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State-of-Art in Computational Simulation for Natural Hazards Engineering

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Edited by:

Gregory G. Deierlein

Adam Zsarnóczay

Contributors

Pedro Arduino
Professor, University of Washington

Jack W. Baker
Associate Professor, Stanford University

Jonathan D. Bray
Professor, UC Berkeley

Joel P. Conte
Professor, UC San Diego

Gregory G. Deierlein
Professor, Stanford University

George Deodatis
Professor, Columbia University

Wael Elhaddad
Postdoctoral Researcher, UC Berkeley

Michael Gardner
Postdoctoral Researcher, UC Berkeley

Sanjay Govindjee
Professor, UC Berkeley

Liang Hu
Grad. Research Assistant, University of Notre Dame

Ahsan Kareem
Professor, University of Notre Dame

Tracy Kijewski-Correa
Associate Professor, University of Notre Dame

Patrick J. Lynett
Professor, University of Southern California

Frank McKenna
Project Scientist, UC Berkeley

Yuki Miura
Graduate Research Assistant, Columbia University

Michael Motley
Associate Professor, University of Washington

Ertugrul Taciroglu
Professor, UC Los Angeles

Alexandros Taflanidis
Associate Professor, University of Notre Dame

Iris Tien
Assistant Professor, Georgia Institute of Technology

Chaofeng Wang
Postdoctoral Researcher, UC Berkeley

Adam Zsarnóczay
Postdoctoral Researcher, Stanford University

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Preface

This report is a product of the NSF NHERI SimCenter and provides an overview and review of simulation requirements and software tools for natural hazards engineering of the built environment. The simulations discussed in this report are an essential component of research to address the three grand challenge areas and associated research questions outlined in the NHERI Science Plan (2017). As outlined in the NHERI Science Plan, the grand challenges entail: (1) quantifying natural hazards and their effects on civil infrastructure; (2) evaluating the vulnerability of civil infrastructure and social vulnerability of populations in at-risk communities; and (3) creation of technologies and tools to design and implement measures to promote resilience to natural hazards. Accordingly, required simulation technologies encompass a broad range of phenomena and considerations, from characterization and simulation of natural hazards and their damaging effects on buildings and civil infrastructure, to quantifying the resulting economic losses, disruption, and other consequences on society. Ultimately, the goal is to enable high-fidelity and high-resolution models in regional simulations that can support technological, economic, and policy solutions to mitigate the threat of natural hazards.

The natural hazards addressed in this report include earthquakes, tsunami, storm and tornado winds, and storm surge. While not an exhaustive list of all possible natural hazards, these are the hazards addressed under the U.S. National Science Foundation's (NSF) NHERI research program. The report is organized in a sequential fashion, including: (1) simulation methods to characterize the natural hazards; (2) response simulation of structural and geotechnical systems and localized wind and water flows; and (3) quantifying the resulting damage and its effects on the performance of buildings, transportation systems, and utility infrastructure systems. Given the inherent uncertainties in all aspects of natural hazards engineering, methods of uncertainty propagation are reviewed, with an eye toward their broad applicability within and between the various simulation components.

Owing to the broad scope of the simulation topics, this state-of-art review is presented with the goal of educating and informing researchers, including both simulation tool developers and users, on key requirements and capabilities within each simulation topic. The report is also a guide for the development of simulation capabilities by the NSF NHERI SimCenter. Each section of the report begins with a brief overview of the purpose of the simulation component, including a discussion of the goals of the analysis (what is being calculated), the underlying physics or principles involved in the simulation, common modeling assumptions and simplifications, and typical input and output of the simulations.

With the aim to take stock of computational simulation capabilities, inform research by the NHERI research community, and position the work of the NHERI SimCenter, the summaries identify and review commonly used simulation software that is widely known and used for research in academia and industry. Particular emphasis is placed on open-source or other software that is hosted on DesignSafe or is otherwise easily accessible to researchers, and a summary table of the simulation software tools is provided as an appendix to the report. In addition to summarizing the state-of-art in the various topic areas, each section of the report identifies major research gaps and needs, with the intent that these could motivate research proposals to NSF or other agencies that will lead to future advancements. The final chapter of the report summarizes how tools being developed by NHERI SimCenter are advancing the state-of-art in simulating the effects of natural hazards on the built environment.

This report is intended to be a living document series, which will be updated regularly based on feedback from the research community and advancements in simulation technologies for natural hazards engineering.

Gregory G. Deierlein
Adam Zsarnóczay

Stanford University

NHERI (2017), *Five-Year Science Plan – Multi-Hazard Research to Make a More Resilient World*, https://www.designsafe-ci.org/facilities/nco/science-plan/

Notice

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1. Hazard Characterization

Characterization of natural hazards for engineering applications aims to quantify the severity of the hazard at a particular location or over a pre-defined region of interest. Quantification is often performed through so-called Intensity Measures (IMs) that describe the hazard with one or a few parameters. Peak ground acceleration, permanent ground deformation, average one-minute wind speed, and peak inundation depth are a few examples of such IMs for various natural disasters. The limited number of parameters allows the development of a stochastic hazard model at the site(s) of interest and propagation of uncertainty in the hazard through engineering analyses.

When structural response is estimated through simulation of the response history of a numerical structural model, the hazard is typically represented by a time-dependent load function. The acceleration time history of a ground motion is an example of such a load function, which is often used for seismic response estimation. These load functions are either selected from historical data (e.g., ground-motion records) or generated based on the stochastic description of local IMs (e.g., local wind inflow conditions for a CFD simulation). The procedures and best practices available for this task will be discussed for each natural hazard below.

Three different types of natural disasters are examined in the following sections: earthquake, hurricane, and tsunami. Some of them present several fundamentally different threats to the built environment, such as ground shaking and liquefaction under earthquakes, or wind and storm surge under hurricanes. These are discussed separately below.

1.1 Earthquake - Ground Shaking

Adam Zsarnóczay
Postdoctoral Researcher, Stanford University

Jack W. Baker
Associate Professor, Stanford University

Wael Elhaddad
Postdoctoral Researcher, UC Berkeley

The purpose of using the software tools presented in this section is to characterize the ground shaking intensity due to earthquakes at a given site or region. Although the amount of historical earthquake data at any particular site is small, the improvements in the field since the seminal paper on earthquake hazard by Cornell (1968) allows engineers to combine the available information from several sites and create a seismic hazard model that can quantify the expected ground-motion hazard and corresponding uncertainty.

Probabilistic Seismic Hazard Assessment (PSHA) and disaggregation of the calculated hazard (Bazzurro and Cornell, 1998) are the most popular methods to characterize ground shaking at a site of interest. The earthquake engineering community is fortunate to have access to a large number of free—and often open-source tools—available for this task. Besides PSHA tools, also presented are tools that perform scenario-based deterministic analysis. Both probabilistic and deterministic analyses are typically based on Ground Motion Prediction Equations (GMPEs)–empirical functions that describe the attenuation of shaking intensity with increasing distance from the hypocenter. Note: the Ground Motion Prediction Model (GMPM) denomination is preferred over GMPE in several recent publications to emphasize that modern attenuation relationships are more complex than a single equation. Other approaches, such as physics-based simulation of ground motions, are also becoming sufficiently robust to be widely applicable for risk assessment and their widespread use is likely to increase in the near future.

This section provides an overview of the above methods, the data they use, and the tools that have implemented them.

1.1.1 Input and Output Data

Ground-motion hazard assessment requires information about the site and the seismic source(s) in its vicinity. These data can be classified as follows:

Site location(s)

These are latitude and longitude pairs for each site of interest. For regional analyses, the ground-motion hazard characteristics at the nodes of a carefully sized lattice grid are used, and the site-specific results are determined by interpolation.

Site data

Local soil conditions have significant influence on the ground motion at the surface at a particular site. Two neighboring sites with practically identical bedrock hazard might experience fundamentally different surface ground motions if their soil characteristics are different.

The difficulty in determining actual soil conditions is that the bedrock is often at large depths, and in the absence of site-specific characterization, there is usually limited data to characterize the complete soil profile. This is especially the case for large regional simulations. The lack of data translates into significant uncertainty in the resulting ground-motion estimate. Regional analyses typically describe soils using estimates of either the soil class (e.g., rock, stiff soil, soft clay, etc.) or the average shear-wave velocity over the top 30 meters of the soil (v_{s30}).

Seismic sources

Ground motions are generated by seismic sources. Depending on the available historical information about the earthquakes in the region, sources might be described as faults, points, or areas with homogeneous seismicity. The abundant information about earthquakes in California allows researchers to develop a detailed map of faults for the state (Field et al., 2014), while the Central and Eastern United States (CEUS) is covered by area sources (Mueller et al., 2015).

Scenario-based analysis typically requires a hypocenter location, earthquake magnitude, and information about the rupture surface and style of faulting. Probabilistic assessments consider all sources that might affect the region along with a stochastic description of those sources using magnitude occurrence rates, hypocenter depth distributions, etc. These stochastic models are usually based on historical ground-motion data. The Uniform California Earthquake Rupture Forecast version 3.0 (UCERF3, Field et al., 2014) is an example of such a stochastic seismic-source model. It is published jointly by the United States Geological Survey (USGS), the California Geological Survey (CGS), and the Southern California Earthquake Center (SCEC). Seismic-source models for other non-US regions have been prepared and made publicly available by the Global Earthquake Model (GEM) initiative (https://www.globalquakemodel.org/). These include Europe (Giardini, 2014), the Middle East (Danciu et al., 2017), and South America (Garcia et al., 2018).

Ground-motion model

The ground-motion model describes the propagation of ground shaking from the earthquake rupture surface to the collection of sites of interest. Ground-Motion Prediction Equations are the commonly used tools for this purpose. They estimate severity of ground shaking in the form of IMs. These estimates are typically based on regression to historical IM data from recorded earthquake ground motions. Depending on the data and the functional form used for the regression, one might arrive at various GMPEs. There are hundreds of GMPEs available (Douglas, 2018). It is important to select the one that is based on data and assumptions matching the seismicity in the region of interest.

Logic tree

Logic trees have become a popular means to consider the epistemic uncertainty in the ground-shaking hazard. Branches of the trees are populated with various modeling assumptions (e.g., GMPEs, seismic-source models, maximum magnitudes, site data, etc.) and a corresponding set of weights are defined that are proportional to the level of confidence experts have in each option. Notwithstanding the problems inherent in such a strategy for uncertainty quantification

(Bommer and Scherbaum, 2008), recent research has shown several examples where the logic-tree approach provides additional insight that would otherwise not be available (see, e.g., Goulet et al., 2017)

One or more of the following outputs are produced to describe the ground-shaking hazard:

Intensity measure (IM)

A measure of the intensity of ground shaking at the site of interest. Examples of IMs are the peak ground acceleration (PGA) or spectral acceleration at a given vibration period [$S_a(T)$].

Seismogram

A plot of ground motion versus time, which would be recorded by a seismometer or other instrument. Synthetic seismograms can also be generated by physics-based ground-motion simulations or stochastic models. Seismograms are typically expressed in terms of ground acceleration, which are integrated to obtain ground-motion velocity or displacement.

Response spectra

A response spectrum is often used as a proxy to describe the ground-motion intensity. It is a collection of IMs that describe the response of single-degree-of-freedom oscillators to the ground-motion record of interest. Acceleration response spectra, for example, are defined through a set of $S_a(T)$ values. The larger the number of vibration periods considered, the more detailed the resulting spectrum becomes. In GMPE-based simulations, the resolution of the response spectrum is typically limited by the vibration-period discretization used in the attenuation relationship. In physics-based simulations, the response spectrum is determined from the simulated ground-motion seismogram.

Hazard curve

Rather than focusing on ground motions from a single event, probabilistic assessments characterize the hazard through the annual exceedance rate of various IMs at the site of interest. This information is represented by a hazard curve. Each IM has its corresponding hazard curve. Studies typically focus on obtaining hazard curves for a set of $S_a(T)$ IMs.

Hazard spectrum

Given a set of hazard curves corresponding to $S_a(T_i)$ for T_i in a sufficiently wide range of vibration periods, it is possible to collect the $S_a(T_i)$ corresponding to a pre-defined annual exceedance rate. These $S_a(T_i)$ values describe the so-called uniform hazard spectrum (UHS), which is the collection of spectral accelerations that have the same (uniform) probability of exceedance. An alternative to the UHS is the so-called Conditional Spectra (CS), where the spectra are conditioned on the probability of exceedance of response at a specified period T. The UHS and CS are often used to describe the hazard in a probabilistic framework.

Hazard map

Given a particular annual exceedance rate (or return period, or exceedance probability over a pre-defined time period) and a corresponding hazard curve at various sites in a region, one can create a map of IM levels that describe the intensity of expected ground shaking. The engineering community uses a small set of pre-defined return periods (such as 475 years, which is equivalent to 10% probability of exceedance over 50 years) to describe the hazard for structural design and performance assessment purposes. Using the same return periods within the community facilitates the comparison of hazard maps among different regions and within different parts of the same region.

Disaggregation of the hazard

Probabilistic Seismic Hazard Analysis aggregates the contributions of several sources to produce a hazard curve for a site. Disaggregation provides a break-down of the contribution of various seismic sources to the total seismic hazard. This allows researchers to estimate the characteristic features of the earthquake scenarios (typically magnitude and source-to-site distance) that are the main contributors to the seismic hazard at the site. Information about such features complements the estimated IMs and provides a more detailed understanding of the seismic hazard at the site.

1.1.2 Modeling Approaches

Two main approaches are typically used in the research community for ground-shaking hazard characterization:

Estimate IMs using GMPEs

This type of methodology describes the hazard using IMs estimated using GMPEs that are based on historical earthquake data. The advantage of using GMPEs is the computational efficiency of the calculation; GMPEs typically describe IMs as random variables. This approach allows engineers to estimate the probability of exceeding a pre-defined IM level given the characteristics of the earthquake scenario, the location of the site, and other parameters (soil conditions, damping, etc.). By aggregating these exceedance probabilities and the occurrence rates of corresponding earthquake scenarios over a region, engineers can arrive at the total probability of exceedance of a pre-defined IM level at the site of interest. Performing such a calculation for multiple IM levels produces the hazard curve for the site. The ground shaking hazard is commonly described using a set of hazard curves that correspond to the spectral acceleration at various vibration periods. These hazard curves can serve as the basis of a UHS or CS for structural response estimation.

Estimate ground-motion records using physics-based wave propagation

This type of methodology relies on a physical model of the crust and propagation of seismic waves in that model. It requires a significant amount of information about local geology to arrive at reliable results. Furthermore, the calculations are computationally expensive and usually require a High Performance Computing (HPC) environment. To the extent that the physics-based models are validated and based on reliable model parameters (geologic data), they can represent local geologic effects (such as deep geologic basins) that are not captured as well by empirical GMPEs. The earthquake simulations also provide ground-motion records directly as opposed to the IM proxies used in conventional GMPE approaches. These records can be applied directly in response estimation, which removes part of the uncertainty and ambiguity associated with GMPEs and ground-motion record selection to match IM spectra. There are computational and modeling challenges before this approach becomes commonplace, but early-adopters in the research community (such as SCEC, https://www.scec.org/ , Lawrence Livermore National Laboratory, https://www.llnl.gov, and USGS, https://earthquake.usgs.gov/) are providing physics-based simulations that are being applied for performance and risk assessment.

1.1.3 Software and Systems

The following is a list of software that is commonly used for characterizing earthquake ground shaking.

AWP-ODC

AWP-ODC is an elastic wave propagation program (AWP-ODC, Cui et al., 2010) that performs a parallel finite-difference wave-propagation simulation. The software can simulate the dynamic rupture and wave propagation that occurs during an earthquake. It was originally written in Fortran and supports parallel computation using the message passing interface (MPI). A version of the software written in C and CUDA is also available to run on graphics processing units (GPUs).

BBP

The Broadband platform (Maechling et al., 2015) is a software system developed by SCEC that can be used to generate synthetic ground motions using wave-propagation models. The BBP is distributed with data products (velocity models and Green's functions packages) that allows for the generation of seismograms for simulating historical or hypothetical earthquake scenarios in California, the northeast of the U.S., and Japan. The software runs on Linux systems and provides different seismogram generation models.

CyberShake

CyberShake is a computational simulation project on physics-based PSHA, developed and hosted by SCEC. CyberShake simulations have been created from studies that define the inputs, computational software, and the outputs. Outputs from studies done using CyberShake are stored in publicly accessible databases, which includes studies performed for southern and central California. Data products of CyberShake include seismograms, hazard curves, disaggregation, duration results, and hazard maps.

HAZUS 4.2

The Federal Emergency Management Agency (FEMA) has been supporting the development of this tool for more than two decades. It is publicly available and provides a convenient way to perform regional risk assessment following the HAZUS Multi-hazard Loss Estimation Methodology 2.1 (FEMA Mitigation Division, 2018a, 2018b, 2018c). The methodology covers earthquake, hurricane, and flood hazards (with tsunami currently under development). Researchers and agencies in the U.S. can download input data with the tool that provides information about the hazard, the exposure (i.e., building locations and characteristics) and the vulnerability (i.e., building fragility and consequence functions) of the region. These inputs are prepared in the standard format required by the software and provide exposure data (building inventories, etc.) at a census-tract-level resolution. The software runs on Microsoft's Windows operating system and has a GUI.

Hercules

Hercules (Tu et al., 2006) is a parallel finite-element wave-propagation software that can be used to simulate earthquake ruptures. It was originally developed by the Quake group in Carnegie Mellon University in collaboration with SCEC. The software is designed to be memory-efficient and highly scalable to run large-scale simulations in an HPC environment (Taborda et al., 2010).

NSHMP-Haz

NSHMP-Haz is a Java-based library for PSHA that has been developed as part of the National Seismic Hazard Mapping Project (NSHMP) within the USGS Earthquake Hazards Program (EHP). The library is the engine driving different USGS web services and applications, and it enables high-performance seismic hazard calculations required for generating hazard maps over large regions using different ground-motion models. A legacy Fortran version of this library is also available, although it is deprecated at the time of writing this report.

OpenSHA

OpenSHA (Field et al., 2003) is an open-source platform for seismic hazard analysis (SHA) that was developed by the SCEC in collaboration with USGS. The platform is comprised of Java libraries and a suite of applications that are suitable for different SHA applications. For instance, OpenSHA provides graphical applications for calculating hazard spectra, hazard curves, hazard maps, hazard disaggregation, and querying site data. In addition, all the features provided by the graphical applications are available programmatically through the OpenSHA Java libraries.

OpenQuake Engine

OpenQuake (Pagani et al., 2014) is an open-source library for seismic hazard and seismic risk computations. The library was developed using Python and is cross platform. The library uses data, methods, and guidelines outlined by GEM.

PEER Ground Motion Database

The PEER ground motion database (NGA-West2, Ancheta et al., 2014) is a comprehensive set of ground-motion records from shallow crustal earthquakes in active seismic regions around the world. The database includes 21,336 records from 599 earthquake events. In addition to the ground-motion records, the database stores detailed metadata that includes different source-site distance measures, site, and rupture characterization. A web service that can perform ground-motion record selection and scaling using the records in database is also provided.

R-CRISIS

R-CRISIS is the latest version of the CRISIS software that has been developed by Ordaz et al. (2008) and supported by the National Autonomous University of Mexico, and the Italian Department of Civil Protection. The latest version of the software is free and publicly available. It is designed to work with a GUI in a Windows environment. The software is designed to perform PSHA calculations with a large number of GMPEs built in and seismic-source models available in the literature.

SW4

Seismic waves, 4th order (SW4, Petersson et al., 2017) is a software developed by Computational Infrastructure for Geodynamics (CIG) that can solve three-dimensional (3D) seismic wave-propagation problems. The software was developed using Fortran and C++ and makes use of a distributed memory-programming model using MPI. The software is suitable for running on HPC and is capable of producing synthetic seismograms in different formats.

UCVM

The Unified Community Velocity Model (UCVM, Small et al., 2017) is a software framework developed by SCEC that provide a common interface to query different 3D seismic velocity models for the State of California. The software allows the use of alternative models to query and visualize seismic-wave velocities. The software provides query scripts to obtain the seismic-wave velocities and density visualized on a horizontal slice, cross section, and depth profile, and can also provide basin depth and v_{s30} maps. The properties provided by the velocity models included with UCVM are crucial for many wave-propagation software that is presented in this section.

UGMS MCE_R

UGMS MCE_R (Crouse et al., 2018) is a web-based tool developed by SCEC Committee for Utilization of Ground Motion Simulations (UGMS) to provide a site-specific Maximum Considered Earthquake (MCE) response spectra for the Los Angeles region according to the site-specific seismic hazard analysis procedure outlined in ASCE 7-16. The tool is user-friendly and is oriented towards practitioners, and only requires the location (latitude and longitude) and site-soil classification (site class or v_{s30}).

1.2 Earthquake – Surface Fault Rupture

Jonathan D. Bray
Professor, UC Berkeley

Michael Gardner
Postdoctoral Researcher, UC Berkeley

Chaofeng Wang
Postdoctoral Researcher, UC Berkeley

Surface fault rupture is a manifestation of subsurface fault displacement through the overlying earth, including soil deposits, resulting in permanent ground surface deformation that can damage engineered systems. The characteristics of the surface deformation depend on the type of fault movement, the inclination of the fault plane, the amount of displacement on the fault, the depth and geometry of the materials overlying the bedrock fault, the nature of the overlying earth materials and definition of the fault, and the structure and its foundation (Bray, 2001). The subsurface movement of the fault may be expressed as a distinct rupture plane or as distributed distortion of the ground surface. Additionally, extensional movement of the fault can cause tensile strains and cracking at the ground surface.

1.2.1 Procedures for Evaluating Surface Ruptures

In the event that surface fault rupture is anticipated to occur at a site, the following procedures can be applied:

Closed-Form Solutions

For free-field analyses, the method presented by Cole Jr. and Lade (1984) can provide predictions of the shape and location of failure surfaces in soil. The required inputs for this procedure are the depth of the overlying soil, the angle of dilation of the soil, and the dip angle of the fault; however, this method is restricted to cohesionless soils above dip–slip faults. Another approach, presented by Berrill (1983), provides analytical solutions for assessing various failure modes for shallow foundations across strike–slip faults.

Probabilistic Assessment of Fault Displacement Hazard

These methods provide a means to evaluate the probability of some amount of fault displacement occurring at a site. Generally, these methods will provide an estimate of the probability of some level of fault displacement being exceeded—analogous to the approach used in PSHA for ground shaking—based on a given set of input parameters that characterize the type of event and location of the site relative to that event. Examples of such methodologies are Wells and Coppersmith (1994), Youngs et al. (2003), Petersen et al. (2011), Moss and Ross (2011), and Oettle et al. (2015).

Pseudostatic Analysis

Pseudostatic numerical analyses can provide estimates of not only the magnitude of surface fault displacement that may occur at a site, but also on the characteristics of the deformation at the site and how structures might interact with the deforming soil. Continuum-based methods, such as finite-element and finite-difference methods, and discontinuous methods, such as the Discrete-Element Method, have been implemented to model surface fault rupture. These methods can capture how fault and soil material properties affect surface manifestations of subsurface fault displacement, providing insight into what potential hazards at a site may be. These methods require more knowledge of site conditions and soil properties such that constitutive model parameters can be calibrated to provide meaningful results for a particular site. For pseudostatic analyses, the dynamics of fault rupture are ignored, and instead the fault displacement is specified while the displacement rate is kept slow enough to avoid dynamic effects. Some research has investigated dynamic surface fault rupture (Oettle et al., 2015), but most analyses are implemented in a pseudostatic manner (Anastasopoulos and Gazetas, 2007; Anastasopoulos et al., 2008; Anastasopoulos et al., 2008; Bransby et al. 2008a; Bransby et al., 2008b; Oettle and Bray, 2016; Garcia and Bray, 2018a; and Garcia and Bray, 2018b).

1.2.2 Systems and Software for Surface Fault Rupture Analysis

Sections 5.1 and 5.2 list relevant software available to simulate earthquake surface fault rupture. It shows which software supports which operating systems, and whether it is open source. Note: there are no software packages available for the closed-form and probabilistic analysis procedures.

The software listed in Sections 5.1 and 5.2 can be used to perform either a pseudostatic or dynamic analysis. FLAC and PFC from Itasca Consulting Group have been used to perform both static and dynamic analyses. FLAC implements the Finite-Difference Method while PFC is based on the Discrete-Element Method (DEM). In general, Itasca software is Windows-based and closed-source software. In addition to the software offered by Itasca, the geotechnical FEM software suite PLAXIS is also able to perform dynamic and pseudostatic analyses, though it is also proprietary, closed-source, and restricted to Windows. General FEM solvers, such as LS-Dyna and ABAQUS, support user-defined constitutive models and have been used successfully for large-scale pseudostatic and dynamic analyses, but these programs are proprietary. The open-source FEM package OpenSees is capable of performing pseudostatic and dynamic simulations, and is supported on MacOS, Windows, and Linux operating systems. LIGGGHTS, an open-source (at least partially) DEM package, is capable of performing both pseudostatic and dynamic analyses. Some functionality within LIGGGHTS is not available in the public version. The source code for the public version is available at https://github.com/CFDEMproject/LIGGGHTS-PUBLIC.

