Community Perspectives on Simulation and Data Needs for the Study of Natural Hazard Impacts and Recovery

Adam Zsarnóczay[1], Gregory G. Deierlein, F.ASCE[2], Caroline J. Williams[3], Tracy L. Kijewski-Correa, A.M.ASCE[4], Ann-Margaret Esnard[5], Laura N. Lowes, A.M.ASCE[6], and Laurie Johnson[7]

[1]Research Engineer, Dept. of Civil and Environmental Engineering, Stanford University, (corresponding author). Email: adamzs@stanford.edu

[2]Professor, Dept. of Civil and Environmental Engineering, Stanford University. Email: ggd@stanford.edu

[3]Graduate Student, Dept. of Civil and Environmental Engineering, University of Delaware. Email: cjw@udel.edu

[4]Professor, Dept. of Civil and Environmental Engineering and Earth Sciences and Keough School of Global Affairs, University of Notre Dame. Email: tkijewsk@nd.edu

[5]Distinguished University Professor, Public Management and Policy, Georgia State University. Email: aesnard@gsu.edu

[6]Professor, Dept. of Civil and Environmental Engineering, University of Washington. Email: lowes@u.washington.edu

[7]Laurie Johnson Consulting. Email: laurie@lauriejohnsonconsulting.com

ABSTRACT

With the aim of fostering the development of robust tools to simulate the impact of natural hazards on structures, lifelines, and communities, the Natural Hazards Engineering Research Infrastructure Computational Modeling and Simulation Center gathered sixty researchers, developers, and practitioners working in Natural Hazards Engineering (NHE) for a workshop to prioritize research questions and identify community needs for data and computational simulation capabilities. Participants used their wide-ranging expertise in earthquake, coastal, and wind hazards from engineering, planning, data sciences, and social sciences perspectives to identify five major thrusts of recommended future work, including detailed suggestions for each : 1) development of housing and household recovery models; 2) integration of existing models into flexible computational workflows; 3) investment in the collection of high-value open data; 4) commitment to sharing and utilizing high-value data; 5) development of versatile, multidisciplinary testbed studies. Participant responses and workshop data were analyzed with the help of an ontology that the authors designed to support data classification in a broad range of NHE applications. The paper also includes observations and suggestions for planning and conducting interactive workshops of this type.

INTRODUCTION

Regional risk assessment models for various natural hazards have advanced dramatically in recent years, but models for different types of hazards have largely been developed independently of each other. The 1971 San Fernando earthquake catalyzed substantial US investment in earthquake engineering and led to the development of methods and tools for some of the first regional seismic risk assessments (FEMA, 2011a) and performance-based earthquake engineering studies (Council, 2018). The development of risk assessment tools for other types of hazards initially lagged but has improved rapidly in recent years. For example, regional risk assessment methods have been released by FEMA for hurricane (FEMA, 2011c), flood (FEMA, 2011b), and tsunami (FEMA, 2017) hazards, in addition to the Florida Public Loss Model (Chen et al., 2009) for hurricanes. Performance-based engineering methods for wind (ASCE, 2019; Barbato et al., 2013) and tsunami (Attary et al., 2017) hazards are currently under development. The traditional reliance on empirical models to estimate response and damage to the built environment within FEMA's Hazus Earthquake Methodology and other initiatives has now been complemented by more sophisticated approaches that take advantage of new data sources to support higher-resolution simulations that can incorporate interdependencies between natural, built, and human systems to reveal multi-faceted consequences and a richer description of recovery processes [e.g., SimCenter's rWHALE (Deierlein et al., 2020) and NIST CoE's IN-CORE (Gardoni et al., 2018) tools]. High-resolution regional and city-level damage and loss simulations, coupled with advanced computational and information technologies to manage and process high-resolution data, are enabling the development of advanced simulation models that consider the disaster recovery process.

Emerging research holds the promise of creating digital representations of cities through the compilation of high-resolution building inventories, demographic information, and economic data sourced from a combination of conventional data sources (e.g., U.S. Census Bureau, U.S. Bureau of Economic Analysis, U.S. Bureau of Labor Statistics) and more novel data harvesting techniques (e.g., satellite image recognition, assessor databases) (Wang et al., 2021; Fan et al., 2021; Shahat et al., 2021; Ford and Wolf, 2020). Digital representations of cities provide a baseline for natural hazards engineering (NHE) researchers to perform city-level assessments that aim to estimate not only the physical damage to the built environment, but also the associated socioeconomic consequences following the natural hazard event. As an extension, these city-level models could support complex, multi-disciplinary studies of questions related to post-disaster recovery, such as behavioral patterns of people and household decisions (Nejat and Ghosh, 2016), compression of redevelopment and decision-making processes (Olshansky et al., 2012), temporary population displacement and permanent relocation (Esnard et al., 2011; Costa et al., 2020), and socioeconomic disparities (Zhang and Peacock, 2009; Peacock et al., 2014; Hamideh et al., 2018; Wyczalkowski et al., 2019). These studies explore disaster impacts for specific neighborhoods, populations, business sectors, and services at a high-resolution and provide outputs that support more sophisticated evaluation of disaster recovery planning alternatives and risk mitigation strategies.

While such simulations offer opportunities for NHE research and practice, it is important to keep in mind that the reliability, reproducibility, and replicability (National Academies of Sciences, Engineering, and Medicine, 2019) of these complex regional simulations heavily depends on the modeling methodologies that are used along with the associated input data, which is often of variable quality (Roohi et al., 2021). This barrier can, to some extent, be overcome through closer collaboration across the related disciplines, including engineering, computer/data science, and social sciences, capitalizing on synergies and leveraging the advances by each to elevate the collective capacity for large-scale computational simulation and robust data management. Given the nature of this input data, success will require partnerships between academic researchers, practitioners, and the public sector, as well as greater investments in federal, state, and municipal data management, standardization, and open exchange of data.

One nexus for such partnerships is available through the Computational Modeling and Simulation Center (SimCenter). The SimCenter is supported by the National Science Foundation under the Natural Hazards Engineering Research Infrastructure (NHERI) to develop computational software tools for the NHE researcher community (Deierlein et al., 2020). The SimCenter's underlying strategy is to leverage past research and development by integrating models and data from the physical sciences, engineering, and social sciences to help advance new lines of research and educational opportunities in NHE. As such, the SimCenter has focused on building collective capacity within the research community, while engaging other public and private sector stakeholders who are similarly committed to the study of hazard impacts on communities. The computational workflows developed by the SimCenter support high-resolution, multi-fidelity simulation of hazard impacts from individual buildings to the regional scale. While there are research gaps remaining in faithfully simulating the damage to the built environment under natural hazards, modeling post-disaster recovery from this damaged state presents a challenge of a different magnitude. It necessitates a multi-disciplinary approach to both (1) compile and standardize large quantities of diverse data, and (2) develop models that can handle the highly complex, nonlinear, and interdependent natural, physical, and societal systems that shape communities and their recovery processes (Miles et al., 2019; Miles, 2018; Deierlein and Zsarnóczay, 2021). The SimCenter is building the foundational computational infrastructure to characterize natural hazards and their effect on the built environment, along with interfaces to demographic and socio-economic data to enable the integration of recovery models into regional simulation workflows.

While the computational infrastructure being developed by the SimCenter and other groups holds great potential, its development requires the engagement of both the NHE researcher community as well as practitioners and policymakers to understand their perspectives and needs. The aspirations of academic researchers need to be weighed against the practical expectations of industry and public-sector practitioners, as evidenced by their reliance on trusted methods and tools, such as the Hazus-MH software (FEMA, 2018), or FEMA's published data products, such as flood insurance rate maps (FEMA, 2021). Thus, it is critical to understand the limits of simulation tools developed for research to address the practical constraints of real-life implementation. Building on past examples of successful research-to-practice collaborations [e.g., Kijewski-Correa et al. (2020); Chen et al. (2009)], there is an opportunity to facilitate further engagement through the development and adoption of common templates founded on open-source principles with standardized data schema to facilitate more collaborative development, deployment, and maintenance of software and supporting data.

To encourage such collaborations and understanding of user needs, several workshops have been organized in the last decade by projects sponsored by NSF, NIST, FEMA, and other organizations to engage diverse experts in natural hazard risk mitigation [e.g, McAllister et al. (2019); Poland (2009); Kwasinski et al. (2016); Slotter et al. (2021)]. These workshops were typically focused on particular research products or mitigation programs, which to some extent limited the scope in terms of hazard, geospatial scale of analysis, and component of disaster risk management. In contrast, for the workshop described herein, the SimCenter aspired to collect qualitative data and actionable information on computational and data needs through a broadly-defined sampling of the NHE community, cross-cutting hazards, expertise, and roles.

