Maximizing Societal Impact of Earthquake Research through Multidisciplinary Integration and Collaboration

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Multidisciplinary integrative research is necessary to transform academic knowledge into tools and products that can be used to further advance research and to develop practical applications for the benefit of society. The next earthquake center(s) should be conceived and designed to invite, embrace, and support multidisciplinary collaboration and integrative research, an endeavor consistent with NSF's concept of Growing Convergence Research. Furthermore, a track record of involvement in research of this kind should be a requirement for those proposing to lead a future earthquake center. In the context of earthquake research, disciplines for which a collaboration is needed include specialties from fundamental geoscience, earthquake engineering, computational science, education and outreach, and social science. The collaboration requires not only a common set of goals, but the development of a language, metrics, and mechanisms that integrate the diverse set of outcomes into products targeted to scientists, communities and societal stakeholders such as policy makers. To make this point, we have selected examples of multidisciplinary research activities undertaken by the Southern California Earthquake Center (SCEC) and demonstrate how instrumental this approach is to identify thrust areas, pursue scientific goals, and to increase their broader societal impacts.

Motivation: improving seismic hazard analysis to support resilient societies.
Stakeholders responsible for large infrastructural portfolios are moving from prescriptive-based regulation to risk-informed seismic design and decision-making. This approach, based on best available science, is preferred as it aims to provide regulatory stability and to improve the seismic resilience of infrastructure over longer timescales. Risk reduction is a long-term endeavor requiring research programs that reduce uncertainties at every step of the evaluation process, starting from the hazard assessment.

Probabilistic seismic hazard analysis (PSHA) is ubiquitous in engineering analysis and design, and is the main tool for integrating science insights into actionable metrics. The process is well established when used to characterize the likelihood of strong ground shaking at a single site, though still subject to large uncertainties, especially at exceedance probabilities relevant to design. The process is more nascent, however, when used to assess different hazards or secondary failures (e.g. fault displacement, liquefaction, landslides, fires) or to assess regional risk for purposes of analysis and design of distributed, interconnected systems.

The reduction of uncertainty in hazard assessment is a very practical problem with a solution that resides in multidisciplinary science. In partnership with engineering, that science can be focused on critical problems and translated into useful products, co-developed through computer science. This, in turn, supports more safe and cost-effective designs. The following examples illustrate the mechanisms and benefits of multidisciplinary scientific integration involving scientists, engineers and computer scientists on 1) new research thrust areas and 2) broader impacts for society.

New integrative tools benefit and enable scientific research.
Our first example involves OpenSHA, an open-source software developed to perform PSHA-relevant research. Early on, OpenSHA was used to better understand the impact of different modeling assumptions on hazard results. It was instrumental in the implementation of site-specific (i.e. semi-ergodic) analysis approaches and in the quantification of their effects on hazard. OpenSHA became the tool in which new earthquake rupture forecasts (ERFs) such as the Uniform California Earthquake Rupture Forecasts (UCERF2 and UCERF3) were developed and thoroughly tested. UCERF3 itself integrates research results from geology, paleoseismology, geodesy and other disciplines into a comprehensive ERF that is now the basis of most design applications. UCERF3 led to the refinement of the current USGS seismic hazard estimates for California, which in turn have led to a reduction of earthquake insurance rates set by the California Earthquake Authority. More recently, OpenSHA integrated new operational earthquake and

aftershock forecast models that were deployed during the July 2019 Ridgecrest Earthquake Sequence to inform the public. While OpenSHA has been used in design applications, it is a research-enabling software at its core and has been utilized as such for over 15 years, with its breadth of reach continually expanding.

A second example is CyberShake. SCEC scientists developed CyberShake as a computational platform for physics-based PSHA. CyberShake, the first of its kind worldwide, simulates ground motions by including complex physics within computational models and by providing hazard results at any location, including those where there are no instrumental records. CyberShake is an ideal platform to study and reduce the uncertainties in hazard, as it provides fault-, path-, and site-specific estimates of ground motions (i.e. non-ergodic motions).

To produce a complete PSHA curve at any given site, CyberShake runs over 400,000 fault rupture and wave propagation simulations. These simulations are accomplished using an integrated software stack and a workflow that runs tens of thousands of jobs automatically on high-performance computers (HPCs). The required workflow tools were not available initially, and were developed through collaboration with computer and earth scientists, driven by CyberShake needs. Known as Pegasus, the improved workflow framework is enabling large-scale computational research in several fields, especially for projects requiring HPCs, such as the Laser Interferometer Gravitational-Wave Observatory (LIGO) project, touted as "opening up a new window onto the nature of the universe". Pegasus' team leader routinely credits their work with the CyberShake team for enabling the capabilities now used in such high-impact projects.