1.3 Earthquake - Soil Liquefaction

Jonathan D. Bray
Professor, UC Berkeley

Michael Gardner
Postdoctoral Researcher, UC Berkeley

Chaofeng Wang
Postdoctoral Researcher, UC Berkeley

Soil liquefaction has cause much damage in recent earthquakes [e.g., Cubrinovski et al. (2011;, 2017 and Bray et al. (2017)]. The recent National Academy of Engineering's recent report "State of the Art and Practice in the Assessment of Earthquake-Induced Soil Liquefaction and its Consequences" states (Kavazanjian et al., 2016): Liquefaction occurs when stresses and deformation in the ground caused by earthquake shaking disturb the soil structure (i.e., the arrangement of individual soil grains—namely, the soil fabric) of saturated, geologically unconsolidated soils. Water in the pore spaces between soil particles will resist the natural tendency of the soils to consolidate into a denser and more stable arrangement during shaking. Because the soil cannot change in volume until water is drained from the pore spaces, porewater pressure will rise, and soil particles may lose contact with each other. This chain of events is referred to as liquefaction triggering. When liquefaction triggering occurs, the soil may lose much of its stiffness and strength, and it may also become easier to deform and may flow laterally. Similarly, the soil may also lose its ability to support an overlying structure or buried utility.

As summarized in the Kavazanjian et al. (2016) report, consequences of liquefaction may include vertically or laterally displaced ground, landslides, slumped embankments, foundation failures, and mixtures of soil and water erupting at the ground surface. These effects may lead, in turn, to settlement, distortion, and the collapse of buildings; the disruption of roadways; the failure of earth-retaining structures; the cracking, sliding, and overtopping of dams, highway embankments, and other earth structures; the rupture or severing of sewer, water, fuel, and other lifeline infrastructure; the lateral displacement and shear failure of piles and pier walls supporting bridges and waterfront structures; and the uplift of underground structures.

1.3.1 Methods for Liquefaction Analysis

Analysis of liquefaction and its consequences remains one of the more active areas of research and development in geotechnical engineering. Methods for estimating liquefaction triggering and its consequences vary. They fall into two categories: simplified methods and mechanics-based numerical methods.

Simplified methods

In 1998, a consensus was reached within the geotechnical community on the use of an empirical stress-based approach for liquefaction triggering assessment called the "simplified method," first developed in Seed and Idriss (1971). This method is still the most commonly used application in practice (Youd and Idriss, 2001, Kavazanjian et al., 2016).

In a simplified method, a factor of safety (FS) against liquefaction triggering, defined as the ratio between the seismic loading required to trigger liquefaction (i.e., the liquefaction resistance) and the seismic loading expected from the earthquake (i.e., the seismic demand), is computed. Both the seismic demand and the liquefaction resistance are characterized as cyclic stress ratios, defined as the ratio of the cyclic shear stress to the initial vertical effective stress. The seismic demand is the earthquake-induced cyclic stress ratio (CSR), and the liquefaction resistance is the cyclic resistance ratio (CRR): that is, the cyclic stress ratio required to trigger liquefaction.

Seed and Idriss (1971) proposed a simplified equation, based on Newton's second law, to compute a representative CSR for a given earthquake magnitude. This model was later improved by Idriss (1999), Cetin and Seed (2004), Idriss and Boulanger (2008), and Idriss and Boulanger (2014).

The most common approaches used in practice to compute CRR are based on geotechnical field data, e.g., the Standard Penetration Test (SPT), the cone penetration test (CPT), and measurement of in-situ shear-wave velocity (Vs).

The most commonly used relationships to predict CRR from SPT blow count are those proposed by Youd and Idriss (2001), Cetin and Seed (2004), Idriss and Boulanger (2008), and Idriss and Boulanger (2014). The most commonly used relationships to predict CRR from a CPT profile are those developed by Robertson and Wride (1998), Idriss and Boulanger (2008), and Kayen et al. (2013). The most popular and best Vs-based correlation method available is that of Andrus and Stokoe II (2000), which is well documented in the NCEER workshop summary paper (Youd and Idriss, 2001).

Mechanics-based numerical simulation

The development and rigorous validation of numerical analysis tools and procedures for predicting the effects of liquefaction on the built environment is identified as an overarching research need (Bray et al., 2017). Numerical analysis is critical for several reasons, including obtaining insights on field mechanisms that cannot be discerned empirically, providing a rational basis for developing or constraining practice-oriented engineering models, and providing the essential tool for evaluating complex structures with unique characteristics that are outside the range of empirical observations.

Finite-element and finite-difference procedures are the most common procedures used in engineering practice. As pointed out in Bray et al. (2017), there are major challenges to developing robust validated numerical analysis procedures for the effects of liquefaction on civil infrastructure systems due to the variety of multiscale, multi-physics coupled nonlinear interactions that come to the forefront in different scenarios where analytical capabilities for liquefaction effects have not been validated (or, worse yet, have been invalidated). Currently, neither research nor commercial software platforms are able to incorporate the best available solution techniques/options for each of the challenging problems, such as the coupled, large-deformation analysis of strain-softening, localizations, cracking, and interfaces in two or three dimensions with complex constitutive models.

1.3.2 Systems and Software for Liquefaction Assessment

Systems for liquefaction evaluation are divided by two categories according to the method used: empirical methods and mechanics-based numerical methods.

Empirical methods have been developed for rapid engineering evaluations of site-specific liquefaction. To date, no open-source software is available. LiqIT, Cliq, NovoLIQ, and LiquefyPro are all Windows based. These tools provide a user interface that can let the user input the soil profiles and earthquake intensity, and then visualize the liquefaction index for each soil layer.

For mechanics-based numerical methods, creating a constitutive model that reflects the soil's behavior under cyclic loads is crucial. Commercial software such as PLAXIS and FLAC are widely used by the geotechnical community. Both of them are Windows based. OpenSees is the only open-source software identified for dealing with liquefaction. Several well-known liquefaction-capable constitutive models are: PM4Sand, PM4SILT, PDMY02, UBCSAND, and DAFALIAS-MANZARI. Except for UBCSAND, they are all available in OpenSees.

1.4 Earthquake – Slope Stability and Landslides

Jonathan D. Bray
Professor, UC Berkeley

Michael Gardner
Postdoctoral Researcher, UC Berkeley

Chaofeng Wang
Postdoctoral Researcher, UC Berkeley

Earth structures and natural slopes may experience deformation when subjected to seismic loading. When considering the response of these systems, it is important to first identify whether materials that may lose significant strength as a result of cyclic loading are present. If so, the system may be at risk of "flow sliding," typically associated with liquefaction, which may lead to large deformations that can severely compromise an engineered system. Except for a dynamic nonlinear effective stress analysis, the methods presented in this section assume that liquefaction does not occur, and slopes will instead undergo some amount of deformation due to incremental displacements during seismic shaking due to inertial loading.

In the simplest case, a pseudostatic seismic slope stability analysis provides a FS for a given system based on a particular seismic event, while more advanced methods will provide estimates of the range of displacements anticipated. Regardless of the analysis procedure employed, important aspects to capture in the analysis are the earthquake ground motion, the material properties of the particular system being considered and its foundation, its geometry, and the initial state of stress- and pore-water pressures in the system and its foundation. Much depends on the intensity, frequency content, and duration of the earthquake ground motion, the dynamic resistance of the earth slope, which is defined by its yield coefficient, and the dynamic response characteristics of the soil system being shaken.

1.4.1 Procedures for Evaluating Seismic Slope Displacement

There are three primary approaches employed currently in estimating seismic slope displacements, which are listed in order of increasing complexity:

Pseudostatic stability analyses

The earthquake loading is represented as a constant horizontal seismic coefficient, which is a function of the characteristics of earthquake shaking and the dynamic response characteristics of the slope. The seismic coefficient can be calculated as the maximum value of the summation of the differential masses of the sliding blocks each multiplied by the acceleration acting on them over time divided by the total weight of the sliding mass. For this type of analysis, the required inputs are soil-strength parameters, slope geometry, water pressures, and the pseudostatic seismic coefficient. The results do not provide information about the anticipated deformation. Prevalent pseudostatic methods used are Seed (1979), Hynes-Griffin and Franklin

(1984), Bray and Travasarou (2009), Rathje and Antonakos (2011), Song and Rodriguez-Marek (2014), and Macedo et al. (2018)

Newmark-type sliding block analyses

Newmark-type sliding block analyses provide a range of anticipated seismically induced permanent deformations that serve as an index of performance of a particular system. These simplified procedures consider the displacement the sliding mass experiences and, in some procedures, the dynamic response of the sliding mass itself. Methods that consider the dynamic response of the sliding mass consider this response as either decoupled or fully coupled. Typical inputs for these procedures provide information about the characteristics of the earthquake shaking being considered—moment magnitude, Arias intensity, PGA, and PGV—as well as dynamic properties of the sliding mass—the initial and degraded fundamental period of the sliding mass, spectral acceleration at the degraded period, and the seismic coefficient at which the sliding mass will yield, which is called the yield coefficient. From these inputs, the analysis provides estimates of the seismic displacement, the probability of some displacement occurring or, in some cases, the probability of exceeding an allowable displacement. Note: these methods are semi-empirical and are applicable primarily to events exhibiting similar features to those contained in the dataset used to develop a particular procedure. Popular procedures include Makdisi and Seed (1978), Lin and Whitman (1986), Rathje and Bray (2000), Travasarou et al. (2004), Jibson (2007), Bray and Travasarou (2007), Saygili and Rathje (2008), and Rathje et al. (2014) for shallow crustal earthquakes and Bray et al. (2017) for subduction zone earthquakes.

Dynamic nonlinear effective stress analyses

Continuum-based methods, such as finite-element or finite-difference methods, are employed with soil constitutive models to analyze the dynamic response of the system to earthquake loading. This type of analysis requires much greater effort computationally as the partial differential equations describing the mechanical response of the soil are numerically integrated over the full time history of various loading events. Additionally, extensive information about the soil conditions at the site is required such that constitutive models can be sufficiently calibrated to attain meaningful results. Unlike the pseudostatic and simplified methods, this type of analysis is still applicable in the event that liquefaction is anticipated to occur at the site. It is the state-of-practice to employ dynamic nonlinear effective stress analyses in the evaluation of critical earth systems, such as dams, tailing dams, ports, and large earth-retention systems. Examples of constitutive models employed for dynamic analyses are Yang et al. (2003), Byrne et al. (2004), and Boulanger and Ziotopoulou (2015).

1.4.2 Systems and Software for Seismic Slope Stability Analysis

Section 5.1 lists the relevant software available for the solution procedures for evaluating slope stability risk due to earthquakes, including which operating systems the software supports and whether it is available open source.

In terms of pseudostatic analyses, spreadsheet solutions or, more commonly, proprietary software is used to solve for the limit equilibrium factor of safety. Commonly-used proprietary packages include Slide from RocScience, Slope/W from GEOSLOPE, and UTEXAS4 from ENSOFT. None of these packages are available open source and only support Windows-based operating systems.

Newmark-type sliding block analyses are widely used in spreadsheet solutions and some authors have released pre-programmed spreadsheets that implement their methods. Additionally, SLAMMER, an open-source Java application, allows users to choose from various simplified methods as well as running rigid block, decoupled sliding block, and fully coupled displacement calculations on time histories selected from an included catalog. Users can also add records to the catalog. Since SLAMMER is Java based, it is capable of running on any operating system through the Java Virtual Machine (JVM). The source code is available at https://github.com/mjibson/slammer.

Should a full dynamic nonlinear effective stress analysis be required, many proprietary software packages capable of performing this type of simulation are available. In both practice and research, FLAC, developed by the Itasca Consulting Group, is commonly used to perform dynamic analyses. In general, Itasca software is Windows based and closed source. In addition to the software offered by Itasca, the geotechnical FEM software suite PLAXIS is also able to perform dynamic analyses; it is also proprietary, closed source, and restricted to Windows. General FEM solvers such as LS-Dyna and ABAQUS support user-defined constitutive models and have been used successfully for large-scale dynamic analyses but are proprietary. The only open-source software available capable of performing dynamic nonlinear effective stress simulations is OpenSees. Though less commonly used in engineering practice, OpenSees has gained in popularity within the research community, and users are able to select from many pre-programmed soil constitutive models. Additional constitutive models can also be added. OpenSees is supported on MacOS, Windows, and Linux operating systems.

1.5 Tropical Cyclone - Wind

Ahsan Kareem
Professor, University of Notre Dame

Liang Hu
Graduate Research Assistant, University of Notre Dame

Extreme wind induced by tropical cyclones (TC - hurricane/typhoon/tropical storm) dominates the wind loading on structures in the U.S. coastal areas. To assess the damage, loss, and performance of buildings probabilistically under wind hazard as well as its secondary hazards (flood, rain, debris, storm surge, etc.), this section describes computational models and inputs available for estimating statistical characteristics of TC-induced wind speeds.

Usually, field measurements of TC are limited and insufficient for estimating the probabilistic description of wind speeds; thus they are usually generated by Monte Carlo-based procedures. Such a simulation procedure starts from sampling input physical properties of a hurricane (e.g., intensity, track, and Holland B parameter) in terms of their individual probabilistic characteristics to simulate the wind field by which the wind speeds at a specific site may be recorded and estimated (Russell 1969). The simulation is carried out by employing phenomenological models of the hurricane wind field with random parameters. Other models based on meteorological aspects [e.g., MM5 (Liu et al., 1997) and WRF (Davis et al., 2008)] are beyond the scope of this section. Three types of TC wind-field models are currently available. The first two models aim to solve the governing equation of motion of the TC atmospheric system directly using the central difference method: (I) height-resolved models, which are able to resolve the vertical structure of a tropical cyclone; and (II) slab models, which include an average or integration over the height of the governing equations. In contrast, the type III physics-based models solve the intensity and radial profile equations instead. The input variables are dependent upon the type of model selected.

1.5.1 Input and Output Data

Measurements

Through the past two centuries, data from recorded TCs have been used by the wind engineering community to create and calibrate probabilistic models. The National Oceanic & Atmospheric Administration (NOAA) provides an extended and comprehensive TC database for the Atlantic and Northeast Pacific, which encompasses data from reconnaissance and microwave and dropsonde radar, as well as anemometer measurements (NOAA Reanalysis Data 2018). Additional field measurements supplement this database [e.g., (Li et al., 2015b; Wang et al., 2016)].

Occurrence rate

This parameter describes the number of hurricanes that occur at a specific site. It is usually described by a Poisson or binomial distribution, whose parameters are obtained by statistics over the hurricane database (Li et al., 2016; Vickery et al., 2009c).

Track model: Initial location, Translation speed, and Heading

The track model describes the genesis point, heading direction, and translational speed of the center of a TC for simulation purposes. For a specific hurricane in the NOAA database, its best empirical track of the hurricane has already been synthesized by data fitting over various measurements. The database also describes how other TC parameters change along the track. For a specific site, the sub-region track model can be used, which only concerns the segment of TC tracks within a circle (often the radius is 500 km) centered at the site. This model is characterized by the perpendicular distance to the center and direction angle of the straight line track (Georgiou, 1986; Xiao et al., 2011). However, the full track model is more popular in describing the genesis to dissipation of a TC because it enables the simulation of extreme TC winds simultaneously for a large region rather than a specific site. The genesis location can be randomly selected from the historical record or generated on the basis of its distribution function (Vickery et al., 2009c). Starting from the genesis location, the track is generated by Markov-type models, represented by auto-regressive functions in terms of TC parameters (latitude translation speed, sea surface temperature, etc.) as well as a random error term (Vickery et al., 2000b), or by the Markovian transition probability function (Emanuel et al., 2006). The parameters of track models must be estimated from the hurricane database as well as other measurements (e.g., HadISST) (Li et al., 2016; Liu 2014; Vickery et al., 2000b). Recent investigations usually apply the kernel method for modeling those parameters (Chen and Duan, 2018; Mudd and Vickery, 2015). Moreover, a dynamic track model (Beta-advection) has been developed based on isobaric wind speed measurements (Emanuel et al., 2006).

Intensity: Central pressure difference or maximum wind speed

Type I and II hurricane models use the central pressure difference as the proxy for the TC intensity. Here, an auto-regressive model for the TC relative intensity (a function in terms of the pressure difference) has been established along with the track models. The Type III model employs the maximum mean wind speed as the intensity measure, which may be predicted by a simple coupled ocean-atmosphere physical model CHIPS (Coupled Hurricane Intensity Prediction System) with its fast simulation algorithm (Emanuel, 2011; Emanuel, 2017; Emanuel et al., 2004) or by the historical record-free generator (Emanuel et al., 2008).

Size: Radius to maximum winds (RMW)

The Radius to Maximum Winds (RMW) denotes the size of a TC and is the only TC size parameter considered in Type I and II models. Type III models need additional parameters, e.g., the radius at the wind speed of 15.5 m/s (Chavas and Lin, 2016). The probabilistic distribution of these size parameters can be estimated from the TC database. However, an empirical model of RMW has been developed in terms of the location and intensity parameters as well as a random error term (Vickery and Wadhera, 2008; Vickery et al., 2009b).

Shape of radial profile: Holland B parameter

The B parameter was introduced by Holland (1980) revised the radial pressure profile in Type I and II models to improve the goodness-of-fit of the maximum wind speed. From the TC database, this parameter can be estimated with respect to the reconnaissance data, which evolves with time. Similar to RMW, statistical models are available for B as a function of RMW and latitude (Powell et al., 2005) or of a dimensionless function involving SST additionally (Vickery and Wadhera, 2008). A physics-based model has also been proposed by Holland (2008) and Holland et al. (2010).

Local terrain

The local topography at a specified site accounts for the boundary layer wind speed profile as well as the gust factor. A typical parameter of local terrain is the roughness length (or equivalently the shear velocity), which reflects the effects of upstream terrain within ~3 km on the near-ground winds. Calculating this parameter is challenging, especially in consideration of the rapid change of wind azimuth during a TC (Vickery et al., 2009a). It can be adopted from existing design codes/specifications and augmented by additional computations by taking average over various terrains along each wind direction. As long as field measurements of gust wind speeds are available at the specified site, the roughness length may also be estimated from the record (Masters et al., 2010). Furthermore, the CFD-based method is also available to estimate the local wind characteristics with detailed modeling of surrounding terrains, which, though computationally inefficient, is expected to yield more accurate results and is often the only reliable method for complex terrain (Huang and Xu, 2013; Ishihara et al., 2005).

Landfall model parameters

After a hurricane makes landfall, the filling model starts to describe the weakening of the TC intensity, or, in other words, the increase in the central pressure difference. This model is typically an exponential decay function, whose decay constant is the filling rate as a statistical function in terms of the intensity, translational speed, and RMW (Vickery and Twisdale, 1995; Vickery, 2005; Vickery et al., 2009b). Moreover, both the mean wind speed vertical profile and radial profile are subject to notable changes after landfall, which may be captured by recently developed empirical models (Fang et al., 2018b; Snaiki and Wu, 2018; Zhao et al., 2013).

Output: Wind field

The main output of a TC simulation from an engineering perspective is the probabilistic model (CDF) of mean wind speed in any specified target location/region. A single hurricane scenario results in a mean wind speed and direction time history, usually at the 6-hour time interval. Additional effects of atmospheric turbulence may be reflected by gust factors as well as spectra. These results serve as the IM for the ensuing performance-based wind engineering analysis (Barbato et al., 2013; Chuang and Spence, 2019; Liu, 2014; Spence and Kareem, 2014; Unnikrishnan and Barbato, 2016; Xiao et al., 2011; Yau et al., 2011).

1.5.2 Modeling Approaches

Provided the inputs stated above, all TC wind field models aim at solving the steady mean wind speed from the 3D governing equation system describing atmospheric motion in a TC. Type I models solve the 3D motion equation system without any dimensional reduction; Type II and III models are, per se, 2D methods. Type II considers the equation system reduced from the original one, whereas the Type III model solves angular momentary equations derived by the physics-based mechanism of the TC rather than the original motion equation. Here, Type I models are able to solve wind speeds throughout the TC boundary layer height, whereas the other two models solve wind speeds at the gradient height, which are then converted to near-ground heights by the boundary layer wind speed profile. All the solved TC wind speeds need to be combined with the surface background wind speed, implying the use of the TC translational speed for Type I and II models. Eventually, the gust factor is applied to the mean wind speed to account for turbulence. Nonstationary effects associated with TC winds may also be considered.

Type I model

The basic atmospheric motion governing equation of TC is nonlinear and 3D, which can be solved numerically by the two-time-level time-split-based central difference scheme (Kepert and Wang, 2001; Kepert, 2011). It accounts for the salient height-related effects of both potential temperature and eddy viscosity (turbulent diffusivity represented by the vertical turbulent exchange coefficient K for momentum and heat) (Kepert and Wang, 2001; Kepert, 2010b). Linearization of the nonlinear equation has been carried out considering the gradient balance wind speed to yield the surface horizontal momentum equations (Kepert, 2001). The linearized equations are then solved by utilizing the perturbation method (Meng et al., 1995) or the Fourier series expansion (Kepert, 2001). Depending on the form of eddy viscosity (constant, height-dependent, or piece-wise linear or nonlinear) and the terms being neglected, various semi-analytical solutions are obtained (Fang et al., 2018a; Huang and Xu, 2013; Kepert, 2006; Meng et al., 1995; Meng et al., 1997; Snaiki and Wu, 2017). In comparison with the nonlinear solution, these linear solutions sacrifice accuracy to reduce computational costs (Kepert and Nolan, 2014).

Type II model

By integrating the 3D equation over the vertical coordinate, a slab (or depth-averaged) model is derived (Kepert, 2010a). This model still involves the vertical turbulent diffusivity and is capable of calculating the vertical wind speed (Langousis, 2008; Smith, 1968; Smith and Vogl, 2008) . Further simplification is achieved by removing both the advective and/or diffusive fluxes at the upper boundary, leading to the common category of TC models popular in the structural engineering community (Powell et al., 2005; Shapiro, 1983; Vickery et al., 2000a; Vickery et al., 2009b). Chow (1971) was the first to develop a central difference scheme to solve the model. Since then, other issues in this model have been addressed to enhance its applicability, e.g., the boundary layer, drag coefficient, track model, and approximate fast algorithm. So far, the parameters of this model have been well-recognized probabilistically based on the TC database (Vickery and Wadhera, 2008). A review paper guiding application of this model is also available (Vickery et al., 2009a). Note: the TC intensity and track inside this model are being updated (Mudd et al., 2015; Vickery et al., 2010).

Type III model

The foundation of this approach is a physics-based intensity model derived by regarding the TC as a Carnot heat engine (Emanuel, 2004; Emanuel, 1988). The maximum wind speed-represented intensity can be calculated along the track (Emanuel, 2011). Although a simple formula was used as the radial profile at the gradient height (Emanuel et al., 2006; Lin and Chavas, 2012), a more reliable model has been proposed by dividing the profile into its inner and outer regions. Physics-based expressions for the two regions have been derived and then joined by a differential equation system to establish the whole profile (Emanuel, 2004; Emanuel and Rotunno, 2011). Given the input, only the equation system of the profile need be solved iteratively (Chavas and Lin, 2016; Chavas et al., 2015) . The empirical models for converting the resulting gradient wind speeds to surface winds are different from the counterparts in the other two types of models.

Validation

All three models have been validated by comparing indicators (characteristics) obtained from the simulation results with those estimated from TC in the database. The validation of the models consisted of taking input adopted from one or multiple TCs and determining if the indicators estimated over the output of a model match their target values (at least in the probabilistic sense). The appropriate indicator of validation may vary as it is dependent on the major characteristics of the specific type of models. Results of Type II models have been validated by almost all recent available TCs in the database in terms of the maximum wind speed as well as the time histories of both wind speed and direction (Li and Hong, 2016; Vickery et al., 2000a; Vickery et al., 2009b). The validation results suggest the Type II model by Vickery qualifies as a design tool in the ASCE specification (Vickery et al., 2009c). The indicators of Type I model include the pressure snapshot, vertical profile of mean wind speeds, and the radial profile, suggesting satisfactory validation. The radial profile using the Type III model also matched the target profiles well (Chavas et al., 2015; Emanuel, 2004; Emanuel et al., 2006). Finally, it is suggested that the CDF of wind speeds generated by all the models should be validated for the Type II and III models [e.g., Emanuel et al. (2006) and Li et al. (2016)].

Comparison

An investigation benchmarked by the MM5 (Liu et al., 1997) suggests that generally the 3D models may outperform the 2D models, underscoring that the nonlinear solution is always superior (Kepert, 2010a; Kepert, 2010b; Kepert and Nolan, 2014). It also states that the Type II model is unable to replicate accurately the TC in the database due to the model neglecting many critical factors that are key for accurate results (Kepert, 2010a). Comparisons have also been carried out between specific models that belong to Type II and Type III (Smith et al., 2008), or between models that belong to the same type (Snaiki and Wu, 2017; Wills et al., 2000). Currently, a comprehensive comparison covering all three model types is not available.