WORKSHOP OVERVIEW

The workshop on simulation and data needs was held at the University of California, Berkeley, in January 2020 and designed to (1) engage the community of disaster risk and recovery experts and stakeholders and (2) identify how computational tools can support fundamental and applied research to promote resilience to natural hazards. The workshop agenda was designed to foster knowledge exchange and collect observations and information from participants across multiple hazards (earthquakes, tsunamis, hurricanes, and storms), between disciplines (engineering, planning, and social-science), and among various roles in the community (policy makers, researchers, practitioners, and software developers). The specific goals of the workshop were as follows:

- Identify the approaches and tools used to evaluate natural hazard impacts and inform risk management strategies.
- Collect and prioritize questions and concerns about mitigating the devastating effects of earthquakes, storms, and other extreme events that have a potential to be evaluated through scenario studies and advanced simulations.
- Identify and prioritize the needs for improved models and supporting data required for computational workflows for advanced simulation of natural hazard impacts.
- Brainstorm strategies to facilitate the development and adoption of multi-disciplinary testbeds and other simulation technologies in research and practice.

Participants

The workshop organizing committee was assembled from SimCenter affiliates with a diverse set of expertise. The number of participants was limited to 60 to foster active discussion, where about 70% of the participants were invited, 20% were selected from respondents to an open invitation, and 10% were graduate students. Invited participants included researchers, developers of natural hazards risk simulation tools, and end-users of regional risk assessment frameworks (see Table S1 for the complete list of participants).

In preparation for the workshop, participants were asked to self-assess where they would position themselves along a spectrum of hazards (multi-hazard, wind, earthquake, or coastal/flood), roles (policy maker, simulation framework specialist, or software developer), and the scales at which they model or analyze data (local, state, or national). As shown in Fig. 1, the distribution of participant responses indicates a reasonable balance across hazards (Fig. 1a), participant roles (Fig. 1b), and scales of engagement (Fig. 1c). About two-thirds of attendees were affiliated with academic institutions (Fig. 1d), and one-third were from public/non-profit (state, federal, and international agencies/foundations) and private/for-profit sectors. Participants were also asked to characterize themselves as data producers and/or consumers, where about ninety percent indicated that they both produce and consume data, with the remainder equally divided between solely producers or consumers of data.

Methods for data collection

The two days were divided into four sessions, each starting with a short plenary that provided an overview of the session theme, followed by a breakout phase. The four sessions focused on (1) connecting to stakeholders, (2) connecting across hazards, (3) data sources, and (4) interdisciplinary engagement (see Fig. S1 for a detailed agenda). During the breakout sessions, participants were divided into three subgroups, based on the backgrounds of participants and focus area of each breakout. Outcomes of the breakout exercises were documented and collected through individual worksheets and group-based easel pads, with pre-defined labels. Artifacts from the breakout sessions were subsequently collected, digitized, processed, and made available to the participants. The discussions in each breakout session were guided by a facilitator, who was briefed on the plan before the workshop and shared highlights and main takeaways of the breakout discussion with the entire workshop group following each breakout.

As an example of how the breakout sessions were organized, the Data Sources session focused on the data needs among disaster researchers and practitioners to improve disaster recovery planning. Following a plenary session discussion on the challenges surrounding open data for disaster research and advances in data science that could overcome these challenges, the breakout session participants examined the gaps in open data practices within the natural hazards community. The first activity in the breakout was a Data Mapping activity to (1) prepare a short list of the data that the participant's organization regularly consumes and produces, (2) identify the source or distribution method used to share that data, (3) quantitatively rate the trustworthiness/reliability and usability/accessibility of that data, and (4) assemble a wish list of data that they would like to have available. Shown in Fig. 2 is an example of the Data Map artifacts collected from the respondents, where they identified and ranked quality and accessibility of the datasets (5 indicating a high/favorable score and 1 indicating a low/unfavorable score). The second activity used a Data Scorecard to (1) identify the five questions participants hope to "ask" of the resilience/risk assessment data they engage, (2) indicate which questions they can answer today with the data available to them, (3) assess which data would be most critical to answering these questions in the future, and (4) specify if this data is accessible today. The Data Sources session concluded with a report out from each group and discussion. The participant artifacts from the Data Sources session were transcribed for subsequent analysis.

REVEALED DATA CHARACTERISTICS

The transition toward standardized workflows and data that enable multi-disciplinary, multi-hazard regional recovery modeling requires a concerted effort to holistically organize high-resolution data so that it is searchable and easily accessible by users. Existing classification systems in the disaster science literature [e.g., IRDR (2014); McAllister et al. (2019); UNDRR (2019)] do not capture details that are important for computational simulations of hazard events or describe information that is relevant to different time scales in the risk management cycle of prevention, protection, mitigation, response, and recovery (DHS, 2016). Existing classifiers tend to narrowly categorize data by the type of natural hazard (Coburn et al., 2014), which while an obvious and important characteristic, may miss opportunities to examine aspects that could unify the hazard engineering community.

To address the shortcomings in existing classifications, a new ontology is proposed in Table 1 that builds upon the concepts in existing classification systems, but aims to better describe features that are important for computational simulation of natural hazard events. The ontology identifies the important features of the data and provides a classification that defines the independent features for characterizing the data. The ontological information provides the basis for creating application-specific taxonomies (with specific hierarchies among the features) or, as in this study, to tag data from several perspectives. For example, the type of natural hazard, the context, and the origin are three independent features in Table 1 that were used to characterize features of the data identified by workshop participants.

The ontology was informed by the range of data types that workshop participants identified in the Data Map worksheets during the Data Sources breakout session. Additional categories, such as the geographical scale of the data, were considered, but excluded because either the classification within the category was ambiguous or the information provided by the category was redundant. This ontology was used to tag data that was identified during the Data Sources breakout session, thereby enabling a cross-sectional analysis of the data to identify (1) which data was of most value to the participants and (2) potential synergies between categories. This ontology is proposed for review by the NHE community as a first step towards a formal ontology to collect and organize data for simulating natural hazard effects on communities.

When identifying the data that participants produced or consumed, each participant named up to five data sets that were later tagged using the ontology terms. Where the data sets identified by the participants described a wide range of data, multiple tags from each category in Table 1 were applied. Tags were assigned based only on the available information, and when the tag in a certain category was ambiguous, an unknown tag was assigned rather than resorting to a default or assumed value. For example, when a participant specified that they use "hazard data" for their work, an unknown tag was assigned for the type of natural hazard category. The Table 1 ontology and tagging process was only applied to artifacts from the Data Sources session. Artifacts from other sessions, e.g., the Regional Simulations session, where participants identified specific software tools to perform simulations of natural hazard effects, were simply reported and collected in lists. The datasets from other sessions were not tagged with the proposed ontology because participants were not instructed to classify responses in a structured way. The artifact data sets are publicly available (Zsarnóczay et al., 2021) and they served as the basis for figures and recommendations summarized later in this paper and the accompanying Supplemental Materials.

IDENTIFIED OPPORTUNITIES TO ENHANCE DISASTER SIMULATION TOOLS AND DATA

During the workshop, participants prioritized questions related to post-disaster recovery that could potentially be answered using advanced computational simulation tools and data, and they identified potential areas where improved simulation capabilities are needed. Examples of the questions raised include: “How does damage to lifelines impact a community’s recovery?”, “How can a community quickly and effectively restore livelihoods after a disaster?", and "What is the best way to characterize and estimate damage states in structures following a disaster event?". When asked to identify the five most important questions in their work, participants focused most prominently on themes related to the following: recovery of households (17%), damage in the built environment (15%), evaluation of mitigation policies (11%), evacuation and population displacement (9%), and recovery of utilities and other critical services (9%), where N=150. A list with additional themes identified is included in Table S2, along with a database of the questions participants prioritized. Participants indicated that over two-thirds of these questions cannot be answered today, and approximately three-quarters of the participants indicated that they are currently unable to answer the majority of their own most pressing questions.

Based on the workshop discussions, combined with the insights generated through processing of the collected data and artifacts, the following five opportunity areas for computational simulation of natural hazard effects were identified:

1. development of housing and household recovery models;
2. integration of existing models into flexible computational workflows;
3. investment in the collection of high-value open data;
4. commitment to sharing and utilizing high-value data;
5. development of versatile, multidisciplinary testbed studies.

Focusing on these areas has the potential to strengthen connections between segments of the NHE community across various hazard types and between disciplines to address the most pressing questions that were raised during the workshop. The following subsections elaborate on the five areas and how they emerged as opportunities identified in the workshop.

1. Development of housing and household recovery models

Housing was singled out by participants as a key entry point to engage in recovery modeling, particularly if linked to the broader context of recovery of neighborhoods, communities, and lifeline infrastructure. Table 2 provides a summary of the housing-related applications and related data needs as identified by the workshop participants. Information on households and their recovery was a prominent theme in the top five questions that workshop participants ask of their data (Table S2), and it was frequently mentioned among the aspirational data they identified (Fig. 5). Many workshop participants emphasized that the understanding and modeling of housing recovery needs to go beyond building damage and population counts to consider socioeconomic aspects of households and communities [e.g., Comerio (1998)].

