochastic loads!
Simulation based!
Interstory drift ratio [%]


Reliability Methods
Takes RV input distributions, define probability or response levels of interest produces probability for those levels of interest, e.g. probability inter-story drift exceeds 10?
workflow_driver
QoI = f(RV1, RV2, ..RVN)
Local Methods (FORM, SORM) & Global Method (best for highly nonlinear responses)
* WORKS FOR ONLY PROBLEMS WITH 1 EDP VALUE


Stochastic Simulations
Spectral Representation
Most Popular
Classical
Stochastic decomposition
AR/ARMA
Orthogonal series
Random trigonometric polynomials
Karhunen–Loeve expansion
Wavelets – Gurley and Kareem, 1999, Zeldin and Spanos 1996
Enhanced Methods
add computational efficiency
SimCenter


Wind Engineering
Quantifies uncertainty in building response when building subjected to a Wind Event by performing multiple linear or nonlinear time history analysis
Application:
Inputs: Building information, structural modeling, wind event & inputs for UQ
Outputs: UQ of building response
Release Dates:
Version 1.0 (2018) CFD Bluff Body
Version 2.0 (2019) Sampling, Stochastic Loading, Wind Tunnel & Online Datasets
V 3.0 (2020) coupled FEM-CFD, more datasets, Sensitivity, Reliability
Research Opportunities:
Finite element modeling
Hazard characterization
UQ including surrogate model generation
Datasets for model calibration
CFD Simulation
Inflow Conditions
Meshes
Coupling CFD-FEM


Sensitivity
Decomposes Variance in Output Into Fractions which can be attributed to Inputs
workflow_driver
QoI = f(RV1, RV2, ..RVN)
Sobol Indices
Monte Carlo, Latin Hypercube Sampling
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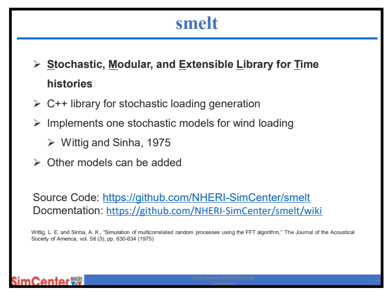
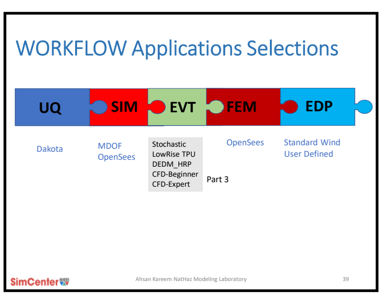

smelt
Stochastic, Modular, and Extensible Library for Time histories
C++ library for stochastic loading generation
Implements one stochastic models for wind loading
Wittig and Sinha, 1975
Other models can be added
Source Code: https://github.com/NHERI-SimCenter/smelt
Documentation: https://github.com/NHERI-SimCenter/smelt/wiki
SimCenter


WORKFLOW Applications Selections
UQ
SIM
EVT
FEM
EDP
Dakota
MDOF
OpenSees
Stochastic
LowRise TPU
DEDM_HRP
CFD-Beginner
CFD-Expert
OpenSees
Standard Wind
User Defined
Part 3
SimCenter
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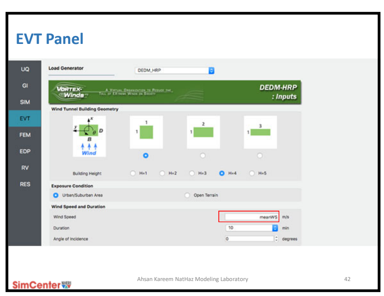
EVT Panel
SimCenter
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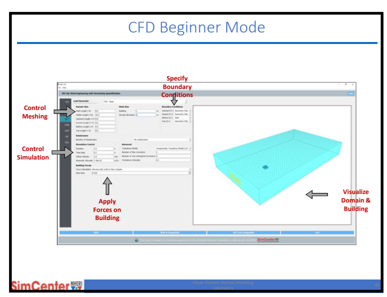
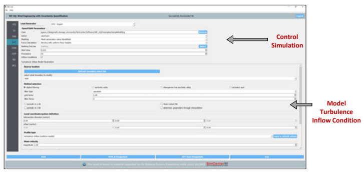

CFD Beginner Mode
Specify Boundary Conditions
Control Meshing
Control Simulation
Apply Forces on Building
Visualize Domain & Building
SimCenter

CFD Expert Mode



CFD Capabilities in WE-UQ

- **Automatic Meshing using Gmsh**
  - Tetrahedral meshing with adjustable size at different locations
- **Turbulence Modeling**
  - Smagorinsky Turbulence Model (LES)
  - Dynamic One Equation Model (LES)
  - S-A One Equation Model (RANS)
  - k-p Epsilon Model (RANS)
  - Spalart Allmaras DDES Model (DDES)
- **Turbulence Inflow Modeling (Part 2)**

Gmsh + OpenFOAM

Peter Sempolinski & Peter Mackenzie-Helnwein. (2018, October 13). NHERI-SimCenter/CWE-Simulation-Tool: Version 1.1.1 (Version 1.1.1). Zenodo. http://doi.org/10.5281/zenodo.1461088

CFD Capabilities in WE-UQ

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Gmsh + OpenFOAM

Peter Sempolinski & Peter Mackenzie-Helnwein. (2018, October 13). NHERI-SimCenter/CWE-Simulation-Tool: Version 1.1.1 (Version 1.1.1). Zenodo. http://doi.org/10.5281/zenodo.1461088