Boundary layer wind speed profile

While a TC is still over the ocean, the marine wind speed profile in the boundary layer varies with model type. Type I models and height-resolved Type II models can generate the profile of the simulated wind field. Whether the generated profile can approximate well the ones estimated by dropsonde measurements in the TC database is still open for debate (Kepert and Wang, 2001; Kepert, 2011; Kepert, 2013; Montgomery et al., 2014; Smith, 1968). For the remaining Type II models, an empirical profile formula has been proposed based on extensive statistics over the TC database and applied to the linearized 3D model of Type I (Vickery et al., 2009b). Although such measurements may occasionally suggest applicability of the power law (Song et al., 2016), this formula is a deeply revised version of the logarithmic law. This profile, developed for the Type II model, may be applicable to the Type III model, but, so far, the latter model simply adopts a constant value of 0.85 to convert wind speeds from the gradient height to 10 m over the ground (Chavas et al., 2015). In contrast to the over-ocean case, after landfall the profile of a TC may be altered as described by the semi-empirical model (Snaiki and Wu, 2018). Finally, for a specific land-based site, the wind speed profile of concern is heavily influenced by its surrounding terrain (Huang and Xu, 2013).

Drag coefficient

The surface drag coefficient is a common parameter shared by all three model types. It can influence significantly the final simulation results, especially the predicted maximum wind speed (Li and Hong, 2015; Powell et al., 2003). Currently, the velocity-dependent and constant models are extensively used for the over-ocean and over-land cases, respectively, but their appropriateness is still arguable (Smith et al., 2014).

Turbulence

Recent empirical data shows no significant difference between gust factors in TC and non-TC winds (Vickery et al., 2009a). This implies that local terrain dominates turbulence effects even in winds generated by a TC, thus allowing for the use of gust factor models based on regular wind data [e.g., ESDU (1983)]. In contrast, a recent study discovers an apparently different spectral model for the turbulence in TC winds. In this conceptual model, the spectral contents of TC winds at the highly reduced frequency range are higher than non-TC winds (Hu et al., 2017; Li et al. 2015a).

Nonstationarity

Typically, TC winds involve both short-term and long-term nonstationary properties of concern in performance-based wind engineering. The mean wind speed, direction, and spectral contents of a TC are all time–dependent, evolving within the lifetime of TC. Considering short-term nonstationarity of winds, the nonstationary wind loading is induced on a target structure, whose effects on structural response as well as performance have been investigated (Kareem et al., 2018; Kwon and Kareem, 2009; Yau et al., 2011). Long-term nonstationarity effects relate to the life-cycle of the target structure. Over the long term, the input of TC models, e.g., the occurrence rate and the intensity, may evolve with time because of climate change (Emanuel, 2005). These long-term nonstationary effects have been assessed by integrating the TC models with the current climate change models (Emanuel et al., 2008; Lauren et al., 2014; Lin, 2015; Liu, 2014).

1.5.3 Software and Systems

Currently, there is no exclusive software publicly available for generating the wind hazard IM for TC simulations; however, a module designed for such a task is included in both the HAZUS (Vickery et al., 2006) and FCHLPM (Florida Commission on Hurricane Loss Projection Methodology (Hamid et al., 2010; Powell et al., 2005) software. Both programs are based on Type II TC models, although the technical details populating the programs are slightly different. The programs are Windows based, publicly available, and controlled by a GUI. Such in-house software exists in research laboratories around the world.

1.6 Tropical Cyclone - Storm Surge

Tracy Kijewski-Correa
Associate Professor, University of Notre Dame

George Deodatis
Professor, Columbia University

Yuki Miura
Graduate Research Assistant, Columbia University

Within the context of the applications envisioned by the SimCenter, coastal simulations must be responsive to a specific tropical or extratropical storm scenario, generally described by a storm track or set of parameters representative of that track, and sensitive to the local topography and offshore bathymetry. These simulations yield geospatially distributed estimates of storm surge (storm-induced rise in seawater levels, primarily caused by wind) for the purposes of direct and indirect loss assessment for coastal communities (Jacob et al., 2011). Estimates of storm-induced inundation, due to combined effects of storm surge and waves driving water over land, are important outputs from any simulation environment that help quantify damage to structures as well as above and below ground civil infrastructure.

In general, it is preferable to manage the model fidelity versus computational efficiency trade off through the use of surrogate models, which can reduce CPU time from hundreds and even thousands of hours to minutes. This enables computationally efficient means to characterize uncertainty in the hazard (e.g., the hurricane track) for the purpose of risk assessment (Kijewski-Correa et al., 2014).

1.6.1 Common Modeling Approaches

This section examines the three classes of models commonly coupled to capture storm surge and accompanying wave effects nearshore and overland, as well as surrogate models that can be tailored to these coupled models for a computationally efficient simulation alternative. Note: this is not an exhaustive presentation of the simulation tools available for coastal hazards but focuses only on those viewed as the industry standard. Simulation tools for coastal hazards have continued to evolve, including the ADCIRC and GEOCLAW/CLAWPACK software (Mandli et al., 2016) with a geographical information system (GIS).

Storm surge heights and inundation

Numerical models for storm-surge simulations are typically based on single-layer-depth average differential equations describing fluid motion driven by storm winds that make assumptions about the ocean's response to the storm. This approach is significantly more efficient computationally compared to using a CFD-based approach, such as OpenFOAM. The available numerical models differ in their computational solution strategies, which has implications on the spatial and temporal resolution of the simulations, the required computational resources and runtimes, and the required input data and model parameters. Generally, these models capture the amplitude of long-period, long-gravity waves and do not simulate short-period wave effects, which are addressed in subsequent sections.

The National Weather Service (NWS) utilizes a storm-surge model called Sea, Lake and Overland Surges from Hurricanes (SLOSH), which solves the water equations using local grids (Jelesnianski et al., 1992). It was developed to provide real-time estimates of storm surge with computational capabilities of the 1990s; therefore, the grid resolution and the resulting spatial resolution of the results are fairly coarse. As reported by Mandli and Dawson (2014), a primary limitation of SLOSH is "the limited domain size and extents allowed due to the grid mapping used and formulation of the equations." Nevertheless, since its initial development, SLOSH has continued to be updated and is used for real-time forecasts of surge for public advisories and to inform emergency responders.

The ADvanced CIRCulation (ADCIRC) methodology is commonly regarded as the state-of-the-art in coastal storm-surge simulation (Luettich Jr. et al., 1992), capable of providing significantly more accurate simulations than methods based on SLOSH (Resio and Westerink, 2008) in near-shore coastal regions. As such, ADCIRC is the preferred methodology for coastal storm-surge investigations by the U.S. Army Corps of Engineers (USACE) and in the generation of FEMA Flood Insurance Rate Maps (FIRMSs). ADCIRC solves the equations of motion describing a moving fluid on a rotating earth, formulated using the traditional hydrostatic pressure and Boussinesq approximations, and discretized in space using the finite-element method and in time using the finite-difference method. ADCIRC can be run either as a 2D depth integrated (2DDI) model or as a 3D model, with elevation resulting from the solution of the depth-integrated continuity equation in generalized wave-continuity equation (GWCE) form. Furthermore, velocity is obtained from the solution of either the 2DDI or 3D momentum equations, retaining all nonlinear terms. ADCIRC simulations have been validated for major hurricanes such as Katrina, Ike, Gustav, and Iniki (Kennedy et al. 2011, 2012).

GEOCLAW, the third computational platform, lies between SLOSH and ADCIRC in terms of modeling resolution and computational cost. Originally developed to simulate tsunami inundation, GEOCLAW has recently been adapted to simulate storm surge (Berger et al., 2011, Mandli et al., 2014). Based on the CLAWPACK software libraries (LeVeque, 2002), GEOCLAW is an open-source, finite-volume, wave-propagation numerical model used to estimate hurricane-induced storm surge along a coastline. For overland flooding, the model uses Manning's N to parameterize roughness due to objects such as trees and small-scale structures that cannot be resolved computationally. Adaptive mesh refinement allows GEOCLAW to place computational resources where and when they are needed during a simulation. Thus, the overall cost of the simulation is reduced, while retaining the same or similar accuracy characteristics to ADCIRC. Shown in Figure 1-1 is a comparison of results calculated using GEOCLAW versus ADCIRC.

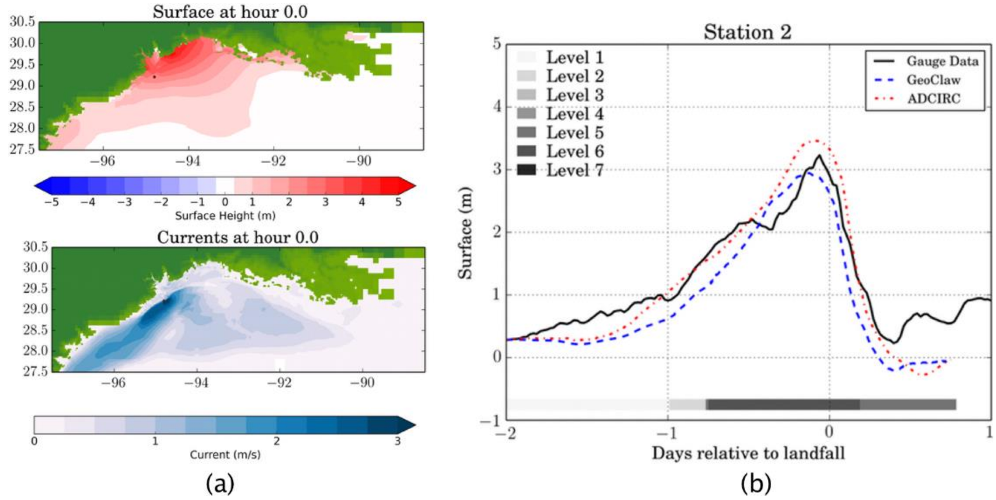

Figure 1-1 (a) A snapshot of a GEOCLAW storm surge simulation of Hurricane Ike at landfall; and (b) tide gauge data computed from GEOCLAW and ADCIRC along with observed data at the same location. (Mandli et al., 2016)

Nearshore wave models

The three platforms described above simulate the long-wave surge heights but do not capture local wave effects. To overcome this limitation, ADCIRC simulations have been coupled with different nearshore wave models. ADCIRC has been coupled previously with Simulating Waves Nearshore (SWAN) (Kennedy et al., 2012), a third-generation wave model developed at Delft University of Technology, that computes random, short-crested wind-generated waves in coastal regions and inland waters (Zijlema, 2010). The most recent North Atlantic Coastal Comprehensive Study (NACCS) (USACE 2015) employs STWAVE, which is a steady-state, finite difference spectral model for nearshore wind-wave growth and propagation based on the wave action balance equation (Smith et al., 2001). STWAVE simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wave growth because of wind input, and wave–wave interaction and white capping that redistributes and dissipates energy in a growing wave field. Figure 1-2 validates the coupled hydrodynamic models used in the NACCS by comparing to measurements across historical storms or tide predictions (Nadal-Carabbalo et al., 2015).

Wave run up overland

Even when coupled with an appropriate nearshore wave model, ADCIRC simulates only the storm-surge elevation and not the additional impact of wave run up, which is particularly important for predicting losses to buildings and infrastructure in a storm event. Supplementary wave run-up simulations are required to capture the interaction of the waves with the shoreline and any coastal protective features along coastal transects. Wave run-up calculations are executed at transect locations generally selected by segmenting the defined coastline in the areas of interest and selecting the transect density proportional to computational demand. Each transect is then discretized to capture the site-specific bathymetry (offshore) and topography (onshore) along its length. Moreover, transects must accurately capture the current condition of coastal protective features, e.g., dunes, in order to effectively predict the total run up inland. Inputs from the ADCIRC+STWAVE model are fed into a one-dimensional (1D) Boussinesq model executed at the pre-selected transects in order to estimate the wave run up overland (Demirbilek et al., 2009).

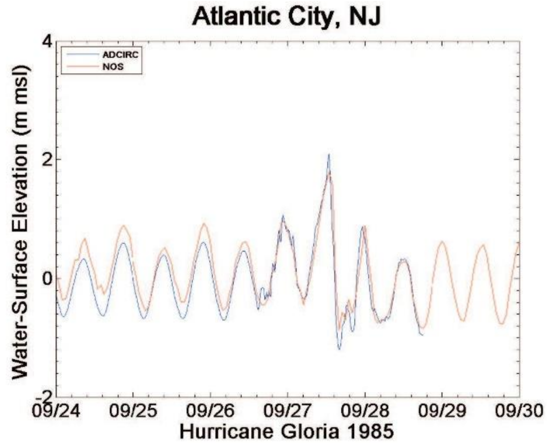

Figure 1-2 Validation of surge simulation in Atlantic City using coupled ADCIRC-STWAVE for historical storm Hurricane Gloria, courtesy of USACE (Nadal-Carabbalo et al., 2015)

Surrogate modeling approach

Given the high degree of sophistication and computational resources required to execute just one high-fidelity simulation (e.g., an ADCIRC+STWAVE/SWAN run), alternative simulation tools have been developed recently to enable a wider range of users to employ these models for hazard characterization, risk assessment, and design of coastal protective strategies. Most notably, surrogate modeling approaches can efficiently evaluate hurricane wave and surge responses by leveraging databases of existing high-fidelity simulations normally driven by a collection of historical and synthetic hurricane tracks (USACE, 2015). This is made possible by formulating a simplified description of a storm scenario by a small number of model parameters corresponding to its characteristics at landfall. The scenarios in the database are then parameterized with respect to this model parameter vector and ultimately provide an input–output dataset. Because the geospatial representation often covers a regional coastline (typically represented by a large number of nodes) and resolves the coastal hazards at different times during the hurricane's history, the dataset is often high-dimensional. After correcting for any dry nodes at inland locations, the surrogate model is then built to approximate this input-output relationship.

Although the initial implementations of the surrogate modeling approach relied upon a moving least-squares-response surface methodology, more recent implementations for natural hazard risk assessment now employ a Kriging metamodel for this purpose (Jia and Taflanidis, 2013). To further reduce the computational burden pertaining to both speed of execution and more importantly memory requirements, this approach is coupled with principal component analysis (PCA) as a dimensional reduction technique. The metamodel is then developed in this low-dimensional latent space (in this case below 100), with the predictions transformed back to the original space for visualization purposes. This PCA implementation contributes to very large computational savings necessary to enable the evaluation of a large ensemble of scenarios as required for a probabilistic evaluation while circumventing the need for HPC resources (Jia and Taflanidis, 2013). Validation of these surrogate models using leave-one-out cross validation (Taflanidis et al., 2017) suggested high accuracy, with coefficient of determination close to 0.96 and a correlation coefficient close to 98%. By permitting rapid evaluation of alternate storm scenarios, surrogate models offer an effective way to communicate simulation results to urban planners and emergency managers. One such implementation is a software system developed to assess storm surge risks on the coast of New Jersey (NJcoast, 2018a).

1.6.2 Required Inputs and Resulting Outputs

High-fidelity computational simulations of coastal hazards require: (1) storm track information, including the relevant description of the hurricane wind field to drive the model; (2) the topography and bathymetry along the coastline; and (3) the land use/land cover data for the simulation of wave run up on shore. The simulations are inherently sensitive to assumptions made regarding tides at the time of landfall. The coupling of a storm surge + nearshore wave + wave run-up model will yield geospatially-distributed, time-dependent responses, i.e., the mean water elevation, max water elevation, max water depth, and significant wave height (or limit of moderate wave action). Such responses can be generated either by the coupling of the aforementioned high-fidelity models or a surrogate model tuned to a database of results from these models. A brief summary of specific inputs required for ADCIRC, the wave run-up models, and the related surrogate models are as follows:

ADCIRC Inputs/Forcing

ADCIRC requires both boundary conditions, as well as forcing as inputs to the simulation. Boundary conditions include:

- specified elevation (harmonic tidal constituents or time series)
- specified normal flow (harmonic tidal constituents or time series)
- zero normal flow
- slip or no slip conditions for velocity
- external barrier overflow out of the domain
- internal barrier overflow between sections of the domain
- surface stress (wind and/or wave radiation stress)
- atmospheric pressure and outward radiation of waves (Sommerfeld condition)

ADCIRC can be forced by

- elevation boundary conditions
- normal flow boundary conditions
- surface stress boundary conditions
- tidal potential
- earth load/self-attraction tide

In the case of a comprehensive evaluation of coastal hazards due to hurricanes and nor'easters, planetary boundary layer numerical models are used to generate wind and pressure fields that drive these high-fidelity storm surge and wave hydrodynamic models (see Section 1.5 for details). These wind and pressure fields are developed for a suite of simulated or historical storm tracks for the targeted region (anywhere from hundreds to even thousands of storm tracks).

Wave run-up inputs

In addition to the topography and bathymetry data at each identified transect, the wave run-up model must receive inputs from the coupled storm surge model, e.g., ADCIRC+STWAVE. As selected transects may not align with saved data points from the ADCIRC+STWAVE simulations, a nearest neighbor approach is required to identify the inputs to the wave run-up models, specifically: the peak wave period from STWAVE, zero moment wave height from STWAVE, and water elevation from the closest ADCIRC data point.

GEOCLAW inputs

GEOCLAW requires gauge and topographical data as inputs to compute depth and momentum of the water at a number of locations. The storm surge simulation is driven by the provided time-dependent wind field and pressure distribution. The full field is constructed using the equations by Holland (1980).

Surrogate model inputs

Inputs to the surrogate model are twofold: the primary input required to develop the surrogate model itself is the aforementioned database of high-fidelity simulations for a family of storm tracks that may include tropical and extra-tropical storms. Once developed, users of the surrogate model input only a collection of parameters necessary to describe the storm scenario based on its characteristics at landfall:

- reference location (latitude, longitude)
- track heading (angle)
- central pressure (or pressure difference)
- forward speed
- radius of maximum winds

More recently, this implementation was further simplified to enable simulation based on only reference location and storm strength (Category 1-5) (NJcoast, 2018a). It is important to emphasize that once the surrogate model is tuned to high-fidelity simulation data for a specific geographic location, it can efficiently provide predictions for storm scenarios of varying characteristics, even if that scenario does not match any of those within the original database of high-fidelity simulations.

1.6.3 Primary Software Environments

The execution environments are briefly summarized below.

ADCIRC and coupled models

ADCIRC has been optimized by unrolling loops for enhanced performance on multiple computer architectures and can be executed on any operating system with a working FORTRAN compiler. These include large commercial Unix systems (IBM Power & Blue Gene, Cray, SGI, and Sun), Linux- and FreeBSD-based clusters, and personal workstations running Windows or Mac OSX. ADCIRC includes MPI library calls to allow it to operate at high efficiency on parallel computer architectures, which is often preferable for simulations over large domains where a single hurricane realization can require thousands of CPU hours. Coupled ADCIRC+SWAN models are available on all of the aforementioned platforms (with the exception of Windows), while the coupled ADCIRC+STWAVE model is available on all the platforms including Windows PCs as part of the Coastal Storm Modeling System (CSTORM-MS). ADCIRC and its parallel implementation, PADCIRC, along with the coupled ADCIRC+SWAN software, are available on DesignSafe.

CLAWPACK/GEOCLAW

Clawpack ("Conservation Laws Package") is a collection of finite-volume methods for linear and nonlinear hyperbolic systems of conservation laws. Clawpack employs high-resolution Godunov-type methods with limiters in a general framework applicable to many kinds of waves. GEOCLAW is an open-source, finite-volume, wave-propagation software, which is implemented in CLAWPACK, to estimate hurricane-induced storm surge with adaptive mesh refinement. The CLAWPACK 5.4.0 suite and the GEOCLAW tools are available through DesignSafe.

SLOSH

SLOSH (Sea, Lake and Overland Surges from Hurricanes) is a computerized numerical model developed by the National Weather Service (NWS) to estimate storm-surge heights determined from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure, size, forward speed, and track data. These parameters are used to create a model of the wind field that drives the storm surge. The SLOSH model consists of a set of physics equations that are applied to a specific locale's shoreline to incorporate the unique bay and river configurations, water depths, bridges, roads, levees, and other physical features. Storm-surge forecasts developed using SLOSH are available at https://www.nhc.noaa.gov/surge/slosh.php.

1.6.4 Major Research Gaps

Given the sophistication and computational demands of high-fidelity models like ADCIRC and GEOCLAW, continued advancements in metamodeling and other similar approaches will ensure that the wider research community can engage with computational simulation tools for coastal hazards without the barrier to entry that currently exists. Note: whether employing these high-fidelity models or a companion surrogate model, the resulting time-evolving water depth and velocity must translate into loadings on buildings and infrastructure. In this regard, these models face similar limitations as wind-field models given the complexity of interactions with their surroundings. Accurately capturing the physics of the flow overland and the effect of its interaction with the built environment on the load description remains a challenging problem, even without further accounting for the effects of debris transported in the flow. Identifying means to reasonably determine the impact of these interactions on the load description—without having to support an intensive CFD investigation—will enable a wider range of researchers to evaluate the impacts of coastal hazards.

1.7 Tsunami - Inundation

Michael Motley
Associate Professor, University of Washington

Patrick J. Lynett
Professor, University of Southern California

The simulation tools used to model tsunami inundation can generally be categorized as either 2D models or 3D models. Three-dimensional models solve Reynolds average Navier-Stokes (RANS) or Large Eddy Simulation (LES) equations numerically using the CFD techniques introduced in Section 2.4. Two-dimensional models often solve a different category of governing equations derived from the 3D Navier-Stokes (NS) equation by integrating in the vertical dimension, e.g., shallow water equations and Boussinesq wave equations where the two dimensions can be characterized as latitude and longitude. Because such equations are computationally much easier to solve than the RANS and LES equations, they are broadly used in large-scale modeling of geophysical flows, e.g. tsunami, storm surge, and flooding. Two-dimensional models are used especially when computational efficiency is a factor. Examples include building an early warning system, which requires tsunami modeling to be done as quickly as possible after an earthquake, versus a probabilistic assessment that often requires thousands of computational simulations.

1.7.1 Input and Output Data

Both 2D and 3D models need boundaries for the simulation and boundary conditions as input. In 2D models, buildings and bridges cannot be described directly, but are often only incorporated with the ground represented by the topography represented as an elevation field that varies in horizontal space. A finite region in the horizontal plane must be specified, inside which the flows are modeled. The boundary conditions on the boundary of this finite region must be specified, e.g., flows are allowed to flow out of the region freely on one side, and/or get reflected on the other. The topography (or bathymetry) data that describe the shape of the ground (or sea floor) must also be specified as input, although these are not interpreted as boundaries since the vertical dimension vanishes in a 2D model, and the topography data are treated as field variables that directly affect other field variables (like velocities) in the solver.

For 3D models, in general, flows must also be bounded in the vertical direction where the top boundary often represents the sky and the bottom boundary represents the ground. Additionally, the simulation incorporates buildings and bridges into the simulation by subtracting volumes that describe the geometry of those structures from the domain. The surface of these volumes thus becomes boundaries of the simulation domain as well, and their boundary conditions must be specified. Thus, the geometry of the structures must be provided as input if one wants to model them as well.

Both types of models also need input of initial conditions: namely, the state of the fluids before the simulation starts. For instance, the initial conditions for some nearshore regions might have the fluid at rest at sea level while somewhere far from shore, a large volume of water is placed above sea level to represent a tsunami wave. Different initial conditions will give different states later in time.

The output quantities from both 2D and 3D models include water surface and flow velocity; however, 3D models are able to output quantities that vary in the vertical direction. The 2D models do not depend on the vertical direction; therefore, its output quantities are generally not a function of positions in the vertical direction. Furthermore, the 3D models can usually output more quantities of interest, e.g., water pressure, which can be integrated to obtain fluid loading on structures.

1.7.2 Models and Software Systems

In general, tsunami simulation requires modeling at a wide range of spatial scales, including (from large- to small-scale) offshore propagation, beach run-up, inland inundation, and impact on individual structures.

For modeling that focuses on the large-scale phases, the 2D models are still the most prevalent choices for their simplicity and computational efficiency. Two major variants in this category are based on the shallow-water equations and Boussinesq wave equations, respectively. Models that are based on shallow-water equations have been applied broadly to ocean-scale tsunami modeling and local flooding as well (Berger et al., 2011; George, 2004, 2008; Hu et al., 2000; Hubbard and Dodd, 2002; Popinet, 2012; Qin et al., 2018; Wei et al., 2013) . Mathematically, the shallow-water equations do not model the dispersion in water waves directly, while the Boussinesq wave equations include an explicit dispersive term. Thus, many models based on Boussinesq wave equations have also been used (Kim et al., 2009, 2017; Lynett et al.,2010; Madsen et al., 2003; Madsen and Sørensen, 1992; Shi et al., 2012).

As computational power has grown, 3D models based on RANS and LES equations have been applied for modeling of near-shore waves and floods, and especially for fluid impact on coastal structures like bridges and buildings, which has relatively smaller scales (Biscarini, 2010; Choi et al., 2007; Larsen et al., 2017; Mayer and Madsen, 2000; Montagna et al., 2011; Williams and Fuhrman, 2016). In addition, the 3D models output directly the pressure field, which can be integrated to obtain fluid forces on structures. In contrast, the 2D models rely on a simplified approach to convert their output to fluid forces on structures (Motley et al., 2015; Qin et al., 2016, 2018; Sarfaraz and Pak, 2017).

Many of these models are built into mostly open-source software packages that are broadly used by the communities and maintained by researchers at research institutes. Examples include GeoClaw (Berger et al., 2011), MOST (Titov and Gonzalez, 1997), and Tsunami-HySEA (Macías et al., 2016).