The following are some of the key priorities that can help advance housing recovery modeling frameworks, computational simulation tools, and workflows.

- **Account for neighborhood conditions and community context:** The ability to characterize and model community and neighborhood facets, such as businesses and lifeline infrastructure, will help quantify the spatial distribution of demands on local and regional systems and institutions after disaster events. This is particularly important to account for in- and out-migration and population displacement and relocation. The long-term recovery and post-disaster redevelopment processes in Christchurch, New Zealand, and New Orleans, Louisiana, provide good examples of how displacement and migration of people can shape the recovery of communities and residential housing.
- **Develop comprehensive and linkable building-level housing inventories to facilitate coupling of engineering and social science data and models:** Data integration and simulation workflows of residential housing damage, restoration, and recovery are predominantly static, often not to the individual parcel or household level, and lacking in demographic and socio-economic characteristics of residents. As tools and computational platforms are developed to perform higher-resolution simulations, semi-heuristic models can be used to generate high-resolution data from census block-level inputs. Methodologies developed by researchers affiliated with the NIST-funded Center of Excellence for Risk-based Community Resilience Planning provide opportunities to link high-resolution spatial data on households and housing units to single and multi-family residential buildings and to critical infrastructure (Rosenheim et al., 2019). Increasing the granularity of such data is critical,

as noted during the workshop, to reveal the benefit of specific planning and policy actions, though with the important caveat that privacy and ethical concerns of collecting input data and reporting risks and vulnerability of residents must be carefully managed.

- **Capture non-engineered residential buildings as part of housing inventory:** Basic building information is available for most areas in the United States at a census block-level resolution. Non-engineered buildings present unique challenges. These typically wooden or unreinforced masonry buildings are designed based on empirical rules in building codes and they often include several undocumented modifications that can have a considerable impact on structural performance (Sparks and Saffir, 1990). Several publications in the literature highlight the disproportionate contribution of these buildings to the damage and losses in recent disasters (Sparks, 1986; Morse-Fortier, 2015; Sandink et al., 2019; Amini and Memari, 2020). Since these buildings are a substantial part of the residential housing inventory and they are key contributors to losses in natural hazard events, it is important to identify and collect additional information on the attributes driving their performance.

These opportunities will require sustained interdisciplinary expertise and contributions. As discussed shortly, empirical studies and testbeds will be particularly critical to the design and development of computational workflows that account for multi-faceted aspects of post-disaster household and community recovery.

2. Integration of existing models into flexible computational workflows

Sessions I and II of the workshop were organized to identify: (1) simulation tools that are currently used by NHE researchers and practitioners to evaluate natural hazard effects on buildings, lifeline infrastructure systems, and other community assets, (2) simulation needs that are not being addressed by current simulation technologies, and (3) factors that impede the use of computational simulations by NHE researchers and practitioners. During the breakout sessions, the 60 workshop participants identified 237 unique analysis tools and software applications for NHE simulations. As shown in Fig. 3, simulation tools are distributed across the risk assessment workflow (Fig. 4), from characterization of assets and hazards to estimation of damage and consequences, along with planning tools. Among the six categories shown in Fig. 3, the one with the fewest tools available is simulation of indirect consequences (e.g., the USGS PAGER software, which provides rapid fatality and economic loss estimates following significant earthquakes worldwide). When asked to identify the challenges associated with simulation to support risk assessment and mitigation, the overwhelming response was that there is a lack of standardization and interoperability between the various software applications. Participants noted that many of the software systems are configured in a stand-alone fashion, such that output from one application requires substantial manipulation before it can be used as input to the next.

Among the 369 non-unique software names recorded by participants, the Hazus (27 mentions) and IN-CORE (18 mentions) software applications stand out by far as the most commonly identified software. These applications 1) span the entire workflow, and thus are identified by participants active in only a particular phase as well as those with activities spanning all phases, 2) are products of two recognized federal agencies (FEMA and NIST, respectively), and 3) are publicly available free of charge. While IN-CORE is Python-based and open source, which facilitates customization by users to meet their specific needs, Hazus is a closed-source system with a fixed set of modules, which has limited flexibility. Hazus offers comprehensive features to estimate losses to a wide variety of assets (buildings, bridges, highways, and lifeline infrastructure) under multiple hazards, which makes it attractive for use by practitioners in the public and private sectors.

Beyond the significant challenges associated with manipulating data and linking software to create integrated multi-phase workflows, workshop participants identified features that would make a substantial improvement to currently available software:

- **Usability:** Software documentation, training resources, and intuitive user interfaces are important to make software easy to use. Documentation of the underlying methods and models is important for users to understand and have confidence in the simulation results.
- **Flexibility:** Software that is open-source and designed with a modular architecture is important to allow users to modify software to their specific needs.

- **Reliability:** Ideally, software components and systems should be verified and validated to ensure that they run correctly and provide accurate results. Verification procedures and practices vary greatly, while rigorous validation is less common because of the inherent uncertainties in the problem, the sparsity of comprehensive damage and loss data, and the lack of standard protocols for validation.
- **Multiple scales:** Few software tools exist to support multi-scale simulation, which could take the form of variable levels of spatial and temporal resolution.
- **Cascading events:** Few software tools are capable of simulating cascading events.
- **Quantified uncertainty:** Characterization and propagation of various sources of uncertainty in a disaster simulation would allow quantification of the uncertainty in the simulation results. Currently available tools do not provide comprehensive uncertainty quantification.
- **Consequences and recovery:** Only a small number of software tools are available for the simulation of consequences and recovery after a disaster. Understanding this stage of the natural hazard cycle is critical to assessing the impact of events and shaping mitigation policy. A large amount of data has been collected after recent disasters (Kijewski-Correa et al., 2021; Wartman et al., 2020; van de Lindt et al., 2018; Sutley et al., 2021; Peek et al., 2020), which should help with the development of new models and tools if there is sufficient interest from the community.
- **High-performance computing (HPC):** Few software tools can take advantage of access to cloud computing or open HPC clusters, such as NHERI DesignSafe (Rathje et al., 2020), and local clusters at universities. Several legacy tools have deprecated dependencies that are not compatible with modern HPC environments and recent data formats.

It is notable that the scientific application framework developed at the SimCenter in part responds to a number of these identified challenges by supporting the integration of existing models into natural hazard risk assessment workflows (Deierlein et al., 2020). Such a workflow is an assembly of software modules (Fig. 4) and interfaces that allow the combination of various methods while maintaining a seamless end-to-end data transfer. The workflow begins on the left with modules that characterize the assets (e.g., buildings and infrastructure) and the hazard (e.g., earthquake ground shaking, wind speed or pressure, etc.). This information provides input to structural analyses to assess the response and damage to the assets. Finally, on the right, the asset performance data is used as input to simulate repairs and the recovery of communities. The application framework provides outputs in a standardized format to facilitate interfacing with tools that support planning and policy-making. The workflow modules are designed to utilize supporting databases and perform simulations with state-of-the-art uncertainty quantification approaches including surrogate models and efficient forward propagation methods. Thus, the outcomes of the workshop and the challenges listed above are guiding the future development of the application framework.

3. Investment in the collection of high-value open data

One of the major barriers to the enhancement and integration of software is the lack of access to critical datasets, particularly those with greater granularity and spatial extent than what is available today. When asked to identify aspirational data sources, the majority of responses (54%, N=183) expressed the need for additional high-value and higher-resolution data that is not available today (see Fig. 5 for details). Among the additional data needed, information on buildings (14%, N=183), households, businesses, and services (13%), recovery processes (12%), and hazards (5%) were frequently mentioned. Examples of high-value data under these sub-themes are reported in Table 3.

Participants also recognized the opportunities generated by improving the accessibility and trustworthiness of existing datasets (23%, N=183, Fig. 5), especially when it comes to information about lifelines; and the need for more data to calibrate and validate numerical models of hazards, damage, consequences, and recovery (17%). These themes are discussed in more detail in the following subsection.