1.7.3 Major Research Gaps and Needs

One challenge in tsunami modeling is to develop models of different fidelity to satisfy different needs. For instance, site-specific inundation modeling and analysis often need to be performed in the design of vertical evacuation structures (Ash, 2015; González et al., 2013). In this case, a more accurate but time-consuming 3D model is desired. On the other hand, compiling tsunami hazard maps—where typically thousands of runs are required—might require using a faster but less accurate 2D model.

Another demand in the area is to update or even re-design the relevant software to capitalize on the rapidly growing computational power. These computational resources often require running code on clusters or newer machines with graphics processing units (GPUs); thus, there is a need to adapt these software packages to take advantage of these HPC machines.

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2. Response Estimation

Response estimation entails computational finite-element and other analysis methods to simulate the physical response of solids and fluids related to natural hazards engineering. The section on structural systems describes simulation technologies to analyze the response of constructed facilities (buildings, bridges, and other facilities) to the loading effects of gravity, earthquakes, storms (wind and storm-surge flows), and tsunami inundation. The section on geotechnical systems describes methods to explicitly simulate the detailed response of soil and soil–structure interaction under input ground motions. The simulation results are used to determine ground deformations, liquefaction, soil–structure interaction, and ground instabilities due to other phenomena (e.g., changes in ground water levels, scour, etc.). The sections on computational fluid dynamics address methods to simulate wind and water flows due to water inundation and tsunami.

2.1 Structural Systems

Gregory G. Deierlein
Professor, Stanford University

Ertugrul Taciroglu
Professor, UC Los Angeles

Response simulation of structural systems is an essential component of natural hazards engineering to quantify the effects of gravity loads, earthquake ground motions, wind and water flows, and other loads on buildings, bridges, piers, pipelines and other constructed facilities. Founded on the principles of structural mechanics, structural response simulation methods encompass a broad range of computational approaches, ranging from simplified phenomenological models to detailed continuum finite-element methods. The required simulations encompass a broad range of structural materials, systems, and scales. Construction materials include wood, masonry, concrete, steel, and other materials configured in multiple ways. The scale of simulations ranges from detailed finite-element models of structural components and connections up through complex 3D structural systems and, in the case of regional simulations, large inventories or networks of structures.

The field of structural and finite-element analysis is well established and documented in academic research papers and textbooks, and it is complimented by a multitude of research and commercial software of varied capabilities. This review is limited in scope to the subset of structural simulation methods and software technologies that are most directly relevant to natural hazards engineering, particularly those that are well suited to the research objectives and questions in the NHERI Science Plan.

2.1.1 Input and Output Data

In the context of natural hazards engineering, structural response simulations entail the development and analysis of idealized structural models to assess the structural responses necessary to evaluate damage and resulting consequences (life-safety risks, economic loss, downtime, etc.) to constructed facilities and systems. In developing structural response models, it is important to clearly define the objectives and scope of the model, specifically with regard to how the hazard loading effects will be incorporated and how the results of the analyses will be used. At one extreme, structural response analyses may involve high-resolution models to interrogate local (pointwise) response of structural materials and components. At the other extreme, highly idealized models of building systems may be used to evaluate economic losses and downtimes for regional assessments of large building inventories. Obviously, the goals of the simulation will dictate the type and resolution of the model employed, including how the input hazard is characterized and how the simulation output will inform downstream calculations.

In earthquake engineering applications, the loading input for structural simulations is usually earthquake ground shaking, which is described in terms of one or more IMs (e.g., spectral acceleration, spectral displacement, duration, etc.) or ground-motion seismograms. In some cases, the earthquake input may be characterized by input ground deformations, such as for buried pipelines and tunnels or structural foundations. In wind engineering, the loading input is typically equivalent static wind pressures or response histories of wind pressures, the latter being more important for flexible structures that interact dynamically with the wind. For assessment of storm surge and tsunami inundation, the loading input is usually equivalent static water pressures or debris flow forces.

Traditionally, structural response simulation has focused on structural framing components and systems; more holistic risk assessments require modeling of so-called nonstructural components that can affect the structural response and final damage state. For wind and water inundation flows, the interaction between the wind/water flows and the architectural cladding, partition walls, and other surfaces is particularly important. For earthquake engineering, architectural cladding and partition walls are important to model for certain types of light-frame construction because these components can provide significant strength and stiffness (e.g., wood-frame residential houses).

2.1.2 Modeling Approaches

As illustrated in Figure 2-1, models for nonlinear analysis of structures can range from uniaxial spring or hinge models, to more fundamental fiber section and continuum finite-element models. In general, all models are phenomenological in that they rely on empirical calibration to observed behavior at some level of idealization. The concentrated models (see Figure 2-1a-b) are highly phenomenological in that the underlying functions that describe the structural behavior are based on semi-empirical calibration to overall component behavior [e.g., Ibarra et al. (2005), Folz et al. (2001), Lowes et al. (2003), and Do et al. (2017)]. While Figure 2-1 illustrates these as moment-rotation hinge models, the concentrated springs can apply to any univariate response quantity, e.g., axial or shear springs. At the other extreme, the continuum finite-element models (see Figure 2-1e) are calibrated at the material level [e.g., Lemaitre and Chaboche (1990), Dettmer and Reese (2003), Lee and Fenves (1998), and Maekawa et al. (2003)], where the kinematics and equilibrium of the components are represented more directly by the model formulation. As such, the continuum models are more adaptable to different geometries and loading regimes; however, to the extent possible, the models should be validated against test data that represents the governing phenomena in the structural components being

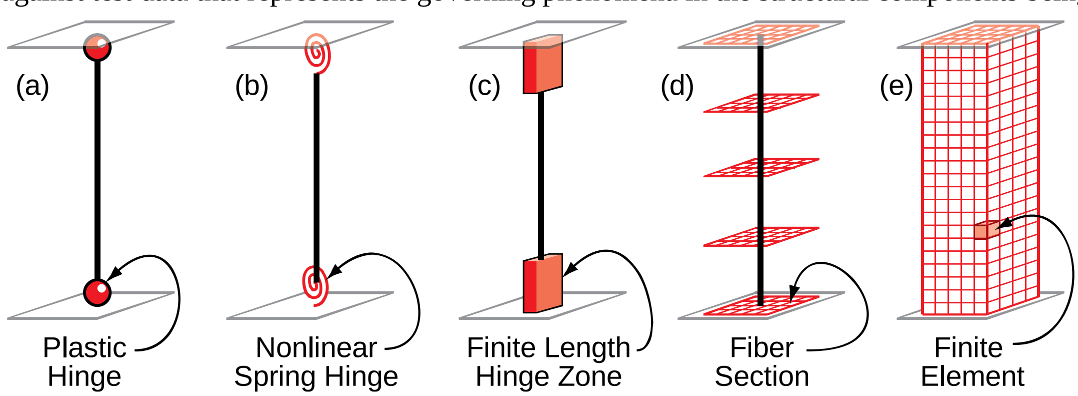

Figure 2-1 Range of structural model types (Deierlein et al., 2010)

modeled. In between the concentrated hinge and continuum models are fiber section or fiber hinge models (see Figure 2-1c-d), where kinematic assumptions (such as plane sections remain plane) are used to relate uniaxial material response to generalized strains and stress resultants (e.g., moment-curvature) at member cross sections. The uniaxial material models that comprise fiber models can be calibrated based on the uniaxial material stress-strain behavior [e.g., Mander et al. (1988), Dodd et al. (1995), and Mengetto and Pinto (1973)] or alternatively on quasi stress–strain, where the properties are adjusted to account for phenomena such as steel reinforcing bar buckling [e.g., Kunnah et al. (2009) and Dhakal and Maekawa (2002)].

The choice of model type for a given application involves a balance between reliability, practicality, and computational efficiency, subject to the capabilities of available software and computational resources. The optimal model type depends on many factors, including the structural system and materials, governing modes of behavior, the expected amount of nonlinearity, and the level of detail available for the input and output data. The reliability of the model comes from its ability to capture the critical types of deformation that are of interest to the modeler and control the response.

In recent years, applications to performance-based earthquake engineering have led to major advancements in the development and calibration of nonlinear structural analysis models to simulate the response of buildings, bridges, and other structures from the onset of damage up through collapse. A series of recent NEHRP publications review structural models and modeling parameters for nonlinear analysis to support seismic evaluation, retrofit, and design of buildings (NIST, 2017a-c). These NIST documents summarize models and parameters, along with references to many of the underlying research publications, for concrete and steel moment frames, steel concentrically braced frames, concrete shear walls, reinforced masonry walls, and light-frame wood shear walls. A NIST technical brief (Deierlein et al., 2013) provides a broader review of nonlinear analysis methods with a summary of proposed research and development needs for performance-based seismic engineering of buildings. Other resources on nonlinear modeling and analysis include: PEER/ATC report on tall buildings (Malley et al., 2010), Spacone and El-Tawil (2004) on composite steel-concrete structures, and Nurbaiah et al. (2017) on masonry infilled RC frames.

A detailed performance-based modeling and analysis guidelines for bridges is described in a PEER report by Aviram et al. (2008), which targets reinforced concrete (single- or multi-span) bridges common in California (NBI, 2016). An example of the components involved in modeling of a typical bridge is shown in Figure 2-2. Research cited in the Aviram report and publications since then address structural modeling details for bridges related to: (1) straight and skew angled abutment backfill models (Shamsabadi et al., 2010): (2) abutment kinematic interaction models (Zhang and Makris, 2002): (3) shear key models [e.g., Silva et al. (2009)]; (4) pile–soil interaction models for conventional (Hutchinson et al., 2001; Taciroglu et al., 2006), group (Lemnitzer et al., 2010) and large-diameter (Khalili-Tehrani et al., 2014) piles; (5) in-span hinge models (Hube and Mosalam, 2008); and (6) column models (Terzic et al., 2015; Xu and Zhang, 2011). The aforementioned models have been used in studies that furthered the state-of-the-art, which include work by Kaviani et al. (2014), who targeted skew bridges, Omrani et al. (2015), who comprehensively examined and improved upon the bridge PBSA guidelines by Aviram et al. (2008), and Omrani et al. (2017), who examined fragility sensitivities to abutment modeling uncertainties. In all these studies, the analysis tool of choice

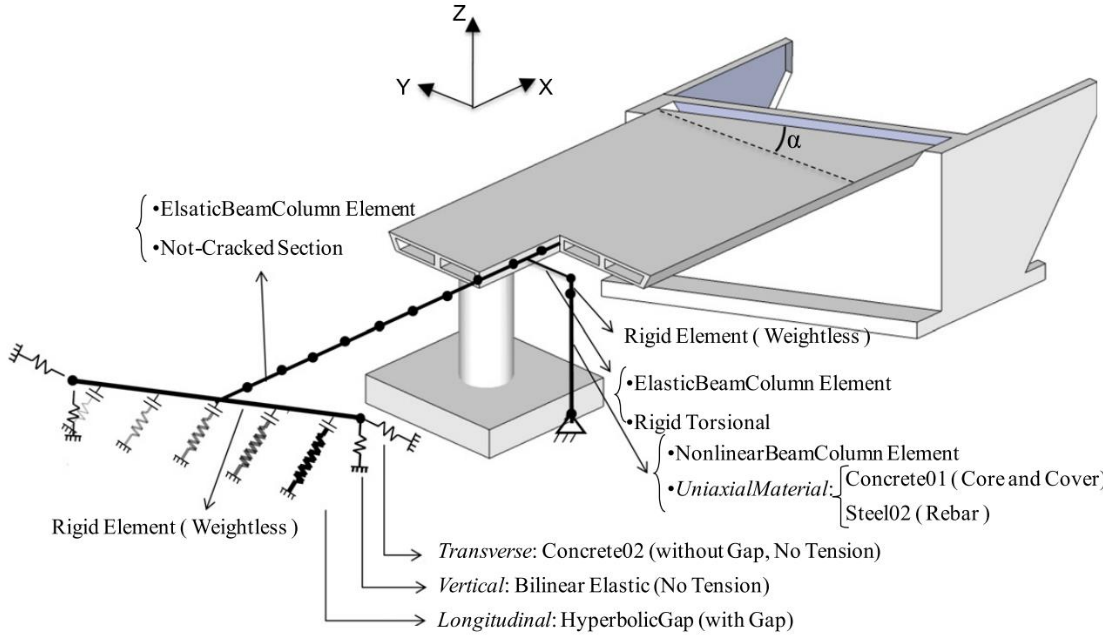

Figure 2-2 Schematic view of a generic bridge numerical model in OpenSees (Kaviani et al., 2012).

has been OpenSees (McKenna, 2011) wherein most, if not all, of the aforementioned models are publicly available.

Most natural hazards research on nonlinear response simulation of structures is related to earthquake engineering where addressing inelastic response has long been recognized as a necesscity under design ground motions. In contrast, inelastic structural effects tend to be less pronounced for evaluation of gravity, wind, and other loading effects. In the case of storm-driven wind and wave loading or tsunamic innundation, the largest nonlinear behavior involves the loading due to the dynamic fluid (air or water) flows and their interaction with the structure. Examples of recent research to study the response of structures to fluid flows include Minjie et al. (2014, 2018), Ataei and Padgett (2015), Petrone et al. (2017), Madurapperuma and Wijeyewickrema (2013), and Attary et al. (2016).

Repeated nonlinear response history analyses for constructing seismic fragilities or for performing simulations of regionally distributed systems typically require large-scale computational resources. Due to the granular nature of each structural analysis, the required computations are embarrassingly parallel (i.e., perfectly scalable in a parallel computing sense). Apart from the computational requirements, analyses of buildings, bridges, or other distributed infrastructure requires consideration of correlations in the hazard demands (e.g., earthquake ground motions) across the region along with correlations of the structural system response. Such regional-scale analyses are uncommon and not standard, but various attempts have been made [see e.g., Miller et al. (2015)].

2.1.3 Software and Systems

While there are a large number of available software systems with various capabilities, this summary focuses on software programs that are well-suited and widely used in research related to natural hazards engineering. Emphasis is on open-source software currently available and supported on the NHERI DesignSafe computing platform along with a few widely used commercial codes.

OpenSees

The Open System for Earthquake Engineering Simulation (OpenSEES) is an open-source object-oriented software framework for simulating the seismic response of structural and geotechnical systems. OpenSees was developed and is maintained by the Pacific Earthquake Engineering Research (PEER) Center for research in performance-based earthquake engineering and is widely used and contributed to by researchers from around the world. OpenSees has advanced capabilities for modeling and analyzing the nonlinear response of structural systems using a wide range of material models, beam–column elements and continuum elements, and solution algorithms. The software is designed for parallel computing to allow scalable simulations on high-end computers or for parameter studies. The software is available on DesignSafe and can be downloaded to run on Linux, Windows, or Mac OS (http://opensees.berkeley.edu/)

LS-DYNA

LS-DYNA is a general-purpose finite element program capable of simulating complex real-world problems with primary users from the automobile, aerospace, construction, military, manufacturing, and bioengineering industries. It has nonlinear frame and continuum finite elements, with material models for steel, concrete, and soils along with fluids. LS-DYNA's origins lie in highly nonlinear, transient dynamic finite-element analysis using explicit time integration, and it is optimized for shared and distributed memory Unix, Linux, and Windows-based platforms. The software is maintained and marketed by Livermore Software Technology Corporation, with licensing available to both the commercial and academic markets. It is available on DesignSafe for users with an academic license. (http://www.lstc.com/products/ls-dyna)

FEAP

The Finite Element Analysis Program (FEAP) is a general-purpose finite-element program for solving nonlinear, static, and transient partial differential equations. Its primary applications are directed to the solution of problems in solid mechanics; however, the system may be extended to solve problems in other subject areas by adding user developed modules to address problems in fluid dynamics, flow through porous media, thermo-electric fields, and others. The software is available to run on UNIX/Linux/Mac or Windows environments (see http://feap.berkeley.edu/)

Other Commercial Software

The following is a list of other commercial software, with simulation capabilities for natural hazards engineering commonly used in both industrial and academic research.

SAP 2000, **ETABS**, **PERFORM3D** (https://www.csiamerica.com)

ABAQUS Unified FEA (see https://www.3ds.com/products-services/simulia/products/abaqus/).

LARSA (https://www.larsa4d.com/)

Marc (http://www.mscsoftware.com/product/marc)

DIANA (https://dianafea.com)

2.1.4 Research Gaps and Needs

While computational tools for simulation of structural materials and systems are fairly mature, there are still significant limitations in the modeling capabilities along with the continuing need for improved calibration and validation of existing models. The limitations and needs depend on the scale and resolution of the models, i.e., whether one is interested in detailed models of structural material and components to examine localized behavior or less detailed models that can reliably simulate the behavior of complete structural systems (buildings, bridges, etc.) or large inventories of systems (e.g., building inventories or geographically distributed infrastructure systems).

At the detailed level, there are continuing needs to develop, implement, and validate continuum finite-element models that can simulate nonlinear behavior and damage to structural materials and components under random cyclic loading, including interfaces and interaction between materials. Models for steel and other ductile materials are fairly well established for simulating large plastic strains and deformations (e.g., to simulate local and overall buckling [see NIST-ATC, (2018)], whereas methods to reliably capture fracture under cyclic inelastic loading are still evolving. For other structural materials, including reinforced concrete, wood-based materials, and masonry, many challenges remain to reliably simulate inelastic damage and degradation as seen in physical tests. In addition to the models themselves, further research and development are needed to implement and validate models in open-source software to run on high-performance computing resources to broaden their impact in natural hazards engineering.

At the large-scale system or distributed inventory/system level, there is a need for systematic approaches that develop, calibrate, and manage models computationally efficient enough to be deployed at scale, which also capture accurately the dominant behavioral effects. For such applications, many of the challenges are more related to supporting modeling and data management tools as much as the models themselves. A related need is to develop inventory data with reliable descriptions of the systems that includes information on the uncertainties and correlations in those uncertainties.

2.2 Geotechnical Systems

Pedro Arduino
Professor, University of Washington

Problems in geotechnical earthquake engineering often involve complex geometries and boundary conditions. Materials comprising the medium over which geotechnical problems are described behave almost always in a nonlinear fashion. Moreover, soils are made of three phases, and interactions between these phases play an important role in the global response, making theories even more complicated. Interaction of structural foundations (e.g., bridges, abutments, or buildings) with the surrounding soil is also a major aspect to consider in geotechnical earthquake analysis and design. Natural material inhomogeneity caused by the way soils are deposited, as well as human influence, contributes to the complexity of the problem. In addition, the dynamic nature of earthquakes and their effects can rarely be considered in simplified models while preserving all their important aspects.

To address these problems, numerical analysis techniques have become the most viable method of analysis for design and research purposes, and extensive numerical analyses are routinely conducted in practice and research environments. In describing the state-of-the-art in numerical modeling in geotechnical engineering, it is necessary to discuss each one of the aforementioned aspects; i.e., numerical methods, coupled formulations, constitutive models, interface elements, and boundary and initial conditions. A list of common geotechnical codes used in geotechnical earthquake engineering is provided below. Although incomplete, this list identifies several common aspects.

2.2.1 Numerical Methods

Among many other methods of analysis, finite elements (FE), finite differences (FD), the material point method (MPM), and smooth particle hydrodynamics (SPH) are used in different geotechnical earthquake engineering applications. Of these four, FE and FD are most common in geotechnical practice and research. Commercial codes like PLAXIS, FLAC, and LSDYNA (to mention a few) and open-source codes like OpenSees are examples of numerical frameworks that offer dedicated geotechnical capabilities. When consideration of large deformations is important, e.g., in the case of debris flows or tailing-dam run outs, then meshless techniques, e.g., MPM and SPH, provide the necessary functionality to account for these conditions. For 1D wave propagation, equivalent linear methods continue to be a common choice, with "shake-like" tools, e.g., ProShake, DeepSoil and DMOD, being popular in practice. Most FE tools offer 1D, 2D, and 3D capabilities. Finite-element formulations that reduce computational demand via coarse mesh accuracy, effective assimilation of nonlinear constitutive models, or general efficiency are ideal in this context. Today, extensive research is being devoted to establish finite-element formulations for solid mechanics that are equally applicable to any arbitrarily-posed problem.

2.2.2 Coupled Fluid-Solid Formulations

Geotechnical engineering requires the evaluation of total and effective stresses. Total stress analysis is based on conventional single-phase formulations. Effective stress analysis requires a method to account for the interaction between the pore fluid and soil skeleton in saturated or partially saturated soil. Various approaches derived from the work of Biot (1941, 1956, 1962) had been developed to accomplish this goal in a numerical setting, each adding fluid degrees-of-freedom to the system according to different assumptions. Three primary approaches are discussed by Zienkiewicz and Shiomi (1984). These approaches are the u-p-U element formulation (which uses the full system of equations developed for the saturated problem), the u-U formulation (which is a simplification of the u-p-U approach that assumes incompressibility for each medium), and the u-p approach (which simplifies the system by assuming that fluid acceleration can be neglected). The u-p approach is most common for use in commercial codes like PLAXIS and FLAC, and is also available in OpenSees. These formulations have also found application in MPM codes, although at this level it is important to completely separate the phases. Extensive research is currently ongoing in this field.

2.2.3 Treatment of Soil-Foundation Interfaces

Interaction of structural components with the surrounding soil is another major concern of geotechnical engineering. This issue arises in many geotechnical problems whether related to retaining soil mass, foundation engineering, underground construction, or even soil improvement systems; and is one of the most important and challenging aspects of geotechnical numerical modeling since it is inherently nonlinear and complex. Different approaches have been proposed over the past 20 years that range from simple interaction springs (*p-y*, *t-z*,and *Q-z* springs) to methods based on contact mechanics (thin layer and interface elements); different codes address the problem differently. Simplified models rely heavily on empirical methods, and extrapolating these methods to more complicated and general cases requires extreme scrutiny of the problem at hand and method used. The more advanced the methods for modeling soil–structure interaction are, the more complex and costly they become in terms of computations. Both PLAXIS and FLAC include interface elements, and OpenSees offers a suite of elements, including nonlinear springs, interface elements, and new developments to characterize beam–solid interaction. Coupling between structural systems and geotechnical domains rely on the appropriateness of these elements. Continued developments are constantly underway in this field. This is an area that fits the SimCenter vision, where continued development through NHERI research could be extremely helpful.

2.2.4 Soil Constitutive Modeling

Soil constitutive modeling approaches in geotechnical engineering have ranged from relatively simple von Mises, Drucker-Prager, and Mohr-Coulomb plasticity models to more sophisticated alternatives as computing power has increased. Cam-Clay and other critical-state-based plasticity models have been of particular interest in geotechnical engineering. Most these models use isotropic hardening and are useful in static and quasi-static applications. All geotechnical FE codes (PLAXIS, FLAC, OpenSees, etc.) include different implementations of these models. For dynamic analysis, kinematic hardening is required to capture the cyclic response. For this purpose, three families of models have been proposed: multi-yield surface models, bounding surface models, and multiple-strain mechanisms models. These approaches differ in the way kinematic hardening is treated. Multi-surface plasticity models (Prevost, 1977, 1985a; Elgamal et al., 2003) have been used to represent the constitutive behavior of both cohesive and cohesionless soils in total and effective stress analyses, respectively, and are available in OpenSees. Bounding surface models were first introduced in geotechnical engineering by Dafalias and coworkers, and extended with critical-state concepts by Manzari and Dafalias to represent the response of liquefiable soils. This model has been implemented and used in OpenSees and FLAC. Variations of this model, (PM4Sand and PM4Silt) have been proposed to better represent aspects of the observed soil response in sands and silts. These models are available in FLAC, PLAXIS, and OpenSees. The multi-mechanisms approach is defined in strain space and has been used in Japan, most particularly in its implementation in the Cocktail model proposed by Iai et al. (2011, 2013).

2.2.5 Boundary and Loading Conditions

Boundary conditions for the soil continuum require somewhat greater care to ensure appropriate results. At a minimum, the boundaries must be fixed such that all rigid-body displacement modes are restricted. In static or pseudo-static analyses, the main concern is related to diminishing the effects of the boundary on the portions of the model that are of primary interest. Boundary effects can be controlled for an analysis of a soil–foundation system by extending the limits of the soil continuum away from the location of the foundation elements. Minimizing boundary effects is also critical in dynamic analysis; however, devising proper boundary conditions is more difficult than in static or pseudo-static cases. The particular method used for this purpose depends upon the objective of the numerical model. When creating a numerical model for a site in the field, the assumption of rigid boundaries is typically no longer valid. Several strategies have been developed to include the effect of semi-infinite subsurface extents in a numerical model of finite size. The use of periodic boundary conditions, in which the lateral extents of the model share translational degrees-of-freedom, is one such approach that attempts to appropriately account for the free-field response of the soil domain.

Lysmer and Kuhlemeyer (1969) introduced a technique to capture a transmitting boundary through the use of viscous dashpots. By defining the viscous response of the dashpots based on the density and the pressure and shear-wave velocities of the material beyond the boundary, this approach appropriately captures the outward propagation of wave energy in the numerical model as long as the waves impinge in a near-normal orientation to the boundary. When defining transmitting boundaries using the Lysmer and Kuhlemeyer (1969) method, accelerations are not directly applied to the model. Instead, a force is applied using the technique developed by Joyner and Chen (1975). This applied force is proportional to the input velocity and the constitutive properties of the material beyond the boundary. This approach is commonly used in numerical analysis for geotechnical problems to account for the compliance between the soil domain of the model and the semi-infinite media outside of the considered domain.

Better results can be attained using a perfectly match layer (PML), which is an artificial absorbing layer for wave equations commonly used to truncate computational regions in numerical methods to simulate problems with open boundaries, especially in finite-differences and finite-element methods (Basu et al., 2004; Bindel et al., 2005). PML's are designed so that waves incident upon the PML do not reflect back to the medium at the interface. One caveat with PMLs is that they are only reflectionless for the exact, continuous wave equation. Once the wave equation is discretized for simulation on a computer, some small numerical reflections appear (which vanish with increasing resolution). To mitigate this problem, the required PML absorption coefficient "σ" is typically turned on gradually from zero (e.g., quadratically) over a short distance on the scale of the wavelength of the wave. In any case PMLs have been shown to produce better results than simple LK dashpots.

Finally, another technique for use in geotechnical simulations to properly account for the differences in wave behavior inside the finite soil domain represented by the model and the wave behavior in the semi-infinite soil medium is the domain reduction method (Bielak et al., 2003; Yoshimura et al., 2003). The domain reduction method (DRM) consists of two phases. The initial phase involves a background geological model that includes both the source of the earthquake and the region of interest. This background model is used to compute the free-field displacement wave-field demands on the boundary of the smaller region of interest. The second phase involves only the reduced region of interest. In this phase, effective seismic forces are applied at the boundary of the local region. These effective forces are derived from the boundary displacement demand obtained in the initial phase. In general, these methods require coupling data from different codes or accessing databases with recorded or synthetic motions. This is of particular importance in geotechnical earthquake engineering. The propagation of waves in geologic media can be simulated using codes like broad band platform (BBP) based on Green functions and stochastic analysis. In general, these codes cannot represent the extreme soil nonlinearity observed at the surface where FE methods are more appropriate. When the response of a basin is of interest, FE and FD codes, like Hercules or SW4, can be used to simulate the propagation of waves in large heterogeneous geologic domains, but they require extensive HPC resources to run properly. Independent of the tool used, coupling between these codes and conventional FE analysis is required. This is an area that fits perfectly the SimCenter vision, and efforts are underway to facilitate these simulations in frameworks like the NHERI DesignSafe.

2.2.6 Initial Conditions

Representation of the initial state of stress is of paramount importance in geotechnical simulations. The soil response (i.e., stress, strain) greatly depends on these initial conditions. Several approaches can be used to create an appropriate initial state. The typical method is to apply gravitational body forces to the elements in the numerical model prior to any further analysis steps. Most tools allow taking this a step further by using a staged modeling procedure in which gravitational stresses are first developed in a base soil mesh. After this stage, soil elements can be removed or added and replaced by foundation or additional soil elements, and gravitational stresses are developed for the new configuration.

2.3 Computational Fluid Dynamics – Wind

Ahsan Kareem
Professor, University of Notre Dame

Buildings exposed to wind undergo complex interactions, which preclude a simple functional relationship between wind and its load effects with the exception of buffeting effects, i.e., turbulence excited wind loads along the direction of wind. Accordingly, wind tunnels have traditionally served as a means of quantifying wind loads that are combined with structural analysis codes based on finite-element analysis.

With burgeoning growth in computational resources and parallel advances in computational fluid dynamics, computational simulations are evolving with the promise of becoming versatile, convenient, and reliable means of assessing wind-load effects. Table 2-1 summarizes salient advantages and disadvantages of the wind-tunnel-based experimental methods and the computational CFD-based schemes.

While developments in CFD as applied to a host of topics in basic fluid dynamics, aerospace, automotive, and urban aerodynamics are evolving at a fast pace, there has been rather limited research focus on the development of CFD-based tools and schema to advance the computational modeling of wind effects on structures. Limited commercial software has been widely utilized by both researchers and industry that, due to the inherent nature of modeling and parametric sensitivities and the lack of flexibility to improvise, has often led to observations that reflect large variability and on occasions depart from experimental observations. This has fueled the misleading impression that CFD is currently inadequate to fully capture wind–structure interactions. Yet the current state-of-the-art of CFD application in wind effects has led to the development of in-house tools wrapped around OpenFOAM, which have advanced to the stage that the Architectural Institute of Japan (AIJ) now permits the use of CFD in lieu of other approaches, e.g., wind-tunnel testing with the stipulation that the AIJ guidelines concerning 3D LES and inflow simulation are followed. At this junction, it is prudent to say that despite advances in CFD, simulation of wind-load effects using CFD still faces challenges; therefore, wind tunnels remain as an essential validation tool.

2.3.1 Challenges of CFD

The computational grid of complex geometries and clusters of structures is fundamental to CFD as it represents the computational domain in which calculations are carried out at regular intervals to simulate the passage of time. The more compact the spatially discretized grid and smaller the time step, the more accurate and realistic are the simulated results. Unfortunately, simply introducing initial and boundary conditions does not ensure a solution because the system being solved is nonlinear, and the interaction among terms of the governing equations leads to the generation of multiple scales. What makes the solution so complicated is that each part of the flow depends on what all the other parts are doing, i.e., global dependence. This also leads to the smallest disturbances at one time promoting completely different simulated patterns of the behavior at a later moment, which is akin to chaotic systems.

Table 2-1. Comparison between experimental and computational approaches

Experimental (Wind Tunnel)	Computational (CFD)
• Quantitative description of flow phenomenon using measurement • For limited quantities at a time • At a limited number of points and time • For a limited range of problem and operating conditions	• Quantitative prediction of flow phenomenon using CFD • For all desired quantities • With high resolution in space and time • For virtually any problem and realistic operating condition
Error sources • measurement errors • flow disturbances by the probes	**Error sources** • Modeling • Discretization • Iteration • Implementation

In addition, the efficacy of CFD is still under debate, although it had been successfully implemented in aerospace engineering and wind tunnels to validate final designs. This is primarily due to the nature of structural shape in aerospace applications like an airfoil with a streamline shape, resulting in flow field around it that essentially stays attached to the surface, which can be numerically captured rather accurately.

Figure 2-3 summarizes the flow field around a streamlined airfoil to a circular cylinder and progressing to a sharped-edged body representing a typical building or a bridge cross section. In contrast, as we move from an airfoil towards a circular cylinder and a rectangular cross-section, the flow field around them gets progressively more complex as the flow cannot negotiate the sharp changes in direction as it moves around the body and hence jettisons away, creating separated flow characterized by flow reversal. Capturing these interacting features numerically poses challenges, which has led to a slower progress in the application of CFD in wind-load assessments on structures. In the following, a basic overview of the issues surrounding flow features around structural configurations and the role of turbulence is presented including ensuing numerical challenges.

The range of the size of eddies that manifest the turbulent flow around structures determines the grid size, which places demands on both the memory size and speed of the computational hardware. Ideally, resolution of all scales in the flow from energetic low-frequency fluctuations to the smallest scale (the Kolmogorov Scale) in the viscous dissipation regime dependent on viscosity would be ideal. This approach is referred to as direct numerical simulation (DNS) and is obviously computationally very intensive as the grid size for a required Reynolds number (Re) flow requires cells equal to $Re^{9/4}$. Although highly desirable, such simulations are currently limited to address basic research in fluid dynamics using CFD.

Figure 2-3 Flow around cross-sections with increasing level of complexity (Ding et al., 2018)

To overcome this challenge, the NS equations of motion are filtered based on a length scale; thus, the motion of eddies smaller than the length scale are not calculated. Rather, the large eddy motion is computed, and the small-scale motions are modeled using ideas that range from enhanced coefficients of viscosity to additional system of equations representing closure models. This results in a smoothing process, which helps to relax the number of grid points necessary to simulate the flow field. This scheme is known as the large eddy simulation (LES). As computer capacity increases, a broader range of eddies can be resolved, thus reducing the scales that need to be modeled.

An alternative schema involves time averaging or ensemble averaging of the NS equations (the Reynolds averaging and referred to as RANS) that result in obtaining only the mean and deviations from the mean of the computed quantities. It requires a coarser grid resolution compared to LES. RANS often has difficulty in capturing flow separation and reattachment as a consequence of averaging (Spalart, 2010). The performance of LES may also be impaired with inadequate grid resolution and the treatment of the subgrid-scale turbulence. A hybrid combination of LES and RANS is referred to as detached eddy simulation (DES), composed of LES in regions for which the grid resolution can economically simulate the inertial subrange and reverts to RANS in near-wall regions where turbulence scale is smaller than the grid size (Hoarau, 2016).

On the one hand, moving from the simulation of flow around isolated buildings to a cluster adds to the demand on computational resources; however, on the other hand, the flow patterns in the street canyons become more forgiving from the simulation perspective as sharply defined features become more unstructured due to mixing and can be resolved with less effort. Similar observations have been made in wind tunnel studies when examining the influence of adjoining buildings in a cluster on the aerodynamic loads. This is akin to adding damping in structures and helps to dampen fluctuations in the flow field. LES nested in weather research and forecasting models (WRF) models may be utilized to predict wind effects in a cluster of buildings in an urban setting under both extra-tropical and tropical systems.

2.3.2 Modeling of Flow around Structures

The CFD simulation process for modeling wind around structures involves the following main steps: problem statement; mathematical model; mesh generation; space and time discretization; inflow generation; simulation runs, fluid-structure interaction (aeroelastic effects); post processing; verification/validation; and uncertainty quantification. Some of the salient aspects are presented schematically in Figure 2-4, with its primary focus on the choice of turbulence model, the mesh requirement especially near the boundaries of the structure, and inflow and boundary conditions.

2.3.3 Inflow Turbulence Generation

In computational wind engineering (CWE) applications, generation of inflow turbulence satisfying prescribed mean-velocity profiles, turbulence spectrums, and spatial and temporal correlations is of great importance for accurate evaluation of wind effects on buildings and structures. Several methodologies have been proposed for this purpose, which can be classified into three general categories: precursor simulation methods, recycling methods, and synthetic methods. Compared with precursor simulation and recycling methods, the synthetic methods in general offer a more practical and relatively efficient approach to generate inflow turbulence.

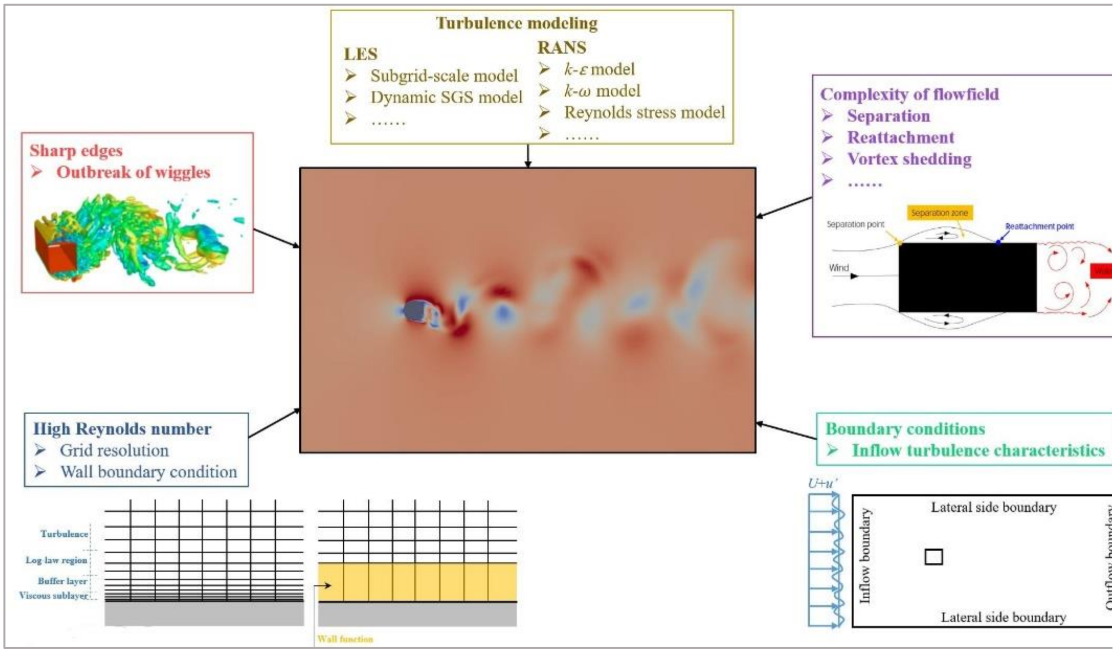

Figure 2-4 Schematic of a digital analog of modeling flow around structures in a wind tunnel. (Ding et al. 2018)

Research activities on synthetic turbulence generation have been vigorous over the past several decades and have branched out into several categories of techniques (Wu, 2017), including the synthetic random Fourier method (Kraichnan, 1970; Hoshiya, 1972), the synthetic digital filtering method (Klein et al., 2003), and the synthetic eddy methods (Jarrin et al., 2006).

2.3.4 Computational Details and Post-Processing

The following discussion addresses computing time for simulation, and how it is influenced by several steps involved in the simulation process. For example, the computing time depends on: (1) the choice of numerical algorithm and data structure; (2) linear algebra solvers and criterion prescribed for interactive solvers; and (3) discretization parameters, such as mesh quality, mesh size, time step; hardware, vectorization, and parallelization. The quality of simulation results depends on: (1) the mathematical model and underlying assumptions; (2) types of approximations implied; and (3) stability of numerical scheme in terms of mesh, time step, error indicators, and iteration stopping criterion. Some of these features operate in isolation while others operate in combination, which influence both the time taken for the simulation and its quality. These processes should be revisited when there is a need to enhance the quality of simulation and/or to reduce the time needed for simulations. Machine-learning tools—such as supervised, unsupervised learning, reinforcement learning, and deep learning—offer exciting avenues to learn from the simulations, help classify regions of similarity and create predictions for future simulations (Kareem et al., 2018).

Once the simulations are complete, one needs to process data. This also entails calculation of derived quantities, e.g., statistics of velocity or pressure fields; integral parameters, e.g., drag and lift coefficients, building response and their spectral characteristics; local zooming for a further look at a region of simulation exhibiting features of potential interest; visualization of data in space and time, a real-time portrait of flow features, digital version of analog flow visualization using smoke in wind tunnels, overall systematic analysis of data using statistical and signal processing tools and debugging, verification and validation of CFD models, and assessing the role of uncertainty.

2.3.5 Verification and Validation

Wind-tunnel validation of CFD-based simulations often serves as the final step in the process. The progressive reduction of the uncertainty (Roache, 1998) is the only practical way to ensure any kind of confidence in a given CFD simulation. This calls for vigorous validation (AIAA, 1998), just as in any other complex numerical simulation. In particular, due to limited analytical solutions being available for simple flows only, CFD validation must be carried out through high-fidelity experimental testing. For this reason, experimental validation often becomes the essential step in ensuring the reliability of CFD simulations (Oberkampf et al., 2004; Oberkampf and Roy, 2004; Oberkampf and Trucano, 2008; Roy and Oberkampf, 2011). This is particularly true in computational wind engineering, where the CFD simulation of a bluff body, like a tall building, immersed in an atmospheric boundary layer is often validated through specific boundary layer wind-tunnel tests (Yu and Kareem, 1998; Yu et al., 2013).

Note: many CFD studies seem to lack a thorough validation process, i.e., grid convergence studies are rarely carried out, and, in general, detailed flow field results are missing. The general lack of code verification, discretization scheme selection, turbulence modeling, mesh quality, and sampling time for statistical analysis, etc., adds more uncertainty. It should be observed, however, that this process is by no means simple and will, in general, be far more involved than the validation of channel or pipe flow, for instance, for a number of reasons including: (1) most experimental wind tunnel tests carried out on civil engineering structures are not exhaustive enough to allow a truly complete CFD validation; (2) the geometric configurations of the bluff bodies tested in wind tunnels are often too complex for an unsteady CFD analysis; and (3) the high Reynolds number in wind tunnel testing also adds difficulties in performing a systematic grid convergence study.

2.3.6 Future Directions

Multi-fidelity modeling

CFD evaluations can feature both the high-fidelity models, which are accurate yet expensive, and the low-fidelity models that are computationally efficient but can produce large modeling errors. RANS and its variants are currently the workhorse of CFD (Kareem, 2017) as the computational requirements are modest, but because its accuracy is compromised in separated flow regimes, it is viewed as low fidelity. LES solves the filtered NS equations at large energy-containing scales and relies on modeling to resolve the smaller more universal subgrid scales. The results thus offer a higher fidelity compared to RANS, but at an additional computational effort. Therefore, the simulation data may involve data sources of multiple fidelities with different computational costs.

In an attempt to blend the variable-fidelity information source, multi-fidelity surrogate modeling is an attractive avenue that utilizes hierarchical surrogate models relating low-fidelity (RANS) to high-fidelity (LES) models to obtain high-quality predictions with a computational effort comparable to RANS. Multi-fidelity surrogate modeling has been successfully applied to a host of engineering problems, including beam design using finite-element analyses with variable mesh sizes (Leary et al., 2003), optimization of a transonic aircraft wing with two levels of CFD fidelity (Forrester et al., 2007), and rotor bade design based on the code with simplified aerodynamics, as well as high-fidelity numerical simulations (Collins, 2008), etc. Therefore, a multi-fidelity surrogate modeling approach in the aerodynamic shape-optimization framework that involves data from sources of both RANS and LES simulations would offer superior surrogates from the context of enhancing the model accuracy as well as maintaining low computational demand.

UQ in CFD modeling

Uncertainties in CFD modeling are primarily associated with the uncertain inflow boundary conditions representing the inherent variability of atmospheric flows and model-form uncertainties originating from the turbulence modeling assumptions applied to the unresolved small-scale turbulent eddies. These sources of uncertainties should be appropriately accounted for, and their impact on the predictive capabilities for the aerodynamic quantities need to be carefully examined since they may impact the aerodynamic loading characterization in CFD modeling. UQ in CFD modeling involve the quantitative estimation of both the inflow and model-form uncertainties, and their resulting impact on the aerodynamic Quantities of Interest (QoIs). Techniques for UQ and uncertainty propagation including Monte Carlo simulations, polynomial chaos, and Gaussian process regression have been explored in many engineering problems as non-intrusive approaches that use solution samples to numerically estimate the output functions (Beran et al.m 2017). An efficient UQ approach that quantifies the effect of coupled inflow and model-form uncertainties would allow propagation of uncertainties to the aerodynamic QoIs.

2.4 Computational Fluid Dynamics – Water

Michael Motley
Associate Professor, University of Washington

Patrick J. Lynett
Professor, University of Southern California

Computational Fluid Dynamics (CFD) uses numerical methods to solve governing equations that arise in fluid mechanics. While the previous section focused on gaseous fluids (e.g., air), here we focus on applications of CFD for liquid fluids (e.g., water), although modeling of the water's free surface arises in many situations, especially those around natural hazard modeling as it requires modelling the air, the fluid, and the interface between the two. For water, the standard governing equations are the incompressible NS equations ('Navier-Stokes equations', 2018). These equations describe the motion of viscous fluid substances; their solution provides much of the useful information for natural hazards engineering problems, e.g., flow current speed and fluid pressures on built infrastructure.

Solving the NS equations without the use of a turbulence model is often referred to as direct numerical simulation (DNS) ('Direct numerical simulation', 2018), in which the whole range of spatial and temporal scales of the turbulence must be resolved. As a result, the expense of using extremely small grid sizes and time steps is unaffordable in many practical engineering systems, especially when the Reynolds number that indicates the intensity of turbulence is high. To accommodate these issues, some variants of the NS equations are often used in practice. The two most popular two approaches are Reynolds-averaged Navier–Stokes equations (RANS, 'Reynolds-averaged Navier-Stokes equations, 2018) and large eddy simulation (LES, 'Large eddy simulation', 2018). The two models, while still able to give satisfactory approximations to the turbulence in the fluid, are much cheaper than DNS.

2.4.1 Input and Output Data

In all situations where CFD is used, the two basic inputs are the boundary conditions and initial conditions. The boundary conditions refer to the boundaries of the computational domain, which may include a wall where water cannot penetrate or an outlet where fluids flow out. For problems in natural hazards engineering, such boundaries can include the ground over which the fluid flows, the outside walls of a building that will affect flow path of the water, or the complex geometry of a bridge hit by a tsunami or storm surge. The initial conditions refer to the state of the fluids before the simulation starts. For instance, in tsunami modeling, the initial conditions for some nearshore regions might have all water at rest at sea level while somewhere in the ocean, a large volume of water is placed above sea level that represents a tsunami wave. CFD solvers predict how the water volume and velocity evolve in time from their initial state. Different initial conditions will give different states later in time.

The output from CFD depends on the equations that are solved but generally includes water velocities, water pressure, and height of water surface (with extra treatment added to the NS equations, e.g., coupling the volume of fluid methods ('Volume of fluid method', 2018) at any specified moment during the simulation and at any location within the domain. The pressure field can be further processed to obtain forces on structures.

2.4.2 Models and Software Systems

The implementation of CFD algorithms is often very complex. Many CFD software systems are developed and maintained by either commercial companies or large development teams with support from user communities. Some popular commercial software include: STAR-CCM+ (2018), ANSYS Fluent (2018), and COMSOL (2018). Commercial software often provides the ability to customize solvers (to some extent) by allowing user-defined functions. Many researchers prefer the complete freedom of modifying the source code and use open-source CFD software, including OpenFOAM (2018), SU2 (2018), etc. By far, OpenFOAM is the most widely used and provides very comprehensive functionality in all areas of CFD. The relevant research communities have also contributed many pre-processing and post-processing tools for OpenFOAM, e.g., wave-generation tools that are often required in hazard modeling. Customized versions of OpenFOAM for certain applications are also available. Some examples include HELYX (2018), olaFlow (2018), and IHFOAM (2018). The latter two are specially designed to simulate coastal, offshore, and hydraulic-engineering processes.

2.4.3 Major Research Gaps and Needs

CFD is a broad concept that is used as a simulation approach in many industry and research fields. Although the general-purpose commercial or open-source CFD packages can provide a broad variety of requirements, cutting-edge research in a specific area often requires tackling very specialized problems. As a result, either in-house code must be developed, or heavy modification and customization must be added to CFD packages. Fortunately, the prevalence and maturity of open-source CFD software has provided a solid foundation or is, at the very least, a very helpful resource for researchers that focus on such software development.

Another challenge is the portability and scalability of CFD software, which allows the code to run on HPC facilities. The explosive growth of computing power in the past two decades has tremendously changed many areas, allowing for the performance of simulations that were impossible in the past. Unfortunately, CFD software, especially in-house code or customized solvers, may not run naturally on new machines. Different implementations in the code must be taken and even new algorithms designed such that the code can run efficiently on a cluster that consists of thousands of computing nodes and a cluster that consists of new architectures like GPUs.

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3. Performance of the Built Environment

The built environment is a collection of various types of assets that affect the well-being and quality of life of residents in an urban area. The list of such assets includes residential and commercial buildings, bridges, networks of roads, railways, pipelines and power lines, and their supporting facilities. The performance of these assets is quantified by *Decision Variables* (DV) that describe the influence of asset damage to the life of the affected community. As their name implies, these DVs are ultimately meant to drive decision- and policy-making.

The performance of assets heavily depends on the determination of the hazard and the asset response to a characteristic event that is consistent with the hazard at the asset location. Although this chapter focuses on performance assessment, some of the tools listed here have hazard and response estimation capabilities as well. Those features have been covered in the previous chapters and will not be mentioned here again. This chapter is organized around the types of assets or asset-networks needed to arrive at a description of the performance of an urban region.

Seismic performance assessment of buildings has received a lot of attention from the research community and funding agencies in the past few decades (ATC, 1985; FEMA Mitigation Division, 2018b, 2018c; Fajfar and Krawinkler, 2004; FEMA, 2012). Consequently, the most sophisticated and mature methods are available in that area (FEMA, 2012). Several researchers have focused on adopting these methods for other asset types (Werner et al., 2006; Chmielewski et al., 2016) and for other types of hazards (FEMA Mitigation Division, 2018c; Attary et al., 2017; Barbato et al., 2013; Lange et al., 2014). This is not a trivial task because damage and subsequent consequences can be fundamentally different for non-building assets and for non-seismic disasters.

3.1 Buildings

Adam Zsarnóczay
Postdoctoral Researcher, Stanford University

Jack W. Baker
Associate Professor, Stanford University

Buildings are arguably the most important asset type when it comes to direct consequences of a natural disaster. A severely damaged or collapsed building may result in loss of life, injuries, and significant capital losses. Community disruption and indirect consequences are heavily affected by damage to transportation infrastructure and lifelines.

Conceptually, building performance assessment has been moving from a holistic towards an atomistic approach. Instead of trying to characterize building damage as a whole, buildings are disaggregated into sets of structural components, non-structural components, and contents (Figure 3-1). Component damage is estimated based on the response of the building to the natural disaster. The information about component damages at various locations in the building allows better understanding of the consequences of the disaster.

Although these sophisticated models promise more information about building performance, their veracity demands more detailed input data about the building and its components. Consideration of the uncertainty that stems from the limited amount of building information available is essential for a robust performance evaluation (Bradley, 2013). The methods available for quantification and propagation of such uncertainty are discussed in Chapter 4.