Participants speculated they would produce only about 22% of the listed aspirational datasets, and more than half of the data they rely upon would be from databases that cover the entire nation and often provided by federal agencies (e.g., probabilistic hazard maps, building inventories, demographic data). Some of the identified needs require new workflows to generate the data, but often it would be sufficient to enhance existing data collection approaches so that they capture additional high-value data and maintain it in desirable formats for computational modeling and simulation. The following should guide such future investments in high-value data:

- **Refine 4D resolution:** The high-fidelity models that guide targeted mitigation decisions must be calibrated and validated against site-specific, parcel-level hazard and exposure data. Achieving the required level of granularity and specificity in building characteristics, behavior, and performance requires navigation of new sets of privacy issues and proprietary restrictions. Furthermore, hazard and exposure characteristics often evolve at a faster rate than the release cycle of the corresponding data, for example, census data is released in decadal cycles. The temporal resolution of datasets needs to be better aligned with the underlying system dynamics to assure availability of more accurate pre-disaster benchmarks. The updating rate may even be adapted when these dynamics change, such as releasing more frequent updates following a disaster to better capture recovery characteristics. In a post-disaster context, longitudinal studies and more granular information about the impact on communities is required to support the development of quantitative models of the recovery process. The NSF, NIST, and other entities are investing in vital disaster recovery research and empirical studies. Such studies, including those that are region- and hazard-specific, can offer a rich source of baseline data for individual sectors (e.g., housing, business, critical infrastructure, civil infrastructure), as well as community systems (e.g., system interdependence, neighborhood decline/stability).
- **Anticipate diverse use cases:** Data collection for a specific purpose is often performed by persons with limited understanding of the potential uses of the data for other purposes. For example, a tax assessor or National Flood Insurance Program (NFIP) claims adjuster has a specific data schema and conducts subjective assessments and classifications of building components. The labels assigned in this process might not be accurate from a structural engineering perspective. Engineers often find it challenging to use such data to infer structural vulnerabilities in a natural hazard risk assessment. To maximize the

likelihood of meeting diverse user needs, the approach to data generation shall be informed by interdisciplinary perspectives when the underlying schema is designed and the data classification within that schema is defined.

- **Promote standards across data providers:** The data needed to explore questions of community resilience is generally fragmented because each producer (e.g., municipal departments, insurers, and federal agencies) uses its own schema and methodology. This leads to diverse standards for collecting, tagging, and vetting this data. The quality and completeness of the produced data and metadata would greatly benefit from enforcing consistency and ideally centralizing the production efforts. At a minimum, producers should be aligned under consensus standards that are communicated and promoted by designated persons [see concept of 'Data Evangelists' Andrei Lyskov (2019)].
- **Value the entire data life cycle:** Producing data that has high value and potential for re-use requires considerable time and effort. Data producers often find this work a heavy burden and they may lack the incentives, expertise, capacity, and resources to follow through. The emphasis is often placed on data collection while the "dirty work" of quality assurance, metadata association, documentation of the methodology, and long-term curation is often not resourced and recognized at the level it deserves.

It is worth noting that the data relevant to community resilience is increasingly being generated and managed through digital workflows, and the cost of collecting several important data types is already low and continues to decrease rapidly. These factors enable the generation of robust repositories of images, documents, and other relevant data. New modalities such as crowdsourcing and citizen science further expand the venues for data generation. Thus, taking the suggested steps toward generating high-value data does not necessarily demand a significant increase in investment. Resourcing seems secondary to the more critical need to redesign policies and practices for data collection and generation.

4. Commitment to sharing and utilizing high-value data

While participants routinely consume open data in their analyses and simulations, the lack of access to high-value data often forces them to limit the scope of their work to problems that can be solved with the data available. During the breakout session on data sources, participants were asked to list up to five data products they consume and produce in their work. This information was processed using the ontology presented earlier by assigning labels to each participant based on the 5 pieces of data they listed. Fig. 6 shows the number of participants assigned to each label—note that each participant could get multiple labels assigned both within a category and across categories. Almost all participants consume data that is publicly available (96%), largely from government providers (96%), and the result of direct observations (98%). Respondents had heavy reliance on data describing the built environment (91%), the natural environment (68%), and households (64%). Table 4 lists examples of consumed data under these themes. Almost every participant needed exposure (98%) data, and a strong majority also used information that characterizes the hazard (70%). The majority (66%) focused on earthquake and geohazards, a direct consequence of the participant demographics (Fig. 1a). Significantly fewer participants mentioned data sources that provide information about direct damages, their consequences, and activities surrounding preparedness and recovery. This lack of utilization is likely due to the scarcity of such data because a large number of participants expressed interest in these themes when listing aspirational data (Fig. 5).

As visualized in Fig. 7, the data consumed by participants in their analyses and simulations had moderate levels of trustworthiness (mean=3.72/5.00, where 5 is highly trustworthy), with only 62.4% scoring 4 or above. Even though these datasets were regularly engaged, participants assessed them as only moderately accessible (mean=3.53/5.00, with 5 indicating highly accessible). In fact, only 56.4% of the data consumed by participants was perceived as easy to access (i.e., receiving a score of 4 or above).

Participants tended to produce data similar to what they consumed (Fig. 6), predominantly focused on the built environment (74%, e.g., city-level building inventories, responses from structural analysis models) and the natural environment (35%, e.g., ground motion datasets, hurricane wind speed projections). The number of responses for consumed datasets was in some cases significantly larger than the number for produced datasets due to a larger proportion of "consumers" among participants (see response totals for consumed and produced datasets in Fig. 6). More respondents produced data through computer simulation than the number of those who consumed such data (19 vs. 12 out of 47 responses). While consumed data was primarily from the earlier phases of the natural hazard risk assessment workflow, the produced data is more evenly distributed across the workflow phases.

As detailed in Fig. 7, the data participants produced is comparable to the data they consumed in terms of perceived trustworthiness (mean=3.65/5.00). Even though participants have greater control over the trustworthiness of their data products, only 57% (N=112) of them scored 4 or higher. Participants further admitted they were not good "data citizens", producing data perceived as markedly less accessible than the data they consume from others (mean=2.79/5.00). Only 32% (N=112) of the data they generate is actually accessible to others (i.e., rated 4 or higher), with only 40% (N=35, see Fig. 6) of them sharing at least some of their produced data publicly. Fig. 6 also visualizes the disproportionate consumption of public data that results in highly private data products—63% (N=35) of participants store some of their produced data privately and 46% (N=35) of participants have none of their produced data published or publicly available.

These observations on data management are not uncommon and stem from the challenges surrounding the adoption of FAIR (Findable, Accessible, Interoperable, Reproducible) data standards (Wilkinson et al., 2016). While frameworks stand ready to guide research communities toward adopting FAIR principles (GoFAIR.org, 2021), it must be acknowledged that FAIR demands more of the data producer than just making the data accessible. Appropriate documentation of the methodology applied to collect and process the data is also an important part of the principles. The benefits of doing so are considerable as other producers within a community also adopt this philosophy when they share their high-value data. More importantly, as noted by Wilkinson et al. (2016), "The primary limitation of humans, however, is that we are unable to operate at the scope, scale, and speed necessitated by the scale of contemporary scientific data and the complexity of e-Science." By embracing FAIR data standards and encouraging data producers to provide sufficient context for their data research, communities will be able to leverage the power of automation and machine learning and can work with data at the scale demanded by current problems.

From a technological perspective, the formula for exposing open data is clear: ensuring published data have appropriate schema, are exposed using open data standards, and take advantage of the interfaces that have been developed to bring it seamlessly into workflows. However, the ability to act upon this formula is considerably hindered in the fields studying disasters and community resilience because the required data is generated in a highly distributed fashion across numerous agencies, municipalities, and institutions. Inevitably, these entities have divergent data sharing policies and practices and often lack expertise in, and capacity for, sound data management. In some cases, local government data providers have partnered with the private sector to manage and share their data [e.g., Socrata (2021); Tyler Technologies (2021)], though not all municipalities have the resources or inclination to do so. These challenges are only compounded by additional barriers erected by the unique cultures, policies, and regulations within these entities. For example, restrictions may limit access to private or sensitive data, possibly regulated by an Institutional Review Board (IRB) protocol or privacy laws. Data producers may further be averse to the risk of liability due to data misuse or misinterpretation. In other cases, business interests (e.g., services that would be obsolete if the data were open) or other concerns over competitive advantage (e.g., desire to maintain exclusive publishing rights) prevail. Thus, while the technical formula is clear, the formula to change human and organizational behavior is yet to be discovered.

Nevertheless, the participants identified several priority areas to increase the amount of high-value data exposed in our community:

- **Enhance discoverability:** While data may be available online, it is not always easy to find. Users struggle to stay abreast of all the new data initiatives, services, and providers. Clearinghouses and centralized data initiatives such as DHS Exchange Core and OpenFEMA are especially valuable in this rapidly evolving landscape. More fundamentally, semantic incompatibilities can inhibit the identification of relevant data through automated queries. Such incompatibilities arise because each data producer uses their own disciplinary views to design a schema for their data. Fortunately, advances in the semantic web can bridge the potentially disparate views of data consumers and producers to make more data discoverable [see Schema.org Publishing Guidelines for the Geosciences v1.1 Shepherd et al. (2020)].