3.1.1 Input and Output Data

The following types of data are required to evaluate the performance of a building:

Hazard characterization

When the building performance is not conditioned on a particular disaster scenario, but it is evaluated considering all possible scenarios within a time period, we need to estimate the likelihood of each possible scenario. The hazard curve describes the rate of exceeding various levels of an *Intensity Measure (IM)* over the time period of interest. More information about the description of the hazard is provided in Chapter 1.

Engineering demand parameters (EDPs)

Modern building performance assessment uses EDPs as proxies for the detailed history of building response under a natural disaster event. EDPs shall have high correlation with the building damage of interest, and they shall be estimable with sufficiently high accuracy through numerical analysis. Estimation of EDPs first requires a building response model that is typically created in one of the environments listed in Section 2.1. Second, the building model needs to be excited with loads that correspond to a particular hazard event. The inputs required for these models and analysis were described in previous chapters.

EDPs are extracted from the structural response history during post-processing. Seismic performance assessment often uses peak responses at every story such as *peak story drift ratios* and *peak floor accelerations* (FEMA, 2012). Because other types of hazards result in different response and damage, they are characterized by other types of EDPs, such as *maximum inundation depth* under a tsunami (Reese, 2011).

Component characteristics

Depending on the complexity of the performance assessment method and data availability, buildings are described as a system of *components* or *component-groups*. For example, the component-group-based approach followed by HAZUS (FEMA Mitigation Division, 2018b) aggregates structural components, non-structural components, and contents into three groups. The FEMA P58 method represents the other end of the spectrum; it disaggregates the building into units of components with identical behavior. The component-group-based method typically requires rather generic inputs such as the *type of structural system* and the *occupancy type* to infer component behavior. The more detailed methods use the *quantity*, *direction,* and *location* of each component unit on each floor of the building to estimate their damage.

Fragility functions

The fragility functions describe the likelihood of exceeding a particular *Damage State* (DS) as a function of EDP magnitude. Component damage is classified into a finite number of DSs, so that each DS groups damage scenarios with similar consequences. Fragility curves are essential for every loss assessment. A large part of fragility data is proprietary, especially in the field of wind and water hazards. HAZUS provides fragility functions for component-groups for various hazards. FEMA P58 enables more sophisticated analysis for seismic hazards by providing a database with detailed description of more than 700 types of components.

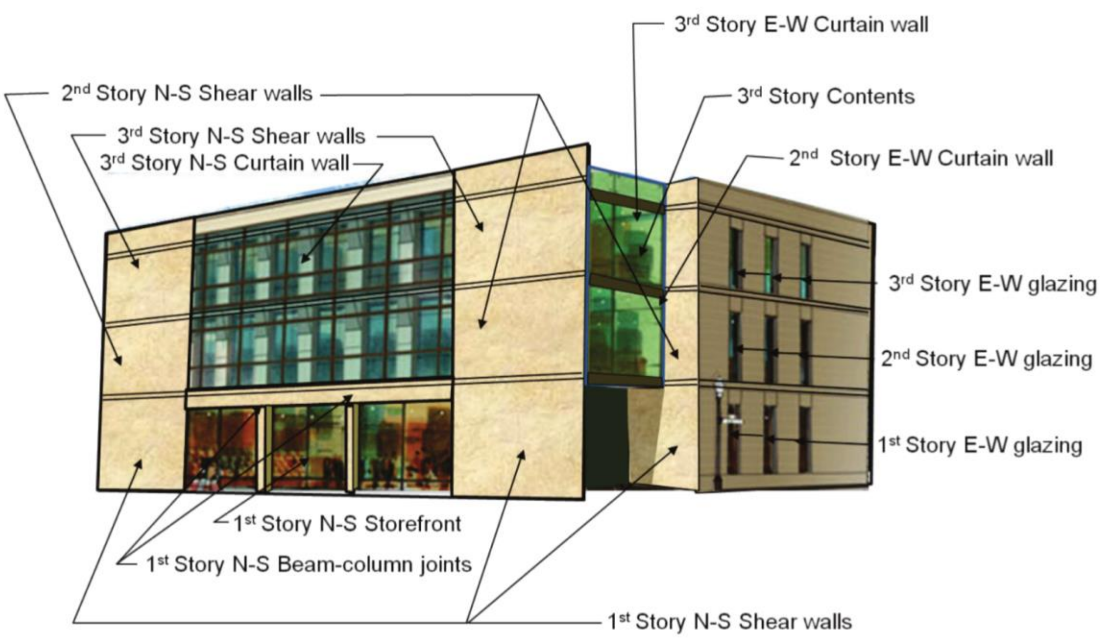

Figure 3-1 Example performance groups (i.e., groups of components with identical behavior) for a three-story office building (FEMA, 2012).

Consequence functions

Direct consequences of building damage are quantified by various types of consequence functions. Each DS has its corresponding set of consequence functions. These functions are defined by additional input data such as *repair cost per component unit*, *affected area* for calculation of injuries, or the probability that a component in that particular DS would trigger an *unsafe placard* for the building. Similar to the other inputs above, these data are not exact, and the description and propagation of their uncertainty is an important part of the calculation method.

Indirect consequences and the influence of building damage on surrounding buildings and infrastructure have been considerably more difficult to model because of the scarcity of data that could be used for model calibration. Decision variables in this group include *non-immediate injuries* and *hospital demand*, *displaced households* and *short-term shelter needs*, *business interruption costs*, *demand surge,* and its influence on reconstruction cost and *downtime estimates* (ARUP, 2013).

Decision variables (DVs)

Performance assessment is typically executed in a stochastic framework; the DVs are considered random, and the raw results of the assessment are at least thousands but often hundreds of thousands of samples of each variable. Therefore, interpretation and visualization of the results is an important part of the process. The majority of applications focus on mean or median values to describe central tendencies with the 10th and 90th percentiles used to illustrate the variability of results. High-performance computing and the improvement in the quality of input data create the incentive to improve estimates of the tails of the distributions and to look at the joint distribution of the variables. These analyses reveal details of complex systems that are often overlooked when focusing only at central tendencies.

3.1.2 Modeling Approaches

The main assumption of the stochastic model for building performance assessment is that the uncertainty in the DVs can be estimated through the following series of independent calculations:

- describe a set of IM levels (e.g., spectral acceleration intensities) and corresponding likelihoods based on the hazard at the building location over a given time period
- describe the building response through EDPs given the level of the IM
- describe component or component-group DSs given a set of EDP realizations
- describe consequences using DVs given the DS of each component or component-group
- aggregate DVs from all components or component-groups

The calculations can be performed independently if the models used for these calculations are decoupled (e.g., the DS for two different IM levels is assumed identical if they result in identical EDPs).

The above methodology has been developed to quantify the seismic performance of buildings. It is the basis of the widely used HAZUS Earthquake Model, and it led to the development of the probabilistic seismic performance assessment framework in the Pacific Earthquake Engineering Research (PEER) Center (Porter et al., 2001). That framework, and the often cited "triple integral," was the foundation of the FEMA P58 document that is considered the state-of-the-art method for seismic performance assessment of buildings today.

When it comes to building performance assessment under non-seismic hazards, the models and methods are typically more approximate. This partly stems from the lack of publicly available high-quality databases—which would drive more sophisticated model development—and from the different nature of the problem. The impact and disruption of earthquakes and hurricanes are very different in both spatial and temporal distribution, with hurricanes having a severe impact on a larger region over a longer time period. Therefore, the focus for hurricane and flood models have always tended to be more regional where capturing the detailed response of individual structures receives less attention.

3.1.3 Software and Systems

The following is a list of software that provides features required for state-of-the-art research in building performance assessment:

CAPRA

Development of the Comprehensive Approach to Probabilistic Risk Assessment (CAPRA) platform was initially supported by the World Bank and the Inter-American Development Bank; it has been managed by Uniandes (Universidad de los Andes in Colombia) since 2017. CAPRA is designed to become a multi-hazard framework based on several modules that handle different tasks of the risk assessment workflow. The currently available modules allow risk assessment using vulnerability functions for several types of hazards (e.g., earthquake, hurricane, and flood). The open source CAPRA framework uses Visual Basic .NET and provides applications in a Windows environment.

ERGO

Developed by the Mid-America Earthquake Center (MAE), ERGO is the successor of mHARP and MAEviz. It is based on the HAZUS methodology for scenario risk assessment and it allows users to write their own extensions. Through these added modules, its functionality is not limited to building performance assessment and allows analysis of infrastructure and lifeline performance as well as indirect consequences in the region. ERGO uses a Windows-based application with a user interface to guide the user through the analysis. It is open source and has been integrated into several European platforms [e.g., SYNER-G (Pitilakis et al., 2014) and HAZturk (Karaman et al., 2008)].

HAZUS 4.2

The FEMA-supported HAZUS tool was already introduced in Section 1.1. The damage and loss assessment modules in HAZUS use the component-group-based approach and categorize components into structural, non-structural, and content groups. The methodology provides estimates of direct and indirect consequences of damage. Its efficiency allows it to be scaled to a regional level without having to resort to HPC.

OpenQuake

The GEM Foundation develops and maintains this tool. The source code is written in Python, open source, and publicly available at a github repository. OpenQuake provides a platform to perform regional disaster risk assessment. The Hazard part of the library has already been mentioned in Section 1.1. The Risk part of the library performs a component-group based performance assessment that is similar to the approach by HAZUS. Input data for the platform is collected and made publicly available in an online repository at platform.openquake.org.

Currently, OpenQuake leans heavily towards seismic hazard and risk assessment, but there are developments towards flood impacts, and the framework is sufficiently flexible to allow other extensions as well.

OpenSLAT

The Open Seismic Loss Assessment Tool is an open-source library developed at the University of Canterbury written in C++ and Python. It is publicly available and allows researchers to use the developed functions in their preferred environment. It implements the Magnitude-oriented Adaptive Quadrature (MAQ) algorithm developed by Bradley (2010) to efficiently solve the integrals involved in PBE calculations.

PACT

The Performance Assessment Calculation Tool developed by the Applied Technology Council (ATC) is a publicly available software that implements the performance assessment methodology in the FEMA P58 document. It is designed to describe the performance of a single building, not a region with a collection of buildings. The software is controlled by a GUI and is available for the Windows platform only. It does not perform hazard and structural response calculations, but rather requires the results of those calculations as inputs. All fragility and consequence functions developed in the FEMA P58 project are conveniently available in PACT.

PBE Application

The Performance Based Engineering Application has been developed by the NHERI SimCenter to provide a convenient GUI-based tool for researchers interested in performance assessment (McKenna et al., 2018). The GUI provides access to the versatile PBE workflow developed at the SimCenter and allows users to choose the tools and methods they wish to use for hazard estimation, response simulation, and loss assessment. The application facilitates the use of high-performance computing resources by providing a built-in connection to the Stampede 2 supercomputer at UT Austin through DesignSafe (Rathje et al., 2017).

Currently, the application is limited to seismic hazards, with wind and water hazards features under development. Seismic hazard assessment uses OpenSHA (see Section 1.1), response estimation uses OpenSEES (see Section 2.1), and loss assessment uses PELICUN (see below) to perform the calculations. Future versions will expand the set of available tools in the application.

PELICUN

The Probabilistic Estimation of Losses, Injuries, and Community resilience Under Natural Disasters is an open-source Python library developed by the SimCenter. It is publicly available at the SimCenter github repository (Zsarnóczay, 2018). The library is designed to provide a versatile, platform-independent and transparent loss-assessment tool for the research community. It is based on a stochastic loss model that allows detailed component-based as well as simplified component-group-based loss assessment. The current version implements the scenario-based assessment from the FEMA P58 methodology. The HAZUS methodology for earthquakes and the time-based assessment option are under development. The library allows researchers to work in their preferred environment and call its functions to perform loss assessment. PELICUN is used in the applications developed by the SimCenter for performance assessment.

SP3

The Seismic Performance Prediction Program (SP3) is proprietary software developed by the Haselton Baker Risk Group. It is widely considered the most reliable implementation of the FEMA P58 methodology and ARUP's REDi framework for downtime estimation; it is used by practitioners and researchers. Besides the high-quality implementation, the tool is also bundled with valuable data that facilitates building response estimation, and damage and loss assessment. The tool can be accessed through a web-based interface that guides the user through the steps of performance assessment. Researchers with programming skills can use it in batch mode that enables more powerful analyses. The calculations run on Amazon EC2 servers, which allow users to run complex, demanding analyses within a reasonable timeframe.

3.2 Transportation Networks

Adam Zsarnóczay
Postdoctoral Researcher, Stanford University

Jack W. Baker
Associate Professor, Stanford University

Ertugrul Taciroglu
Professor, UC Los Angeles

Hazard resilience studies and system interdependencies at regional scales must consider all transportation systems, i.e., roads, railways, and bridges. As such, performance of the transportation system components and the traffic network are the key ingredients in hazard resilience assessment of communities. The challenge in performance assessment of these transportation links lies in sufficiently accurate assessment of the IMs that drive their damage estimation.

3.2.1 Input and Output Data

Performance of the transportation infrastructure requires inputs and provides outputs at a regional scale. Conceptually, some of the inputs are similar to those required for building performance assessment, but the regional analysis introduces additional challenges such as the consideration of spatial correlation and the significant increase in computational complexity of consequence estimation. The following list focuses on the differences and the additional details required when compared to building performance assessment.

Hazard characterization

Regardless of the type of hazard considered, its spatial distribution has to be described using a *random field* that considers the interdependencies between the experienced IMs at different locations. This has been recognized by researchers and several methods are available to prepare a 2D spatially correlated array of IMs for the seismic hazard [e.g., Lee and Kiremidjian (2006), Han and Davidson (2012), and Loth and Baker (2013)]. The probabilistic description of wind-flow characteristics under a hurricane are considerably more challenging and not part of the typical research workflow. Non-seismic hazards are typically investigated based on scenario events. This significantly reduces the uncertainty in the hazard description and the complexity of the stochastic model for the hazard.

Traffic model

Network performance assessment and evaluation of the consequences of network component damage at a regional scale require a model of traffic flow with source and destination data. Development of a traffic model for a large urban area is a large undertaking. Such models are prepared and used by local transport authorities, and are typically not publicly available. There are good examples of collaboration between academia and local authorities that allow researchers to take advantage of the mature models and vast data available at the authorities.

Engineering demand parameters

Road and railroad track damage is usually estimated using vulnerability functions that link intensity measures directly to damage states (e.g., relationships between ground movement and road damage). In such cases, because performance assessment of these network components does not involve explicit simulation of the roadway (or railroad) components, it does not involve calculation of EDPs. Exceptions to this may include cases where empirical relationships do not apply (e.g., roadways along natural or engineered embankments) or to critical infrastructure (e.g., high-speed rail tracks).

In contrast, the performance of bridges usually involves structural simulation to relate specific EDPs to critical damage states in structural components. Depending on the component these are *local deformations, internal forces*, or a DM derived from these quantities [e.g., Park and Ang (1985)] that are well-correlated with the damage states of the particular component (Choi et al., 2004). Estimation of these EDPs with sufficient accuracy requires nonlinear response history analysis on reliable models; hence the computational resources available are an important factor when deciding the level of modeling fidelity. Simplified approaches using vulnerability functions are also available for bridges in HAZUS (FEMA Mitigation Division, 2018b).

Fragility and vulnerability functions

These functions describe the probability of exceeding a particular DS of the component given either an EDP that describes component response (fragility function) or the IM that describes the severity of the hazard at the site (vulnerability function). Both are based on laboratory tests and past experience in post-disaster inspection. Conceptually, they are similar to building fragility and vulnerability functions.

Consequence functions

The likelihood of direct loss of life and injury due to transportation network damage is significantly lower than the likelihood of such events due to building damage. Hence, studies focus more on estimating the cost of reconstruction and downtime for each component as a function of the damage severity expressed by the DS (Stergiou and Kiremidjian, 2006).

Decision variables

Transportation network performance is described by the change in traffic or the change in network capacity given the traffic model described above. Probabilistic assessment of network performance requires a complex and computationally demanding analysis. Performance metrics that shall serve as decision variables are a topic of ongoing research (Miller and Baker, 2016). Changes in travel time (either regional statistics or focusing on a particular route) and accessibility are two commonly used metrics.

3.2.2 Modeling Approaches

Natural disaster impact on a transportation network uses the assumption of independent calculation steps from building performance assessment (Change et al., 2000; Kiremidjian et al., 2006). Hence, the hazard characterization, response estimation, damage estimation, and consequence estimation are performed by independent stochastic models. This allows for the following approach to regional simulation:

- characterize the hazard in the region using a random field of spatially correlated IMs;

- estimate the response and the corresponding damage in each network component given the IM at the location of the component;
- estimate the downtime and repair cost for each network component and assess the performance of the transportation network given the level of damage in network components.

Structural response and damage (but not the consequences) in one network component is typically assumed to be independent of other components. This assumption enables more efficient simulation through parallel calculation of component damage in the region. Note: this may overlook correlations in certain bridges that are designed and detailed in similar ways (e.g., bridges along major highways that may have been designed and constructed under one project). The spatially correlated IMs still ensure that similar components within a small area will experience similar demands and, consequently, similar damages (Figure 3-2).

If sufficiently detailed information of the transportation network is available, the cascading failure of components can be considered; for example, if one overpass fails, its collapse triggers the collapse of others in a complex highway interchange. Consideration of this type of interaction between network components prohibits independent, parallel assessment of network component damage.

A special but important case of transportation network analysis is the investigation of flood risk to the underground transport infrastructure. Such risk can be evaluated by computing the volume of water entering the tunnels based on the time history of flood height at each opening. The performance of the underground system can be evaluated based on the degree of flooding in each of its tunnels. This methodology is available in the GIS-based analysis tool of Jacob et al. (2011).

3.2.3 Software and Systems

The software that helps with characterization of the hazard and estimation of network component response were introduced in Chapters 1 and 2, respectively. Some of the following tools have such capabilities, but the focus here is on the performance-assessment-related features.

HAZUS 4.2

This FEMA-supported tool has been introduced in Section 1.1. The HAZUS Multi-hazard Loss

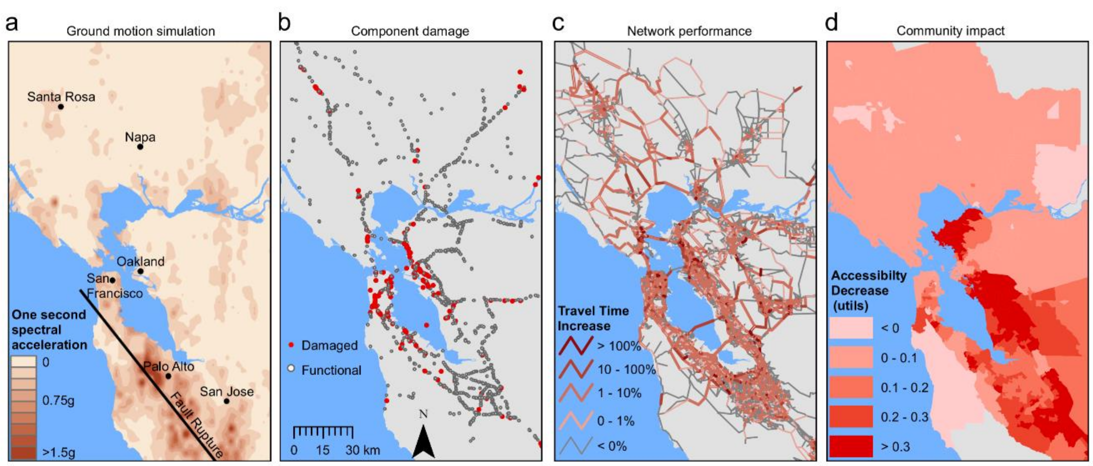

Figure 3-2 Illustration of the transportation network risk assessment framework from Miller and Baker (2016).

Estimation Methodology provides a comprehensive framework, vulnerability, and consequence functions for seismic damage and reconstruction time assessment for bridges and transportation links. It also provides a model for assessment of bridge damage due to storm surge. Evaluation of the impact of component damage on network performance requires external tools.

OpenQuake

The risk assessment framework of the OpenQuake tool (introduced in Section 3.1) is sufficiently flexible to enable the assessment of damage and consequences for transportation network components. Unlike HAZUS, the vulnerability and consequence information is not provided with the tool. The functions available in the HAZUS technical manual (FEMA Mitigation Division, 2018b) can be adopted with minor effort.

3.2.4 Research Gaps and Needs

The regional assessment methodology for transportation networks in HAZUS 4.2 is known to have critical shortcomings [see, e.g., Mangalathu et al. (2017)]. State-of-the-art transportation network analyses need to develop tools to construct robust bridge models. These bridge models should be shared with the broader research community so that bridge inventories at regional scales can be compiled and analyzed. Such a capability stands to revolutionize seismic resilience assessment studies and could be extended to other hazards (e.g., tsunamis and hurricanes). This would provide a natural interface between engineers, researchers, and practitioners, including insurance agencies/companies, emergency response managers/planners, traffic engineers, social scientists, etc.

The following areas appear ripe for directing and supporting research efforts:

- Development of tools to generate large inventories of bridge models that can improve upon as more data is available and shared with other members of the natural hazard engineering community. These efforts will likely feature computer vision, machine learning, and data-harvesting techniques.
- Studies on devising system-level hazard resilience metrics that take into account the inherent dependency of the subject infrastructure (e.g., port facilities) to regional transportation network performance
- Development of workflows and tools to facilitate regional-scale risk and loss assessment studies involving transportation networks
- Development of new tools to accurately estimate bridge downtimes and the resulting effects on mobility

3.3 Water, Sewer, and Gas Pipelines

Iris Tien
Assistant Professor, Georgia Institute of Technology

Jack W. Baker
Associate Professor, Stanford University

Adam Zsarnóczay
Postdoctoral Researcher, Stanford University

There are many methods available for modeling and simulation of lifeline networks. These include empirical, agent-based, system dynamics-based, economics theory-based, and network-based approaches. The reader is referred to resources including Ouyang (2014) and Johansen et al. (2016) for a discussion of the general methods available and the varying measures existing for assessing community outcomes based on lifeline performance. The techniques described in the works referenced are general and can be applied to any lifeline network; they are not described in more detail here. The focus in this report is on modeling and simulation software for specific lifeline types with parameters particular to the lifeline and resource flow type. The emphasis is on open and publicly available software tools.

The objective of water, sewer, and gas pipeline network simulation is to assess the ability to provide critical water, wastewater, and natural gas services for populations under varying scenarios. As relevant for natural hazards engineering, the purpose is to assess the states of these lifeline systems under hazard events and inform decision making on approaches to improve the expected performance of these systems when subjected to these hazards. The underlying physics of water, sewer, and gas pipeline simulation lie mainly with the simulation of individual components in the system, e.g., pipes, junctions, and valves, and subsequently system-level analysis based on the component-level information through the use of network graphs or by more detailed hydraulic flow and pressure analysis through the network.

3.3.1 Input and Output Data

The information needed to describe the natural hazard at a regional scale is similar to the hazard characterization explained for transportation networks in the previous section. The hazard models provide a regional distribution of IMs that are used as proxies to express the severity of the hazard in the area. The type of IM depends on the hazard type and the network component under investigation. While the effect of a seismic event on structures is typically described using PGA or spectral acceleration, the analysis of pipelines requires information about the PGV and the permanent ground deformation (Romero et al., 2010).

Lifeline models require information about the geographical location and classification of the lifeline components. Such information is often hard to obtain, especially at a sufficiently high resolution for detailed regional assessment. This lack of data stems partly from privacy and national security concerns and partly from the fact that the databases are privately owned. Water, sewer, and gas pipeline simulation relies on information about component locations, size (e.g., pipe diameter), pressure, and connectivity.

Output data will typically be water, wastewater, or gas pressures, flows, or volumes at specific locations. Of particular interest is the ability to provide these services at final distribution points in the network.

3.3.2 Modeling Approaches

The modeling approach in the simulation is often determined and constrained by the amount and resolution of available information. Regardless of the modeling fidelity, the approach is almost always based on the following two steps:

- First, given an IM at the site, component damage is estimated by assigning a DS to each component. In HAZUS, this is done using component-specific fragility curves to estimate the damage to a given component under the hazard. For facilities and building-like structures, the damage evaluation is similar to the HAZUS method described in Section 3.1. For pipeline networks (i.e., water, sewer, and gas), two types of damages are considered: leaks and breaks. The sophistication of damage evaluation heavily depends on the level of analysis and the available IMs.
- The second step, given estimated damage to lifeline components, is to assess network-level consequences. In HAZUS, the direct consequences are evaluated using empirical relationships based on past experience. Direct consequences are typically limited to restoration time and replacement cost in HAZUS.

The HAZUS earthquake model is the most sophisticated among the HAZUS models for lifeline modeling and simulation. For natural hazards engineering, HAZUS hurricane and tsunami models are limited to buildings and do not cover lifelines. The HAZUS flood model provides damage and loss estimates only for a subset of potable water, wastewater, and natural gas facilities. Damage is a function of flooding as measured by water level in feet. The information below is based on the earthquake hazard modeling.