- **Enhance integration:** Disaster simulations require continuously evolving data from diverse sources. Even open data is often difficult to retrieve and consume. Onerous access restrictions and cumbersome formats may require users to manually download and pre-process the data. Large-scale, automated disaster assessments will require federated databases that allow producers to maintain and update the data while providing seamless integration with consumers' computational workflows. Data producers should publish Application Programming Interfaces (APIs) and expose their descriptions in a machine-consumable manner (e.g., OpenAPI). Shakemap from USGS is a good example. Although several producers share geospatial data through ArcGIS Online, this data would have even greater value when exposed through Web Map Service (WMS) or Web Feature Service (WFS) endpoints using non-proprietary Open Geospatial Consortium (OGC) standards (see the emerging OGC Web API Guidelines: Open Geospatial Consortium (2019)). Updated versions of OGC standards are adopting semantic principles to improve discoverability and foster seamless integration within workflows. These are currently being integrated into open-source tools like GeoServer (GeoServer, 2021) and QGIS (QGIS, 2021).
- **Expose more than data:** As reliability and trustworthiness of data is as critical as access itself, the adoption of data standards and establishment of consistent data processing methods is critical. Ideally, these standards and methods are coupled with quality control processes that include quantifiable confidence measures [see StEER QC codes as an example Roueche et al. (2019)]. Standardized data must be exposed with well-structured metadata and appropriate documentation of associated data collection, processing, and quality assurance methodologies. Standard data schema can be shared at schema.org to encourage adoption.

To further support robust verification and reproducibility of results, producers should expose not only derived data (e.g., statistics and calibrated models), but also the raw data itself. Data producers should strive to leverage platforms that provide tools for automated testing and versioning such as GitHub (GitHub Inc., 2021) and GitLab (GitLab Inc., 2021).

- **Promote community validation.** As more high-value data—including models—is exposed, its wider use will foster the discovery of errors and omissions. Data producers can improve the trustworthiness of their data by supporting cross-validation studies and establishing a mechanism for user feedback, rating, and issue reporting.
- **Convert legacy data.** There is valuable legacy data that has yet to be brought into repositories, and in some cases, will require digitization from archival files. Data from landmark disaster events is particularly valuable and an initiative to compile, digitize, process and expose these legacy datasets would be highly beneficial for the disaster science community.

Ultimately, the true potential of open data is only realized when enough of us—and ideally all of us—commit to the above initiatives. This level of adoption necessitates a substantial shift in the politics and culture surrounding data. Such a shift can be facilitated by the alignment of corresponding incentives (possibly by creating higher consequences for non-compliance through data publishing requirements of sponsors and journals) and by lowering the barriers to publishing data openly considering the limited capacity and experience of most data producers. Given the considerable reliance on external data providers, particularly at all levels of government, the suggested efforts must be coupled with their sustained advocacy on the importance of reliable and accessible data.

5. Development of versatile, multidisciplinary testbed studies

In addition to diverse data needs, diverse disciplinary expertise is required to simulate and study the recovery of communities after a disaster. The opportunities listed above outline initiatives that would facilitate data access, enable the exploration of impactful questions, and promote sharing these results with others. In spite of those improvements, entering this space will remain challenging and will still require a substantial time investment. Participants agreed that testbeds provide helpful and much-needed examples that can encourage interested newcomers, such as graduate students and non-academic professionals, to invest in recovery simulation. Testbeds can be designed around the opportunities revealed in this paper and become vehicles of change while serving their main purpose as illustrative examples. A modular testbed that integrates various tools and corresponding data could serve multiple functions:

- **Benchmark models:** Testbed exercises can become benchmarks to evaluate and periodically assess the performance of various natural hazard risk assessment workflows. Such evaluations could inform the community about the expected benefits of choosing a particular workflow or, within a workflow, making different choices regarding the level of fidelity, the specific input data, the hazard scenario, or a subclass of models. Reporting results from alternative solutions of the same problem would also facilitate verification and measuring the robustness of various workflows. If the testbed location is chosen to coincide with a historical event site, it can also be used for hindcasting exercises and validation purposes.
- **Serve as a template:** As long as both the simulation platform and the input data are publicly available, testbeds are large example problems that can be used as a template to develop new workflows or initiate new studies. This promotes technology transfer from academia to the private sector and can encourage large government organizations to update their tools more frequently. Reproducing results is easier if a large part of a community works from the same template and builds credibility and trust in both the models and their outputs.
- **Demonstrate best practices and serve as a proof-of-concept:** Testbeds can demonstrate best practices in workflow design, present caveats, and illustrate how lack of data or low-fidelity models in one phase can compromise the entire simulation. These illustrations can also promote robust data management—i.e., data standardization and documentation of all models and data used for a simulation, including appropriate citations to their DOIs. When it comes to sensitive demographic data, testbeds can present best practices to work with the typically lower-resolution available information and still provide meaningful insights.

- **Promote tools and datasets:** Although many well-known proprietary tools have free, open-source alternatives, these are less promoted and the majority of the community is often not aware of them (e.g., ArcGIS and QGIS). A comprehensive collection of data and software resources in testbed examples facilitates the discovery of open-source tools and public data. Additionally, testbeds can expose gaps in workflows (i.e., desirable functionality not supported by any open software) and provide a platform to curate and explore new methods and models to fill those gaps.
- **Promote interdisciplinary collaboration and engage stakeholders:** Testbeds designed around a tangible narrative about important problems (e.g., disproportionate impact of disasters on vulnerable populations) can raise awareness and solicit feedback from disaster recovery researchers, affected community members (residents, leaders, and policymakers), and other stakeholders. Observing how data and models from one domain affect the simulations in another can also generate feedback and collaboration across disciplines.

The location or geographic focus of a testbed can have a large impact on its utility in serving the above functions. A good location has substantial data available to characterize the hazard, the built and natural environments, and the socioeconomic attributes of the population. It also helps if the local government is interested, supports these simulations with data, and brings forward local policy-related questions that can be informed by simulation results.

Groups of participants reviewed existing studies during breakout sessions and suggested eight potential testbed locations that we grouped into four geographical areas. Table 5 provides a summary of the opportunities in each area (a detailed description of the desirable features is available in Table S3). The suggested locations reinforce that natural hazard risk is governed by different hazards in the West and East Coasts of the United States. While Christchurch in New Zealand and Kathmandu in Nepal were suggested as good examples that were recently impacted by severe earthquakes and have both valuable data and support from the local government, participants (primarily from a North American context) were generally concerned about data availability and lack of familiarity with the local environment in non-US regions.

Within the United States, regional studies on the West Coast often focus on the San Francisco Bay Area (Deierlein et al., 2020; ATC, 2018; Detweiler and Wein, 2018b), but there are recent examples from Los Angeles (Kang et al., 2019; Cook et al., 2021) and Seattle (Marafi et al., 2020) as well. In California, wildfires (Lautenberger, 2017), fires following earthquakes (Detweiler and Wein, 2018a), and flooding due to atmospheric rivers (USGS, 2011) present additional hazards on top of the earthquake risk. In the Northwest, subduction earthquakes and potential tsunamis can represent a markedly different environment. The East Coast has several large metropolitan areas that are affected by various wind and water-borne hazards. The consequences of hurricanes in the coastal regions of Texas (Hamideh and Rongerude, 2018), North Carolina (Wang et al., 2019), and New Jersey (Deierlein et al., 2020; Kijewski-Correa et al., 2020) have been studied recently. The longitudinal study in Lumberton, NC (Sutley et al., 2021) already offers valuable data and the city is expected to become a prime location for hindcasting and recovery model calibration. Three groups of workshop participants independently suggested South Florida for consideration because a large population is frequently exposed to severe storms, in addition to threats from sea level rise and other climate change effects. Miami-Dade County was specifically mentioned because there is a large number of industrial facilities in the region as well as because Miami is a major city and tourist destination with considerable high-rise residential development.

Besides large regional studies with millions of households, recently created smaller testbeds [e.g., Seaside, OR in Park et al. (2019)] demonstrate that by focusing on a few thousand buildings, researchers can develop high quality exposure and household data. These smaller testbeds can also be computationally more affordable to run large sensitivity studies that might not be feasible for large regions. Such smaller studies can serve as proofs-of-concept and benchmarks for new models and methodologies.

CONCLUDING REMARKS

The workshop organized by the NHERI SimCenter in early 2020 to review and discuss simulation and data needs to support disaster recovery planning provided important insights into the prerequisites for the next generation of studies on the regional impact of disasters and post-disaster recovery of communities. The investigation of households and their homes emerged from discussions as an area with abundant opportunities for collaboration between various disciplines in natural hazards engineering. Participants identified a large number of existing tools and recognized the need to better integrate these into computational workflows to facilitate sharing and re-using models and results. The high-fidelity simulations that can support more nuanced risk mitigation policies and recovery planning will require additional building and demographic information. Investments in robust and trustworthy methods to collect such information and make it publicly accessible in a standardized format is necessary for our community to be able to tackle large-scale problems at high fidelity. In this paper, and in the supporting digital data, the authors share specific examples of high-value data that participants frequently mentioned as critical information for their work. Finally, testbeds were highlighted as multi-purpose tools for sharing, benchmarking, and promoting data, models, and workflows in the NHE community and beyond.

In addition to the opportunity areas that are the main focus of this paper, a few remarks about workshop design are shared below to support future organizers:

- Breakout sessions with structured exercises rather than only discussions allow organizers to collect rich insights and evidence from participants. This increases the likelihood of identifying pathways for meaningful advancements in the NHE field. We hope that the collected data—published at DesignSafe (Zsarnóczay et al., 2021)—provides a helpful reference.
- Designing workshop exercises around the data that we intended to collect worked well for this workshop, although further improvements might have been possible if the post-processing methodology and ontology had been conceived beforehand.
- The choice between labeling artifacts ourselves or asking participants to assign their own labels is not trivial. The former requires more work after the workshop and leaves more to interpretation when confronted with ambiguous answers. The latter requires more time in each breakout during the workshop to ensure participants understand the ontology and are not overwhelmed by the task. We advise against asking participants to choose from pre-

defined labels without first providing specific and detailed descriptions of each label to avoid them inadvertently biasing the labeling process. Even then, participant-assigned labels are subject to greater inconsistencies due to variances in interpretation and participants' perceptions of themselves and their responses. Alternatively, labels can be more consistent when assigned after the event by a limited number of persons with a common frame of reference.

- Successful workshops organized since the one in this paper, with a similar approach to bringing several projects together and focus on overarching issues and synergies [e.g., Rosinski et al. (2021); NIST Center for Risk-Based Community Resilience Modeling (2021)], affirm that the NHE community continues to benefit from this type of interaction. Future workshops could expand to international events. Such a broad audience would provide opportunities to recognize diverse NHE contexts and to promote changes that support greater collaboration and reproducible research at a global scale.

DATA AVAILABILITY

Some or all data, models, or code generated or used during the study are available in a repository online (Zsarnóczay et al., 2021) in accordance with funder data retention policies.

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SUPPLEMENTAL MATERIALS

Tables S1-S3 and Figure S1 are available online in the ASCE Library (ascelibrary.org).

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List of Tables

TABLE 1. Proposed ontology for natural hazard engineering data.

Category	Description
Natural Hazard	**Which type of natural hazard does the data describe?**
Earthquake & Geo	Ground motion, Liquefaction, Landslide, Sinkhole
Wind	Hurricane, Tropical storm, Nor'easter, Tornado
Water	Flood, Storm surge, Tsunami, Sea level rise
Climate	Extreme temperature, Drought
Fire	Wildfire, Fire following earthquake
Phase	**Which phase of the simulation workflow does the data belong to?**
Exposure	Characterize the built and social environment and how it changes over time before or between disasters.
Hazard	Characterize historical hazard events or parametrize models to simulate the frequency and intensity of synthetic scenarios.
Damage	Describe the damage after past events or parametrize models to simulate the damage in synthetic scenarios.
Consequences	Describe the consequences (e.g., losses, injuries, disruption) after past events or parametrize models to simulate consequences in synthetic scenarios.
Recovery	Describe the recovery process after past events or parametrize models to simulate recovery after synthetic scenarios.
Context	**Which part of the local environment does the data belong to?**
Natural env.	Topography, bathymetry, soil conditions, etc.
Built env.	Structures and infrastructure components in the area
Households	Individual members or households in the population
Businesses	Individual businesses in the economy at-large
Services	Education, insurance industry, medical infrastructure, etc.
Origin	**How was the data generated?**
Simulation	Computer simulation using numerical models to produce synthetic data
Experiment	Controlled experimental tests (both engineering and social sciences)
Observation	Field data, including satellite, street-view, and reconnaissance images, surveys, polls, data from social media, and data from monitoring systems and sensors.
Provider	**Who provides the data?**
Public sector	Government agencies
Private sector	For-profit and non-governmental organizations
Academic entity	Universities
Access	**Where is the data stored?**
Private	Available only to the producer and is difficult or impossible to share; for example, results stored in a non-standard format on a local hard drive.
Shared	Available upon request or subscription to a service run by the producer; data is stored in a format that is readable at least by expert users.
Published	Available upon subscription to a journal or a service independent from the data producer; for example, data archived or published by journals.
Public	Open access

TABLE 2. Examples of housing-related applications and related data needs for planning and policy-making (source: Workshop participants)

Context	Examples
Session I Connecting to Stakeholders	Simulation of cascading effects. Modeling of post-disaster recovery to anticipate potential long-term effects of different disaster scenarios, and to be applicable to a range of temporal and spatial scales.
Session II Connecting Across Experts	Simulation of re-occupancy and functional (physical) recovery of homes. Comparison of various policies and strategies for funding and prioritization of building retrofits. Ability to prioritize among multiple housing restoration or recovery options.
Session III Data Sources	Most household data consumed is sourced from the US Census Bureau, specifically the American Community Survey (ACS); few researchers are producing household-level data. Data relating to structural features of houses, damages to homes, and socio-economic characteristics of households.
Session IV Interdisciplinary Engagement	Longitudinal studies and investigations of multiple facets of community recovery. Testbeds that explore various scenarios and plausible futures to enhance our understanding of myriad impacts, consequences, and patterns of recovery spatially and temporally.

TABLE 3. Examples of additional high-value data listed among aspirational data needs (source: Workshop participants)

Theme	Recurring Examples
Buildings	Information on the structural system in tax assessor databases; Information on structural retrofits and modifications; Inventories with building-specific information for entire cities.
Households, Businesses, and Services	High-resolution insurance penetration data; Information on supply chains for local businesses; High-resolution information about workplaces of each household (both location and industry)
Recovery	Longitudinal data about household decisions after a disaster; Population displacement and its effect on neighborhood recovery; Availability and timeline of various funding sources
Hazard	Real-time, high-resolution inundation hazard data (flood, storm surge, tsunami); High-resolution (parcel-level) hurricane wind data

TABLE 4. Examples of Consumed Data by Dominant Theme (source: Workshop participants)

Dominant Themes	Recurring Examples
Built Environment	Tax assessors; FEMA (Hazus exposure data and performance models); Microsoft (building footprints); Homeland Infrastructure Foundation-Level Data (HIFLD); Zillow
Households	US Census Bureau (specifically the American Community Survey); Bureau of Labor Statistics
Natural Environment	US Geological Survey (USGS); National Oceanic and Atmospheric Administration (NOAA); Pacific Earthquake Engineering Research Center (PEER)
Structural damage	Damage assessments sourced from images; Component-level damage data (e.g., walls, roof, interior contents)

TABLE 5. Recommended testbed locations and corresponding research opportunities (source: Workshop participants).

Location	Opportunities
State of Florida / Southern Florida / Miami-Dade County	Topology, bathymetry, land use and land cover data available. Detailed information available about historical storms. Exposure data available about buildings and transportation infrastructure. First-floor elevation information needed—machine learning opportunity. Several industrial facilities are major contributors to local employment while contributing to the risk of environmental damage. High insurance penetration and information about insurance is available.
Pacific Northwest / San Francisco Bay Area / Los Angeles Metro Area	Local governments have a history of collaboration with experts from academia and industry. Post-disaster damage and consequence data available for recent earthquakes and some of the recent wildfire events. Maps of historical event intensities and probabilistic forecasts of future events are available for earthquakes and tsunamis. Tall building inventory available in San Francisco and water network information available in Los Angeles. First-floor elevation information needed—machine learning opportunity. High-resolution geographical information about known structural vulnerabilities (e.g., cripple walls, soft-stories) is needed. Tech companies are major employers in the LA, SF, and Seattle metro areas. Investigation of the displacement of their workforce presents an opportunity for collaboration. Existing benefit-cost analysis (BCA) models by FEMA could be benchmarked and enhanced. Investigation of the impact of disasters on the wine industry is another opportunity for collaboration.
Christchurch, New Zealand	Rich data available on the impact of the earthquakes in 2011; including data on cordons and their effects on local businesses. Liquefaction-prone area with detailed information available about soil characteristics.
Kathmandu, Nepal	Rich data available on the impact of the earthquake in 2015; including shaking intensities, damage, and aggregate casualty information