The default inventory for potable water networks in HAZUS contains estimates of pipelines aggregated at the census tract level (based on U.S. Census TIGER street file datasets). The HAZUS methodology suggests three levels of analysis for potable water networks:

- Level 1 is based on the default HAZUS inventory (i.e., census tract estimates).
- Level 2 requires additional information on transmission aqueducts, distribution pipelines, reservoirs, water treatment plants, wells, pumping stations, and storage tanks.
- Level 3 requires additional information on junctions, hydrants, and valves, and further data about connectivity and serviceability (i.e., demand pressures, and flow demands at different distribution nodes). Such information is typically available in KYPIPE, EPANET, or CYBERNET format.

Analysis of other lifelines requires similar types of information:

- Wastewater networks are described by the geographical layout and characteristics of the transmission network and its treatment components.
- Natural gas networks are described by the geographical layout and characteristics of buried or elevated pipelines and compressor stations.

The diameter of pipes is not considered as a parameter in the damage functions. However, it may be a good proxy for capacity of the given network element and used in network performance assessment in more sophisticated analyses. The rigidity of the pipes in a network is an important input parameter that heavily influences the damage to the pipelines by earthquakes.

In HAZUS, three levels of modeling fidelity are described that correspond to the previously introduced analysis level:

- Level 1: Results are limited to number of leaks and breaks per census tract resulting in a simplified evaluation of network performance (i.e., total number of households without water).
- Level 2: The network is modeled as a graph. This approach allows for estimates of component functionality, component damage ratio, and flow reduction to each area served by the network. Overall network performance can be estimated as a function of the average repair rate (repairs/km) of the pipes in the network. Such evaluations have been performed for San Francisco (Markov, Grigoriu, O'Rourke, 1994), Oakland (G&E, 1994), and Tokyo (Isoyama and Katayama, 1982).
- Level 3: The suggested model is based on the work of Khater and Waisman (1999). It provides more accurate estimates of the hydraulic flow in the network. This translates into improved accuracy and reliability of results when compared to Level 2 analyses.

3.3.3 Software Systems

HAZUS 4.2

This methodology classifies potable water, wastewater, oil, natural gas, electric power, and communication systems as lifelines. It provides a similar methodology for the modeling and simulation of these systems. Electrical networks are the only lifelines that have influence on other lifelines in the HAZUS methodology (i.e., damage to the electrical network and the consequent loss of power results in loss of function and potential damage in other lifelines). Electrical system modeling is described in more detail in Section 3.4.

The dependency between network component repair times is not considered by HAZUS. The dependencies of one lifeline damage or the consequences of such damage on other lifelines is not taken into consideration in the HAZUS methodology, with the exception of electrical networks. Assessment of network performance is out of the scope of the HAZUS methodology for wastewater systems. In general, HAZUS 4.2 allows estimation of lifeline damage and consequent reduction in network performance. Further details of the software and its limitations are explained in Section 1.1.

EPANET

EPANET is a software package developed by the U.S. Environmental Protection Agency (EPA) for water pipeline distribution modeling and simulation. It has been widely adopted by municipalities and water utilities as a standard format to evaluate their systems. Its two main uses are for hydraulic modeling, including for maintaining flows and pressures in a system, and for contaminant transport simulation. EPANET files can be used as input files for water distribution pipeline information. EPANET modeling and simulation does not include the ability to assess the impacts of natural hazards on lifeline components or network performance.

GIRAFFE

The Graphical Iterative Response Analysis for Flow Following Earthquakes (GIRAFFE) was developed at Cornell University to provide a performance assessment tool for pipeline networks (Wang and O'Rourke, 2008). It uses the EPANET engine to define the water network and perform hydraulic network analysis. Performance estimates are presented in a user interface using a GIS framework.

WNTR

WNTR (Water Network Tool for Resilience) is an open-source library of functions developed in the Python programming language by Sandia Laboratories. It uses input data in the EPANET format to define a network and perform an analysis that is similar to the Level 2 and 3 analyses in the HAZUS methodology. WNTR adds the hazard element to water pipeline simulation. Using WNTR requires basic Python programming skills, but in return it provides a platform-independent solution that can easily work in a HPC environment. In addition to the damages and estimated restoration times, it provides estimates of the hydraulic performance of the damaged network. The library is hazard-agnostic; as long as the IMs and the corresponding fragility curves are supplied, it performs the damage calculations and evaluates the estimated consequences of the damage.

Gas pipeline simulation software

Compared to water pipeline simulation software, natural gas pipeline modeling and simulation software is mostly commercial and proprietary, e.g., **Synergi Gas** from DNV-GL that conducts hydraulic modeling and analysis and **NextGen** from Gregg Engineering to create hydraulic simulation models to run simulations and calculate pressures, flow rates, and other operational parameters. Given the emphasis on open-source software in this report, these are not discussed in more detail.

3.3.4 Research Gaps and Needs

In lifeline modeling and simulation, there is the need for improved consideration of interdependencies between lifelines. This will enable researchers to better understand the impacts of natural hazards on communities. Advancing component-level fragility curves and improved simulation of structural response for critical facilities will lead to a better estimate of expected damage, both in terms of accuracy and resolution in a simulation. Finally, improved simulation of the recovery process will enable researchers to better understand performance and recovery of lifeline services during and after disasters.

3.4 Electrical Transmission Substations and Lines

Iris Tien
Assistant Professor, Georgia Institute of Technology

Adam Zsarnóczay
Postdoctoral Researcher, Stanford University

The objective of the simulation of electrical substations and transmission and distribution lines is similar to that of other lifelines. Namely, the objective is to assess the ability to provide critical electricity services for populations under varying scenarios. As relevant for natural hazards engineering, the purpose is to assess the state of these lifeline systems under hazard events and inform decision making on approaches to improve the expected performance of these systems under hazards. Compared to hydraulic or pressure flow analyses for water, sewer, and gas pipeline simulation, the underlying physics of the simulation relies on power voltage flow analysis in addition to system-level analyses that can be conducted through the use of network graphs, for example.

3.4.1 Input and Output Data

Modeling electrical networks requires information about generation facilities, substations, and transmission and distribution circuits. In addition to the geographical location, the level of voltage is an important property. Depending on the type of hazard, other details can be required, such as anchorage of components for seismic analysis.

Communication networks are defined by the central offices, broadcasting stations, transmission lines, and cabling. The communication cables are assumed to be able to accommodate ground shaking and are not considered damageable by earthquakes.

3.4.2 Modeling Approaches

In general, given the IM at the site, component-specific fragility curves can be used to estimate the damage to a given component under a hazard. For facilities and building-like structures the damage evaluation is similar to the HAZUS method described in Section 3.1. Given the damage to the network component, the direct consequences are evaluated using empirical relationships based on past experience. Direct consequences are typically limited to restoration time and replacement cost in HAZUS. In HAZUS, fragility of electrical substations and distribution circuits is defined with respect to the percentage of subcomponents being damaged. The research of Tang and Wong (1994) on the performance of telecommunication systems after the Northridge earthquake suggests prompt recovery. The system recovered to 96% performance within three days.

Modeling indirect consequences of damage in the electric power network is an area of active research [e.g., Moore et al. (2005)]. In HAZUS, interaction between nodes of the power network is not considered. Interaction between other lifeline systems is considered with the following approach: the loss of electric power is assumed to influence the slight/minor and moderate DSs of components in other lifelines that depend on power. More severe DSs are not influenced by the lack of power. The substation that serves connected components is assumed to experience the event at the location of the served component. An even more simplified approach uses a generic damage algorithm to describe the availability of power as a function of an IM.

3.4.3 Software Systems

HAZUS 4.2

As mentioned in Section 3.3, HAZUS groups electric power and communication networks with the other lifelines and provides similar methodologies for their analysis. Electrical networks are the only lifeline type that has influence on other lifelines in the HAZUS methodology (i.e., damage to the electric network and the consequent loss of power results in loss of function and potential damage in other lifelines). HAZUS 4.2 software allows estimation of lifeline damage and consequent reduction in performance. Further details of the software and its limitations are explained in Section 1.1, and its application to lifeline simulation and pipelines in particular are described in Section 3.3.

OpenDSS

OpenDSS is a software package developed by the Electric Power Research Institute (EPRI). It conducts electrical power system simulation for electric utility power distribution systems. It supports simulations of power flow across frequencies and is mainly used to evaluate distributed energy resource generation, its integration with utility distribution systems, and grid modernization technologies. Assessments do not include the impacts of natural hazards on the system components or network performance for natural hazards engineering applications.

3.4.4 Research Gaps and Needs

Similar to the description of the research gaps and needs in pipeline simulation, there is the need for improved consideration of interdependencies between lifelines as related to electrical systems. Given the criticality of electricity for many lifelines, this will enable researchers to better understand the impacts of natural hazards on communities. Advancing component-level fragility curves and improved simulation of structural response for critical facilities will lead to a better estimate of expected damage, both in terms of accuracy and resolution in a simulation. Finally, improved simulation of the recovery process will enable researchers to better understand performance and recovery of lifeline services during and after disasters.

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4. Uncertainty Quantification

Uncertainty quantification (UQ) represents one of the fastest evolving scientific fields, with advances in computer science and statistical computing promoting constant developments in the way uncertainty is incorporated in the predictive analysis of engineering systems (Smith, 2013). In particular, over the last decade(s) the popularity of HPC and of machine-learning tools have dramatically impacted the way computational simulation is utilized within the UQ field, lifting many barriers that were traditionally associated with simulation-based UQ techniques, and allowing the detailed characterization and propagation of uncertainties even for problem with highly complex (computationally intensive) numerical models. It is the current consensus within the UQ community that these advances will/have remove(d) the need for simplified approaches with respect to both the uncertainty characterization (assumptions/models used to describe uncertainty and system performance) or uncertainty propagation (estimation of statistics of interest).

When discussing computational advances and state-of-the art tools in UQ, greater emphasis is typically placed on algorithmic approaches rather than the corresponding software facilitating the implementation of these approaches. The reason for this is that development of scientific tools for UQ has focused traditionally on a specific UQ sub-field [for example, surrogate modeling to support UQ analysis (Lophaven et al., 2002; Gorissen et al., 2010)], with a large number of researchers [for example, Bect et al. (2017) and Clement et al. (2018)] offering open-source algorithms to even address specific class of problems within each of these subfields. Although many of these algorithms have been developed in MATLAB, in recent years significant emphasis has been placed on open-source libraries developed using Python and typically distributed though GitHub.

Since UQ is a very broad field, here discussions focus on applications within the natural hazards engineering field, with some references to relevant general UQ advances also offered. Emphasis is on computational aspects, the most pertinent UQ feature for a state-of-the-art review of UQ simulation methods. Additionally, discussions focus on algorithmic developments, with some references also on relevant software. With respect to description of uncertainty emphasis is placed on probabilistic characterization; even though alternative approaches exist, such as use of fuzzy sets and interval analysis, the current standard of practice in natural hazards engineering is to rely on probabilistic UQ analysis. This can be attributed to the tradition in civil engineering codes to describe performance with respect to statistical measures (probability of exceeding performance limit states), or to the fact that hazard exposure, the most significant source of variability when discussing risk in the natural hazards engineering context, is almost always described using probabilistic measures (McGuire, 2004; Resio et al., 2007).

All references provided are merely indicative ones (though a few of them can be regarded as recent seminal work), since the field is very broad and constantly expanding.

4.1 Uncertainty: Basic Issues

Alexandros Taflanidis
Associate Professor, University of Notre Dame

Joel P. Conte
Professor, UC San Diego

Sanjay Govindjee
Professor, UC Berkeley

George Deodatis
Professor, Columbia University

4.1.1 Uncertainty Characterization

In natural hazards engineering, characterization of the uncertainties impacting predictions is integrally related to risk quantification. Performance based engineering (PBE) (Goulet et al., 2007; Riggs et al., 2008; Ciampoli et al., 2011; Barbato et al., 2013) represents undoubtedly the foundational development for this task. Performance-based engineering decouples the risk quantification to its different components, mainly hazard analysis (exposure), structural analysis (vulnerability), and damage and loss analysis (consequences), with uncertainties included (and impacting predictions) in all these components. Variability of the hazard itself, in terms of both occurrence and intensity, is widely acknowledged to correspond to the most significant source of uncertainty in this setting. Frequently hazard variability is represented through a resultant IM (Baker and Cornell, 2005; Kohrangi et al., 2016), though comprehensive approaches that focus on connecting the excitation to parameters of the geophysical process creating it also exist, for example in earthquake engineering description of time-histories through use of stochastic ground motion models dependent on seismological parameters (Bijelić et al., 2018; Vlachos et al., 2018) or in coastal risk estimation use of surge modeling numerical tools dependent on atmospheric storm characteristics (Resio et al., 2007). Beyond the hazard variability, uncertainties related to parameters of the structural model or generalized system model (for applications not examining directly structural risk) and to the characteristics for describing performance are also recognized as important for inclusion in risk estimation (Porter et al., 2002). The term “system” will be used herein to describe the application of interest; this may pertain, for example, to a building model, to an infrastructure network, or to a soil–structure interaction system configuration.

Uncertainty within this natural hazards engineering risk characterization setting is ultimately described through a discrete number of parameters (random variables) pertaining to either the hazard or the system/performance model. Even when the uncertainty description for the underlying problem actually entails a stochastic sequence or a random field, a discretized approximation of these functions is commonly utilized, as necessitated by the numerical tools used to compute the system response (Gidaris et al., 2014). This translates into use of a parameterized realization for the excitation or model characteristics, an approach that seamlessly fits within the overall PBE framework. Exceptions exist primarily for stochastic dynamics problems, for which propagation of the stochastic excitation uncertainty can be performed using random vibration theory, such as exact or approximate solution of stochastic differential equations or estimation of stationary statistics in the frequency domain (Li and Chen, 2009). Though such approaches offer substantial benefits, their implementation is primarily constrained to linear systems or nonlinear systems with moderate degree of complexity (dos Santos et al., 2016; Wang and Der Kiureghian, 2016), such as systems with very small number of degrees-of-freedom or nonlinearities having simple, analytical form. As such, their utility within natural hazards engineering is limited to specialized applications. Even in such cases, the remaining uncertainties, beyond the stochastic excitation itself, must be described using a parametric description. The overall parameterized uncertainty description promoted within PBE is therefore well aligned with such approaches, as their adoption simply requires substitution of the deterministic simulation system model with a stochastic simulation system model, the latter representing the solution of the stochastic dynamics problem.

When using Monte Carlo simulation techniques to propagate uncertainty (see discussion in the next paragraph), a critical part of the methodology is the numerical generation of sample functions of the stochastic processes, fields, and waves involved in the problem, modeling the uncertainties in the excitations (e.g., wind velocities, seismic ground motion, and ocean waves) and in the structural system (e.g., material and geometric properties). These processes, fields, and waves can be stationary or non-stationary, homogeneous, or non-homogeneous, scalar or vector, 1D or multi-dimensional, Gaussian or non-Gaussian, or any combination of the above. It is crucial for a simulation algorithm to be computationally efficient as a very large number of sample functions might be needed. A wide range of methodologies is currently available to parametrically describe uncertainty and perform these simulations, including the spectral representation method, Karhunen-Loeve expansion, polynomial chaos decomposition, auto-regressive moving-average models, local average subdivision method, wavelets, Hilbert transform techniques, and turning bands method.

The setting outlined in the previous two paragraphs leads, ultimately, to risk characterized as a multidimensional integral over the parametric uncertainty description (*input*), with uncertainty propagation (*output*) translating to estimation of the relevant statistics (estimation of integrals representing moments or reliability with respect to different limit states). The aforementioned integral is frequently expressed with respect to the conditional distributions of the different resultant risk components (Goulet et al., 2007; Barbato et al., 2013), for example {hazard / response given hazard / consequences given response}. This represents merely a simplification for risk quantification purposes as allows for the decoupling of the different components. Even when this simplification is invoked, risk ultimately originates from the uncertainty in the model parameters of the system, quantified by assigning a probability distribution to them, representing the UQ input.

4.1.2 Uncertainty Propagation

For uncertainty propagation, the traditional approach in natural hazards engineering has been the use of point estimation methods, either methods that focus on the most probable values of the model parameters like the first-order second moment (FOSM) method (Baker and Cornell, 2008) and its variants (Vamvatsikos, 2013), or methods that focus on the peaks of the integrand of the probabilistic integral (design points) like the first- and second-order reliability methods (FORM/SORM) (Koduru and Haukaas, 2010). As point estimation methods are inherently approximate, with no available means to control their accuracy, advances in computer science and statistics have encouraged researchers the past decade to rely more heavily on Monte Carlo simulation tools for uncertainty propagation in natural hazards engineering (Smith and Caracoglia, 2011; Taflanidis and Jia, 2011; Vamvatsikos, 2014; Esposito et al., 2015).

Although point estimation methods do still maintain utility and popularity, natural hazards engineering trends follow the broader UQ community trends in promoting computer and Monte Carlo simulation approaches, as these techniques facilitate high-accuracy uncertainty propagation (unbiased estimation) with no fundamental constraints on the complexity of the probability and numerical models used. Of course, computational complexity is still a concern for Monte Carlo simulation. The current state of the art in natural hazards engineering for addressing this challenge is to leverage both advanced Monte Carlos simulation techniques (Li et al., 2017; Bansal and Cheung, 2018) and, more importantly, machine-learning and computational statistics tools (Abbiati et al., 2017; Ding and Kareem, 2018; Su et al., 2018; Wang et al., 2018). Relevant recent advances for Monte Carlo simulations focus on variance reduction techniques and rare-event simulation, with some emphasis on problems with high-dimensional uncertainties, whereas for machine learning, focus is primarily on use of a variety of surrogate modeling (metamodeling) techniques. Most machine learning implementations in natural hazards engineering fall under the category of direct adoption of techniques developed by the broader UQ community, though a number of studies do address challenges unique to the integration of surrogate modeling in natural hazards engineering problems, for example, the need to address the high-dimensionality of input when a stochastic description is utilized for non-stationary excitations (Gidaris et al., 2015).

Note: the natural hazards engineering modeling community has been continuously increasing the complexity of the models they adopt. Such high-fidelity numerical models, able to capture the behavior of structural, geotechnical, and soil–foundation-structural systems (all the way to collapse or the brink of collapse) are inherently nonlinear hysteretic (path-dependent) and frequently degrading/softening; therefore, they present (significant) challenges in term of robustness of convergence of the iterative schemes used to integrate their equations of motion. The significance of these challenges will further increase in the context of Monte Carlo simulation-based UQ and requires significant research efforts to be overcome.

Discussing more broadly advances in the UQ field, emphasis is currently strongly placed on machine learning techniques for accelerating UQ computations (Murphy, 2012; Ghanem et al., 2017; Tripathy and Bilionis, 2018). The relevant developments are frequently integrated with advanced Monte Carlo simulation techniques, particularly for simulation of rare events (Li et al., 2011; Balesdent et al., 2013; Bourinet, 2016). With respect directly to machine learning, some emphasis is given on approaches for tuning and validation (Mehmani et al., 2018), though the primary focus is on the proper design of the computer simulation experiments (DoE) (Kleijnen, 2008; Picheny et al., 2010) that are used to inform the development of the relevant computational statistics tools. Adaptive DoE is widely acknowledged to offer substantial advantages in balancing computational efficiency and accuracy for UQ analysis when machine-learning techniques are used, and significant research efforts are currently focused on advancing DoE techniques; however, it remains an open challenge for the community.

The concept of model fidelity remains unexplored within the natural hazards engineering community, but it plays a central role in modern UQ techniques, with a range of algorithms developed to properly integrate hierarchical fidelity models to promote efficient and accurate uncertainty propagation (Geraci et al., 2017; Peherstorfer et al., 2018). Combination of machine-learning (primarily surrogate modeling) techniques with different fidelity models is also a topic that has been receiving increasing attention for facilitating the use of expensive numerical models in UQ (de Baar et al., 2015; Zhou et al., 2016). In the natural hazards engineering setting, discussions on explicitly exploiting model fidelity for risk estimation are very limited; therefore, the community still heavily emphasizes use of high-fidelity models without, yet, examining how different levels of simulation fidelity and the use of reduced order models can be properly combined to promote efficient and accurate risk estimation. Multi-fidelity Monte Carlo and hierarchical surrogate modeling techniques constitute, undoubtedly, important opportunity areas for advancing UQ analysis in natural hazards engineering.

Another important aspect of uncertainty propagation is the concept of sensitivity analysis. In natural hazards engineering, this has been primarily implemented as local sensitivity analysis (i.e., estimation of gradient information) since this fits well with the point estimation methods used frequently for calculation of statistics, which aids in the identification of design points. Of greater importance within a UQ setting is a global sensitivity analysis (Sobol, 1990; Saltelli, 2002; Rahman, 2016) that allows identification of the relative importance of the different sources of uncertainty, offering insights with respect to both accelerating UQ computations as well as to understanding of the critical factors impacting the overall risk. Though global sensitivity analyses can be particularly useful for hazard applications (Vetter and Taflanidis, 2012), it is currently receiving limited practical interest within natural hazards engineering [though implementations do exist even for all purpose codes; see Bourinet et al. (2009)]. More formal integration of global sensitivity analysis tools within the natural hazards engineering community represents another topical area where advancements can/should be made. Note: the computational cost for global sensitivity analysis, e.g., calculation of first and higher order sensitivity indexes, is much higher than the cost of simple uncertainty propagation; relevant techniques range from use of quasi-Monte Carlo (Saltelli, 2002) to surrogate modeling (Sudret, 2008) to sample-based methods relying on approximation of conditional distributions (Jia and Taflanidis, 2016; Li and Mahadevan, 2016).

4.2 Uncertainty: Applied Issues

Alexandros Taflanidis
Associate Professor, University of Notre Dame

Joel P. Conte
Professor, UC San Diego

Sanjay Govindjee
Professor, UC Berkeley

George Deodatis
Professor, Columbia University

4.2.1 Model Calibration and Bayesian Inference

Model updating/calibration plays an important role in natural hazards engineering, with data coming from both component (or system)–level experiments or system–level observations during (or post) actual excitation conditions. Within a UQ setting, the current standard to perform this updating is Bayesian inference (Beck, 2010; Kontoroupi and Smyth, 2017). Using observation data, Bayesian inference can be leveraged to provide different type of outputs/results (Beck and Taflanidis, 2013) through the following three tasks: identify the most probable model parameters or even update the entire probability density function for these parameters (obtain posterior distributions); perform posterior predictive analysis, and update risk using the new information; when different numerical models are examined, identify the probability of each of them (as inferred by the data) to either select the most appropriate or calculate the weights when all of them will be used in a model averaging setting (model class selection). The typical implementation refers to model parameter updating, what is traditionally viewed as model calibration, with model class selection less frequently used, especially within natural hazards engineering community applications. Still, Bayesian model class selection offers a comprehensive tool for evaluating appropriateness of different models (Muto and Beck, 2008), and especially for natural hazards engineering applications that can be integrated with health monitoring tools (Oh and Beck, 2018).

From a computational perspective, Bayesian updating can incur computational burden, especially when complex FEM models are utilized and a variety of approaches are used to address this challenge. Common approaches include the use of advanced MCS techniques to reduce the total number of simulations needed (Quiroz et al., 2018), the integration of metamodeling to approximate the complex system model (Angelikopoulos et al., 2015), or the use of direct differentiation tools to accelerate computations (Astroza et al., 2017). Bayesian updating may rely on point estimates, which are equivalent to identifying and using only the most probable model parameter values (based on the observation data)—expressed as a nonlinear optimization problem—or leveraging the entire posterior distribution—expressed as a problem of sampling from this distribution.

For the latter, Markov Chain Monte Carlo (MCMC) techniques need to be used for any of the three tasks entailed in Bayesian inference (Catanach and Beck, 2018). For problems involving inference for dynamical models (germane to the majority of applications in natural hazards engineering), updating can be done in batch mode that uses all observation data or recursive mode that sequentially updates model characteristics during the time history for the observations (Astroza et al., 2017). The batch approach is a direct implementation of the broader Bayesian inference framework. The recursive implementation typically leads to filtering approaches, including Kalman filters (KF) and its variants (Extended KF or Unscented KF), that rely on linear or Gaussian assumptions (Astroza et al., 2017; Kontoroupi and Smyth, 2017; Erazo and Nagarajaiah, 2018), and particle filters (PF) that rely on a sequential MCS approach and do not involve any type of (linear/Gaussian) assumptions (Chatzi and Smyth, 2009; Wei et al., 2013; Olivier and Smyth, 2017). The recursive approach is used primarily for real-time or online applications and focuses primarily on the most probable parameter values.

4.2.2 Design under Uncertainty

In natural hazards engineering, design under uncertainty has been traditionally expressed as a reliability-based design optimization (RBDO) (Spence and Gioffrè, 2012; Chun et al., 2019) or as a robust design optimization (RDO) (Greco et al., 2015) problem. Some recent approaches deviate from this pattern and follow directly PBE advances by formulating the design problem with respect to life-cycle cost and performance objectives (Shin and Singh, 2014), and even adopting multiple probabilistic criteria to represent different risk-attitudes (Gidaris et al., 2017). Practical applications focus on design of supplemental dissipative devices (Shin and Singh, 2014; Gidaris et al., 2017; Altieri et al., 2018) and member-sizing (Huang et al., 2015; Suksuwan and Spence, 2018), and in some cases on topology-based optimization of structural systems (Bobby et al., 2017; Yang et al., 2017).