List of Figures

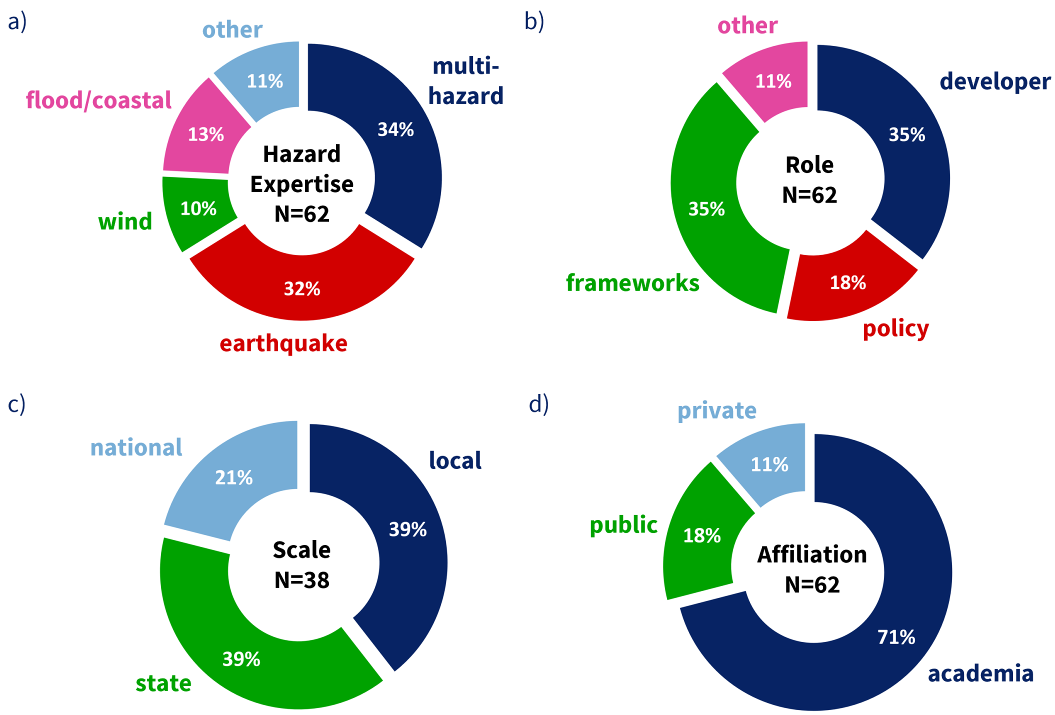
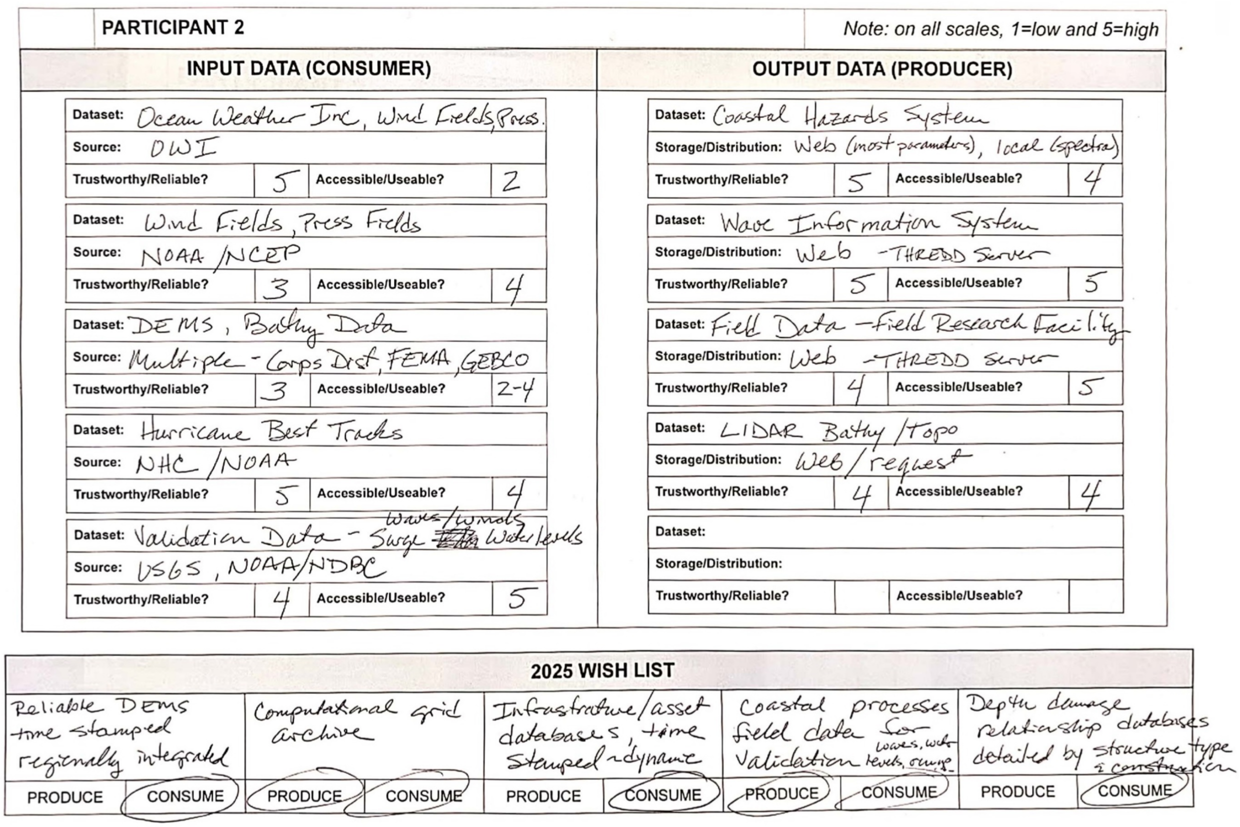


Fig. 1. Distribution of participants' self-reported (a) hazard expertise, (b) role, (c) scale in their work on disaster risk and resilience, and (d) affiliation. N in the middle of the charts shows the number of responses received from participants for each question.



PARTICIPANT 2 — Note: on all scales, 1=low and 5=high

INPUT DATA (CONSUMER)

Dataset: Ocean Weather Inc, Wind Fields, Press.			
Source: OWI			
Trustworthy/Reliable?	5	Accessible/Useable?	2
Dataset: Wind Fields, Press Fields			
Source: NOAA /NCEP			
Trustworthy/Reliable?	3	Accessible/Useable?	4
Dataset: DEMS, Bathy Data			
Source: Multiple - Corps Dist, FEMA, GEBCO			
Trustworthy/Reliable?	3	Accessible/Useable?	2-4
Dataset: Hurricane Best Tracks			
Source: NHC /NOAA			
Trustworthy/Reliable?	5	Accessible/Useable?	4
Dataset: Validation Data - Surge Waves/winds Water levels			
Source: USGS, NOAA/NDBC			
Trustworthy/Reliable?	4	Accessible/Useable?	5

OUTPUT DATA (PRODUCER)

Dataset: Coastal Hazards System			
Storage/Distribution: Web (most parameters), local (spectra)			
Trustworthy/Reliable?	5	Accessible/Useable?	4
Dataset: Wave Information System			
Storage/Distribution: Web - THREDD Server			
Trustworthy/Reliable?	5	Accessible/Useable?	5
Dataset: Field Data - Field Research Facility			
Storage/Distribution: Web - THREDD Server			
Trustworthy/Reliable?	4	Accessible/Useable?	5
Dataset: LIDAR Bathy /Topo			
Storage/Distribution: Web / request			
Trustworthy/Reliable?	4	Accessible/Useable?	4
Dataset:			
Storage/Distribution:			
Trustworthy/Reliable?		Accessible/Useable?	

2025 WISH LIST

Reliable DEMS time stamped regionally integrated	Computational grid archive	Infrastructure/asset databases, time stamped - dynamic	Coastal processes field data for Validation waves, water levels, currents	Depth damage relationship databases detailed by structure type & construction
PRODUCE / CONSUME	PRODUCE / CONSUME	PRODUCE / CONSUME	PRODUCE / CONSUME	PRODUCE / CONSUME

Fig. 2. Data map example.

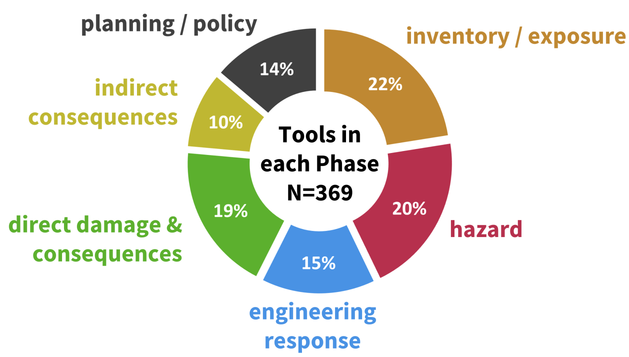


Fig. 3. Relative number of available software tools in each phase of the natural hazard risk assessment workflow. (source: N=369 responses from Workshop participants).