With respect to the solution of the corresponding optimization problem, the natural hazards engineering community follows the broader UQ trends. Design under uncertainty optimization problems undoubtedly present significant computational challenges since they combine two tasks, each with considerable computational burden: uncertainty propagation and optimization. Discussed next is how uncertainty propagation is handled within this coupled problem.

Common approaches, especially within context of RBDO and RDO, typically rely on approximate point-estimation methods like FORM/SORM (Papadimitriou et al., 2018) and some sort of decoupling of the optimization/uncertainty-propagation loops to accelerate convergence (Beyer and Sendhoff, 2007). Over the past decade, advances in the use of simulation techniques within UQ have created new opportunities that incorporate MCS techniques to solve design-under-uncertainty problems (Spall, 2003; Li et al., 2016), thereby lifting some of the traditionally associated computational barriers. Greater emphasis is continuously being placed on solving design-under-uncertainty problems using advanced Monte Carlo techniques (Medina and Taflanidis, 2014), which are frequently coupled with an intelligent integration of surrogate modeling tools (Zhang and Taflanidis, 2018). It is expected that this trend will continue since computer science and machine-learning advances have dramatically altered the computational complexity for leveraging MCS for design optimization under uncertainty, offering an attractive alternative to traditional approaches that relied on the approximate (but highly efficient) point estimation methods.

4.2.3 Relevant Software

Beyond specific UQ algorithms developed by individual researchers and shared in repositories like GitHub or MATLAB’s File Exchange, two other important UQ software categories exist

- Libraries integrated with existing modeling tools appropriate for natural hazards engineering analysis, like the general purpose FEM reliability tools offered through FERUM (Bourinet et al., 2009). These libraries frequently address a specific type of UQ analysis, e.g., direct MCS or reliability estimation.
- Software that looks at UQ analysis with a broad brush could be appropriate for use in natural hazards engineering applications (but as of yet has not necessarily been developed specifically for that purpose). Such software typically covers the entire range of UQ analysis, with continuous integration of the relevant state-of-the art advances. They are composed of scientific modules that perform different UQ tasks, connected through the main software engine and, in addition, are commonly equipped with an appropriate GUI.

The last category of UQ software packages is of greater interest, especially since it covers the entire domain of a rapidly expanding field and facilitates the integration of the relevant developments, which typically leverage different classes of tools (e.g., rare-event simulation using surrogate models with adaptive refinement. UQ software programs typically address the following tasks:

- Probabilistic modeling. This pertains to standard uncertainty characterization, extending from simple parametric description to stochastic characterization and represents the input to the UQ software.
- Monte Carlo and reliability analysis, extending from direct MCS with Latin hypercube sampling, to use of point estimation methods (FORM/SORM), to variance reduction, to rare event simulation. UQ outputs considered correspond typically to statistical moments, probabilities of exceedance for different limit states, or fitted distributions. The numerous software programs adopt different tools for the aforementioned tasks and most lack a complete adaptive implementation; some degree of competency on behalf of the end-user for selecting appropriate algorithms and parameters is assumed. Many types of software have started recently to integrate multi-fidelity MCS approaches.
- Surrogate modeling. Common classes of metamodels used include Gaussian processes, polynomial chaos, support vector machines, and radial basis functions. The developed surrogate models can be then leveraged within the software to accelerate computations for other UQ tasks. Adaptive DoE options are typically available and used frequently; standard DoE approaches are not, however, necessarily tailored to the specific UQ task the end-user is interested in applying. Most software programs sacrifice robustness (an approach that is reliable and works independent of the end-user competency) for efficiency (the ability to develop high-accuracy metamodels with the least number of simulation experiments).
- Global sensitivity analysis. This is typically performed through calculation of Sobol indices (UQ output) using some approximate (quasi-Monte Carlo) technique or surrogate modeling (polynomial chaos expansion).
- Data analysis and model calibration, with some emphasis on Bayesian inference techniques. Although Bayesian updating is very common, model class selection is not. Addressing modeling complexity remains a bigger challenge for Bayesian inference applications since integrating metamodeling techniques is not trivial. The challenge here is to establish a fully

automated integration that can address different degrees of competency for the end-user and a wide range of application problems with certain degree of robustness (impact of meta-model error). For problems with dynamical models, the typical approach is to use the batch updating method since that leads to a common broader Bayesian inference framework.

- Design-under-uncertainty. Though this is not a common option, some software programs do offer the ability to perform some form of optimization under uncertainty and are most applicable to RBDO and RDO problems. Integrating state-of-the-art MCS techniques in this setting remains also a challenge. Implementations are typically computationally expensive or rely on approximate approaches for the uncertainty propagation.

Out of the different UQ software programs that exist, the following are worth direct mention as representing the state-of-the-art:

DAKOTA (https://dakota.sandia.gov/)

Developed by the Sandia National Laboratory and written in C++, DAKOTA is widely considered as the standard for UQ software and delivers both state-of-the-art research and robust, usable tools for optimization and UQ (Adams et al., 2009). It has a range of algorithms for all aforementioned UQ tasks and has a wide community that supports its continuous development.

OpenTURNS (http://www.openturns.org/)

It is an open-source (C++/Python library) initiative for the treatment of uncertainties and risk in simulations (Andrianov et al., 2007). It addresses all aforementioned UQ tasks apart from design under uncertainty.

UQLab (https://www.uqlab.com/)

Developed at ETH Zürich, UQLAB is a MATLAB-based general purpose UQ framework (Marelli and Sudret, 2014). Like OpenTURNS it addresses all the aforementioned UQ tasks apart from design under uncertainty.

OpenCossan (http://www.cossan.co.uk/software/open-cossan-engine.php#)

It is the MATLAB based open-source version of the commercial software COSSAN-X (Patelli et al., 2017), which was initially developed to integrate UQ and reliability techniques within FEM analysis, with modules that extend across all aforementioned UQ tasks.

Beyond these specific software, there are a constantly increasing number of Python-based open-source package libraries offered by researchers for UQ analysis; e.g., **UQ-Pyl** (http://www.uq-pyl.com/) and **UQpy** (https://github.com/SURGroup/UQpy/).

4.3 References

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5. List of Software Tools

5.1 Hazard Characterization

Name	Category	Public Access	Operating System	DesignSafe	Comments
HAZUS 4.2	EQ – Shaking, Fault Rupture, Liquefaction, Landslide TC – Wind Tsunami - Inundation	Yes	W	N	Graphical User Interface
OpenSHA	EQ - Shaking	OSS	ALL	P	Java Applications and Libraries
OpenQuake Engine	EQ - Shaking	OSS	ALL	P	Python Library
NSHMP-Haz	EQ - Shaking	OSS	ALL	P	Java Library
UGMS MCE_R	EQ - Shaking	OSS	ALL	N	Web-based
BBP	EQ - Shaking	OSS	U	P	
Cybershake	EQ - Shaking	OSS	U	N	
Cybershake Data	EQ - Shaking	OSS	N/A	P	Public database
AWP-ODC	EQ - Shaking	OSS	U	N	
Hercules	EQ - Shaking	OSS	U	N	
SW4	EQ - Shaking	OSS	U	N	
UCVM	EQ - Shaking	OSS	U	P	
PEER NGA DB	EQ - Shaking	Limited	N/A	N	Requires signup
PFC	EQ - Fault rupture	No	W		Pseudostatic & Dynamic Analyses
LIGGGHTS	EQ - Fault rupture	Limited	ALL		Pseudostatic & Dynamic Analyses
LiqIT	EQ - Liquefaction	No	W		Simplified Methods
Cliq	EQ - Liquefaction	No	W		Simplified Methods
NovoLIQ	EQ - Liquefaction	No	W		Simplified Methods
LiquefyPro	EQ - Liquefaction	No	W		Simplified Methods
Slide	EQ – Landslide	No	W		Pseudostatic Analyses
Slope/W	EQ – Landslide	No	W		Pseudostatic Analyses
UTEXAS4	EQ – Landslide	No	W		Pseudostatic Analyses
SLAMMER	EQ – Landslide	OSS	ALL		Newmark Sliding Block
ERN Hurricane	TC - Wind	Yes	W	N	Graphical User Interface
ADCIRC	TC - Storm surge	Yes	ALL	Y	
GeoClaw	TC - Storm surge Tsunami	Yes	U	Y	
SLOSH	TC - Storm surge	No	?	N	Surge hazard results available from NOAA
MOST	Tsunami	OSS	U	P	
Tsunami-HySEA	Tsunami	OSS	ALL	P	GPU-based CUDA implementation

ACRONYMS	Categories	EQ: Earthquake TC: Tropical Cyclone
	Public Access	OSS: Open-Source Software Yes: Publicly available, but not OSS No: Proprietary
	Operating System	W: Windows U: Unix M. Mac OX-X ALL: All of the above
	DesignSafe	Y: Yes, available P: Possible, but not yet available N: Not available

5.2 Response Estimation

Name	Category	Public Access	Operating System	DesignSafe	Comments
OpenSEES	Structures Geotech	OSS	ALL	Y	FE
FEAP	Structures Geotech	No	ALL	P	FE
LSDyna	Structures Geotech	No	W/U	Y	FE
ABAQUS	Structures Geotech	No	W/U	Y	FE
PLAXIS	Geotech	No	W	N	FE
FLAC	Geotech	No	W	N	FD
UINTA	Geotech	OSS	U	N	MPM
Anura3D	Geotech	No	W	N	MPM
Pro Shake (2018)	Geotech	No	W	N	1D TF / FD
DEEPSoil (2018)	Geotech	No	W	Y	1D TF / FD
DMOD	Geotech	No	W	N	1D TF
BBP	Geotech	OSS	U	Y	Green Functions
Hercules	Geotech	OSS	U	N	FE
SW4	Geotech	OSS	U	N	FD
OpenFOAM	CFD				

ACRONYMS	Public Access	OSS: Open-Source Software Yes: Publicly available, but not OSS No: Proprietary
	Operating System	W: Windows U: Unix M. Mac OX-X ALL: All of the above
	DesignSafe	Y: Yes, available P: Possible, but not yet available N: Not available
	Comments	FE: Finite-Element based FD: Finite-Difference based MPM: Material Point Method TF: Transfer Function

5.3 Performance of Built Environment

Name	Category	Public Access	Operating System	DesignSafe	Comments
ERGO	All assets	Yes	W	N	HAZUS-based Regional level
CAPRA	All assets	Yes	W	N	HAZUS-based Regional level
HAZUS 4.2	All assets	Yes	W	N	HAZUS MH only Regional level
OpenQuake	All assets	OSS	ALL	P	Python Library Regional level
PACT	Buildings	Yes	W	N	FEMA P58 only Building level
SP3	Buildings	No	Web	N	FEMA P58 only Building level
pelicun	All assets	OSS	ALL	P	Python library
PBE App	Buildings	OSS	ALL	Y	Building level
OpenSLAT	Buildings	OSS	ALL	P	Building level
EPANET	Potable water net-work	Yes		N	
GIRAFFE	Potable water net-work	Yes	W	N	
WNTR	Potable water net-work	OSS	ALL	P	Python library
Synergi Gas	Gas network	No		N	
NextGen	Gas network	No		N	
OpenDSS	Electrical network				

ACRONYMS	Public Access	OSS: Open-Source Software Yes: Publicly available, but not OSS No: Proprietary
	Operating System	W: Windows U: Unix M. Mac OX-X ALL: All of the above
	DesignSafe	Y: Yes, available P: Possible, but not yet available N: Not available

5.4 Uncertainty Quantification

Name	Category	Public Access	Operating System	DesignSafe	Comments
DAKOTA		Yes	ALL	Y	
OpenTURNS		OSS			
UQLab		OSS			MatLab-based
OpenCossan		OSS			MatLab-based
UQ-Pyl		OSS		P	Python library
UQpy		OSS		P	Python library

ACRONYMS	Public Access	OSS: Open-Source Software Yes: Publicly available, but not OSS No: Proprietary
	Operating System	W: Windows U: Unix M. Mac OX-X ALL: All of the above
	DesignSafe	Y: Yes, available P: Possible, but not yet available N: Not available

6. Summary and SimCenter Goals

Gregory G. Deierlein
Professor, Stanford University

Sanjay Govindjee
Professor, UC Berkeley

Frank McKenna
Project Scientist, UC Berkeley

Computational simulation is as an essential component of natural hazards engineering research and practice to assess and mitigate the damaging effects of earthquakes, wind storms and associated tsunami, and storm surge effects on communities. Recognizing the challenge as broad and multi-disciplinary, and encompassing natural hazards across a wide range of scales, the SimCenter's approach is to leverage existing software platforms by creating computational workflow technologies that can seamlessly integrate a broad array of simulation software with high-performance computing platforms and data repositories. In addition to developing and releasing the computational workflow tools and training modules, the SimCenter is engaging with researchers to extend the simulation capabilities through collaboration with NHERI researchers. Collaboration opportunities range from facilitating research on application testbed studies to implementation of new computational formulations.

The SimCenter is creating workflow tools that range from ones that enable the study of the response of single buildings given a natural hazard event to others that perform end-to-end simulations of natural hazard effects on communities. An important emphasis of the workflows are capabilities to incorporate and propagate inherent variabilities and modeling uncertainties through the computational simulations. Another focus is on tools to develop datasets and integrate them with the computational tools, with particular emphasis on data and simulation software available on the NHERI DesignSafe platform.

To a large extent, the most distinguishing innovation of the SimCenter simulation tools are to provide a computational ecosystem that will enable the NHERI research community to achieve unprecedented capabilities to conduct end-to-end simulations. By employing an open-source framework, the ecosystem will allow researchers to contribute to some or all aspects of the simulation capabilities. The overall concept is illustrated in Figure 6.1, where the challenge is to link models and data from descriptions of the assets (buildings, bridges, civil infrastructure, and other components of the built environment), hazard effects (earthquake ground motions, wind, water inundation), through to effects on the assets and implications on community function and recovery. The SimCenter computational and data tools lie at the heart of the simulation, linking upstream data from natural hazard models to downstream socio-economic outcomes and models of communities. Figure 6-1 illustrates where four SimCenter tools (*uqFEM*, *EE-UQ*, *CWE-UQ*, and *PBE*) fit into the computational workflow. Underlying these tools are software applications that can be incorporated in specific tools (with graphical user interfaces) or incorporated in workflow scripts that are more fluid and adaptable to alternative regional hazard scenario simulations.

The following is a summary of computational workflow implementations that the SimCenter is actively working on and has either already deployed or will deploy in the immediate future:

- ***uqFEM*****:** The *uqFEM* application facilitates uncertainty quantification, model calibration, optimization and sensitivity analyses of structural and geotechnical materials, components, and systems by combining existing finite element applications with uncertainty quantification (UQ) application. The V1.1.0 release links two finite-element codes (OpenSEES or FEAPpv) with uncertainty quantification functions in DAKOTA. A graphical user interface is provided with basic functionality to define random variables in the finite-element models and invoke certain UQ methods from DAKOTA. Running through the HPC capabilities of DesignSafe, or on a user's desktop computer, the system makes available unprecedented capabilities for natural hazards researchers to perform UQ simulations. Future plans include extensions to include links to other

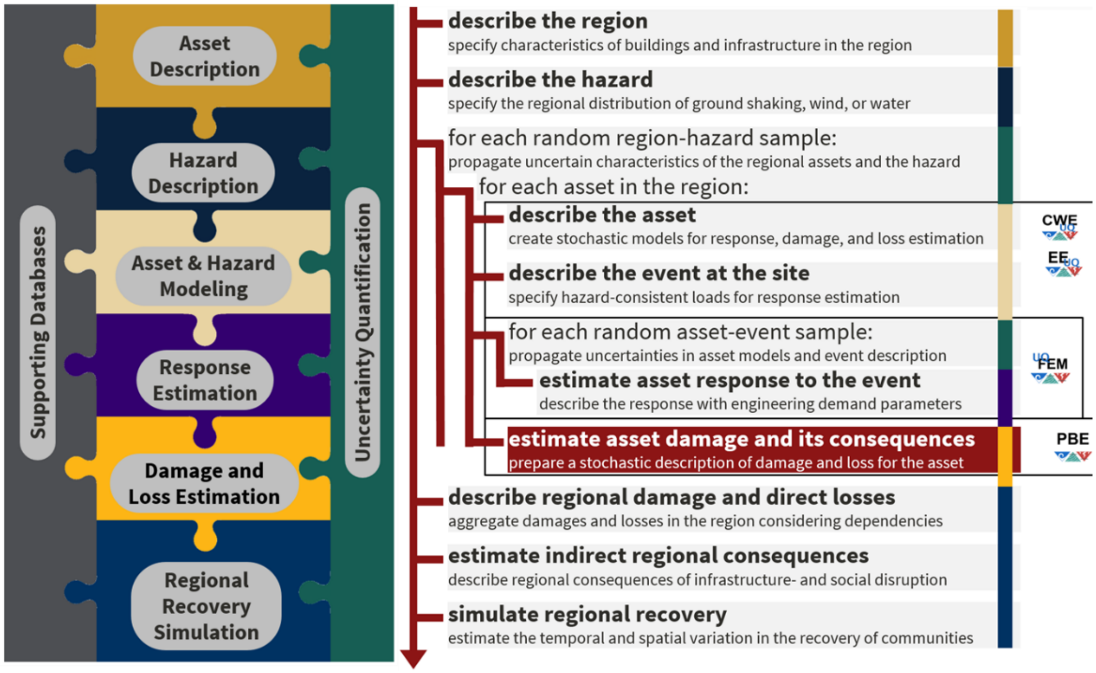

Figure 6-1 Computational framework for end-to-end simulations of natural hazard effects on damage and recovery of the built environment and communities

finite element codes that are running on DesignSafe (e.g., LSDyna) and uncertainty quantification toolboxes (UQ-Pyt, UQpy).

- ***CWE-UQ*:** The Computational Wind Engineering (CWE) Tool is an application to simulate the response of structures to wind forces. The V2.0 release of the tool will allow users to select from a variety of options for specifying wind forces on structures from stochastic loading models and online wind engineering databases through to performing computationally intense Computational Fluid Dynamics (CFD) analysis utilizing applications such as *OpenFOAM*. The tool is intended to make detailed CFD modeling more accessible to NEHRI researchers in conjunction with wind tunnel testing (e.g., to validate computational models and extrapolate beyond the scale and parameter space that can be tested in the NHERI wind facilities), to allow researchers to consider more realistic conditions from field studies, and assist in the creation of surrogate models for regional simulations. For the CFD analysis in particular, the *CWE-UQ* tool is organized around a template-based model. Currently (in V1.1.1) there are two templates: 2D simulation of a rigid building geometry using an unstructured mesh; and 3D simulation of a rigid building using an unstructured mesh. Capabilities for the simulation of desired inflow conditions for LES, aeroelastic response, and multi-fidelity simulations are in the development stage.

  Exploratory work is underway to investigate adaptation of the *CWE-UQ* tool to simulate water flows for modeling tsunami or storm surge effects on structures. Future releases will incorporate Uncertainty Quantification (UQ) in a similar fashion to *uqFEM*.

- ***EE-UQ*:** The earthquake engineering, *EE-UQ*, tool is an application to simulate the response of structural and soil–structure systems to earthquake excitations. The current

(V1.0) release focuses on quantifying the uncertainties in the structural response, given that the properties of buildings (or other structures) and the earthquake events are not known exactly, and that many simplifying assumptions are present in the numerical models (epistemic uncertainties). By embedding features of the *uqFEM* tool, *EE-UQ* enables the user to specify statistical distributions of the model input parameters and Monte Carlo and other sampling methods are used to characterize the output. The current implementation employs *OpenSees* for finite-element simulation of the structural models and *DAKOTA* for uncertainty propagation. The tool has features to select and input ground motions to match specified earthquake hazard targets. Work is underway to extend *EE-UQ* to include soil-structure interaction models where rock ground motions are propagated through nonlinear soil models into the structural system.

- ***PBE*:** The *PBE* tool is an extensible workflow application to perform Performance Based Engineering computations for various hazards. The current (V1.0) release provides researchers a tool to assess the performance of a building subjected to earthquake ground motions. The application focuses on quantifying nonlinear building response and damage through decision variables. *PBE* builds upon the *EE-UQ* tool using the estimates of structural response to assess the damage to building components and the consequences of such damage. The user characterizes the simulation model, and the damage and loss models of the structure, and the seismic hazard model in the *PBE* tool. The tool incorporates an underlying workflow application called *PELICUN* (Probabilistic Estimation of Losses, Injuries, and Community resilience Under Natural disasters), which is a hazard and asset agnostic library for evaluating losses. *PELICUN* is modeled after the FEMA P58 framework for earthquake loss assessment but with a broader vision to address alternate hazards (wind, water inundation, etc.) and facilities beyond buildings. All components within the *PBE* tool are interconnected by an uncertainty quantification framework that allows the user to define a flexible stochastic model for the problem.
- ***RDT:*** The *RDT* tool is to be an extensible workflow application to quantify the effects of hazards on regional communities. This tool is scheduled for initial release in 2020. It will provide the users with options for selecting regions, hazards, and viewing the results at a regional scale. The tool will utilize much of the workflow developed for the *CWE-UQ*, *EE-UQ*, and *PBE* tools. As part of the development of the tool, two command line workflow applications are being developed and made available: (1) the *Regional Earthquake Workflow* and (2) the *Regional Storm Workflow*. The *RDT* tool, when completed, will provide a graphic front-end to these command line applications.
- ***Regional Earthquake Workflow:*** The *Regional Earthquake Workflow* is an application to quantify the damaging effects of earthquakes on society at a regional scale. The workflow implements a comprehensive end-to-end hazard simulation along the lines shown in Figure 6-1. Further details of the workflow, including definitions of the workflow components, are shown in Figure 6.2. Two testbed examples have been released to demonstrate the *Regional Earthquake Workflow.* The first testbed estimates downtime and loss for every building in the San Francisco Bay Area after a simulated magnitude 7.0 earthquake on the Hayward fault. The second testbed is a smaller study on the 2018 M7.0 event in Anchorage, Alaska. Following a similar strategy to the other SimCenter tools, the workflow integrates various stand-alone software applications

Type	Name	Description
createBIM	GenericBimDatabase	Creates a simple BIM from a building flat file (csv)
	UrbanSimDatabase	Creates a simple BIM fromUrbanSim simulation outputs
createEVENT	LLNL_SW4	Gets Event input from SW4outputs
	SHA-GM	Computes event input using SHA and record selection/scaling
createSAM	MDOF_LU	Creates a MDOF shear building model
createEDP	StandardEarthquakeEDP	Defines the standard EDPs used for a seismic event
performSIM	OpenSeesSimulation	Performs simulation usingOpenSeesand calculates the EDPs
createLOSS	FEMAP58_LU	Calculates damage and loss estimates using FEMA P58 procedure
performUQ	DakotaFEM	Propagates uncertainty in all applications using Dakota

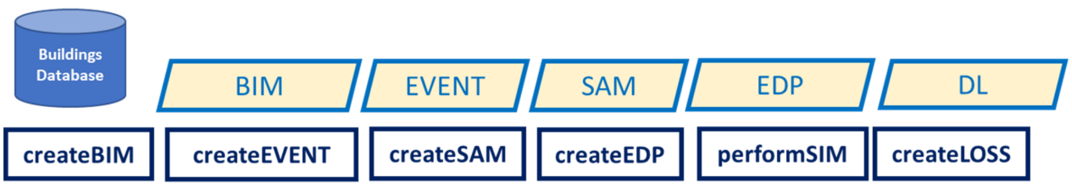

Figure 6-2 Computational workflow and registered applications for the San Francisco Bay Area Earthquake Scenario

and modules. Some applications, such as "performSIM", utilize existing software such as OpenSees, whereas other applications are developed specifically for the initial testbed workflow. Two instances of the framework application were developed: (1) HPC resources at DesignSafe are used for simulation of a large (1.6 million) inventory of buildings, and (2) local computational resources for testing, development, and smaller-scale simulations (thousands of buildings) are used. The workflow applications are seeded with ground-motion tools and data sets to show extensibility and provide resources that inspire research activities. In the coming year, a ***Regional Storm Workflow*** is being developed, that will parallel the earthquake scenario testbed for a hurricane scenario testbed at a location on the eastern coast of New Jersey.

- ***AI Applications:*** One of the key challenges for building regional hazard scenarios is creation of actual BIMs (Building Information Models) and SAMs (Structural Analysis Models) for the buildings in the region. To address this, the SimCenter has ongoing development to apply Artificial Intelligence (AI) methods to develop "*aiBIM*" and "*aiSAM*" applications. The "*aiBIM*" application utilizes visual imagery combined with other databases (e.g., parcel level tax data, LIDAR imagery, etc.) to develop a detailed database of buildings and their features. The "*aiSAM*" application translates BIM information into SAM to simulate the damaging effects of earthquakes, wind, and water inundation.

This report has laid out the state of the art as seen by the authors of the respective sections as of the date of this report and how the SimCenter's current and future developments are aligned with these observations. The report thus serves not only as a state-of-the-art report for general consumption but also as a guiding document for the SimCenter. We hope that its contents find wide use and help focus research and software development needs in the NHERI community.