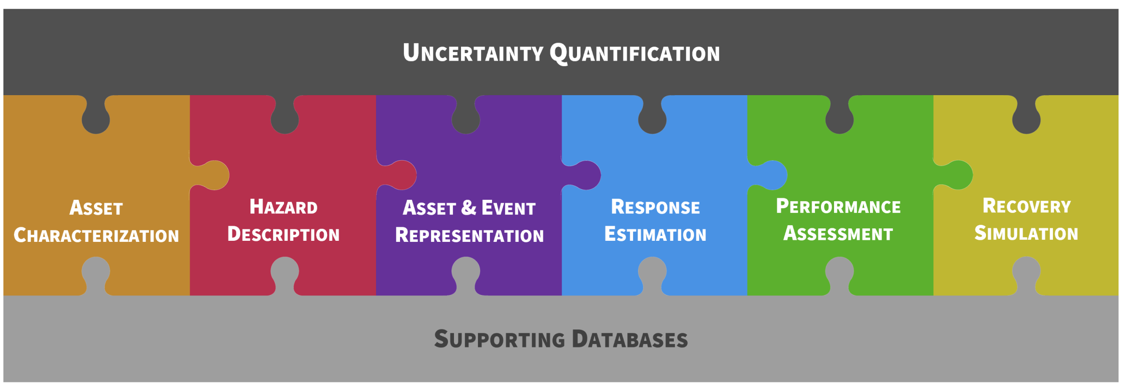


Fig. 4. Conceptualization of the SimCenter's natural hazard risk assessment workflow.

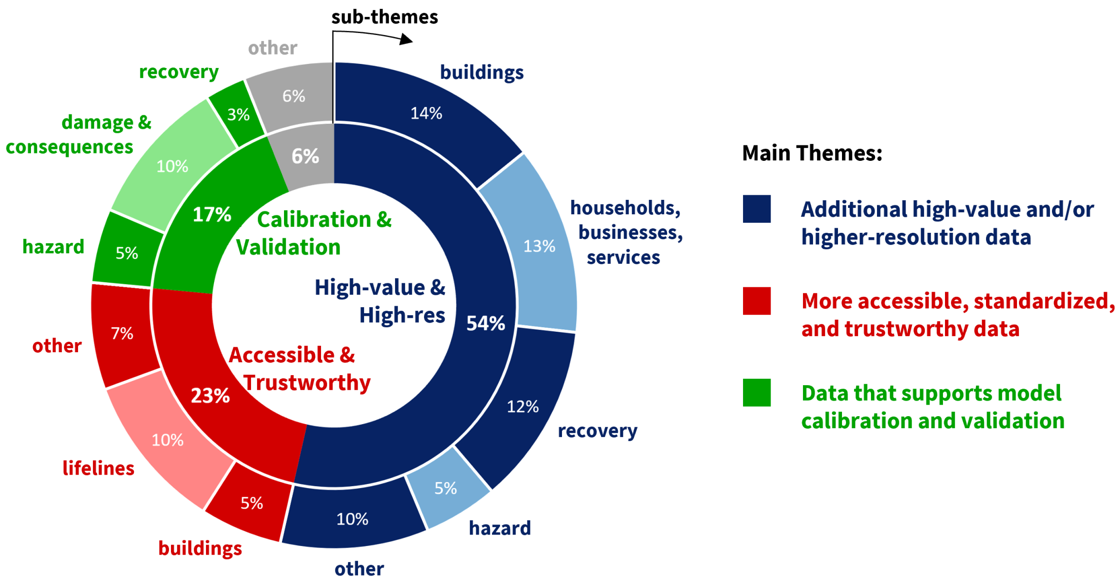


Fig. 5. Popular themes in aspirational data sources (source: Workshop participants, N=183)

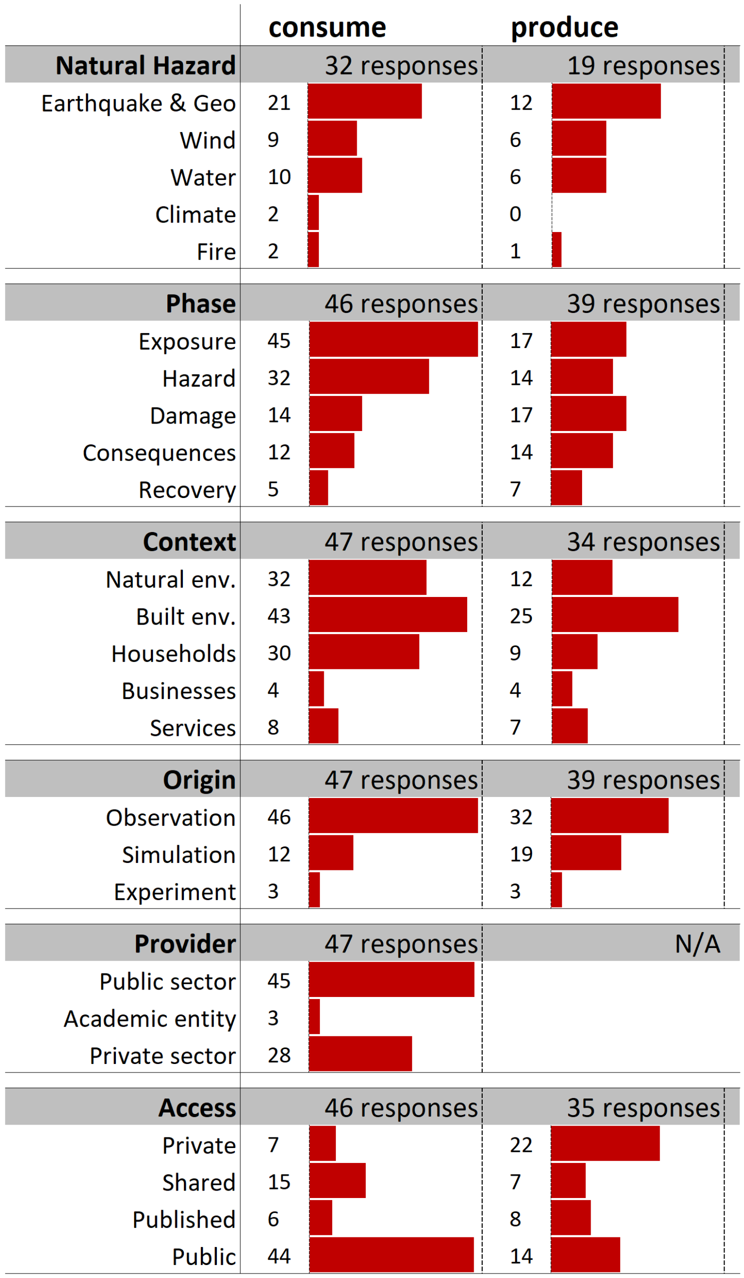


Fig. 6. Distribution of consumed and produced data across key attributes. The provider class for produced data could not be reported to protect respondent anonymity. (source: Workshop participants)

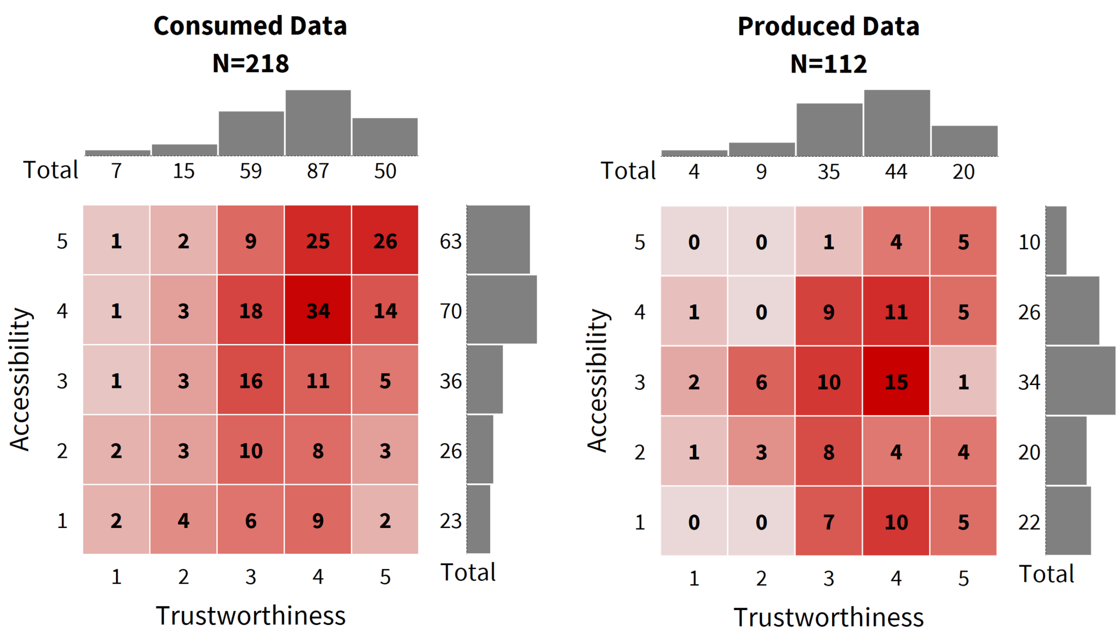


Fig. 7. Distribution characterizing the accessibility and reliability of consumed and produced data (source: Workshop participants).