To date, CyberShake has been run up to 1Hz, and we strive to increase the upper frequency limit to provide useful information for a larger portion of engineering structures. Increasing the ground motion frequencies requires high-resolution crustal models, the development of which became an important field of research on its own. In addition, the development and integration of realistic physical models that incorporate material heterogeneities, nonlinear rheology, and surface topography, is also needed for these higher resolutions and frequencies. The need for modeling these features continues to drive several scientific research activities on the physics of earthquake processes, on the dynamics and mechanics of materials, and on their related HPC applications. The validation of CyberShake simulations for engineering applications brought research engineers to also collaborate and develop new tools that are implemented as part of the simulations. The feedback loop between this group of technical users and the scientists continues to support model improvements throughout the CyberShake platform.

The software packages cited above were developed to support specific research needs, and required a multidisciplinary team from the beginning as they both were integrating products from several areas of specialization. Through their evolution, they became the source of new research ideas and drew in a wider range of contributors, serving not only their original research goals, but expanding their applicability and enabling new exciting research pursuits.

Making the world a safer place: broader impacts of science, engineering and policy integration. The benefits and impacts of a multidisciplinary collaborative framework are not only at the science and research level, but also at the broader societal level. Simulations, for example, have led to greater public awareness and preparedness, and spurred changes in policy for earthquake resilience in southern California and elsewhere. The ShakeOut scenario, a hypothetical M7.8 earthquake on the southern San Andreas Fault, was simulated and used to assess the state of emergency response and preparedness in southern California in the case of a large but plausible earthquake. The Great ShakeOut earthquake drill was then developed by a team of experts in emergency response and preparedness, public education, and outreach, to engage individuals, corporations, schools and several levels of government to improve earthquake resilience. The drill has been conducted annually since 2008 and in 2019 involved over 67 million participants worldwide. Related activities following the release of the ShakeOut scenario revealed that pre-existing disaster plans were inadequate overall, even for Los Angeles (LA), a city deeply invested in earthquake safety. This led to the development of the 2014 LA Seismic Safety Task Force report

"Resilience by Design," which recommended, among other measures, the fortification of the water distribution system and the enhancement of telecommunication networks. This was followed in October 2015 by LA Mayor Garcetti signing into law a historic mandatory retrofit ordinance to strengthen the city's most vulnerable buildings to prevent loss of life in the event of a major earthquake. The 2018 release of "Resilient Los Angeles" further built on the aforementioned seismic documents with a detailed action plan. In coordination with these reports, the Los Angeles Water System implemented a comprehensive seismic resilience program which used results from UCERF2, UCERF3 as well as other research products, and identified the need for increased fundamental and multidisciplinary earthquake research in order to increase infrastructure system resilience.

In addition, regional CyberShake simulations were used to train the USGS Earthquake Early Warning system, activated in California in 2019. They are also the basis for a new LA urban seismic hazard map being developed by the USGS. CyberShake results are included in new simulation-informed response spectral acceleration maps for southern California, aimed to improve the design of tall buildings. The new risk-targeted, maximum considered earthquake response (MCE_R) spectra were developed by the SCEC committee on Utilization of Ground Motion Simulations (UGMS), working within the framework of the Building Seismic Safety Council (BSSC). These UGMS products are available through web-based data access tools released to the public in 2018 and 2020. The tools and associated maps are being considered for inclusion in the American Society of Civil Engineers (ASCE) 7-22 Seismic Provisions as well as in the LA City Building Code.

A laudable aspect of all these efforts is that their impacts have not been limited to California. As the awareness and preparedness aspects of ShakeOut expanded worldwide, so did the scientific, engineering, and computational applications developed through SCEC's collaborations. Examples include OpenSHA, now used by the USGS to generate their nation-wide seismic hazard products. The engineering-driven validation techniques pioneered by SCEC are also adopted by ground-motion simulation researchers around the world. In turn, new research centers, such as New Zealand's QuakeCoRE Center for Earthquake Resilience, largely build upon SCEC's ideas, technologies, and scientific advances, including OpenSHA and CyberShake to develop their program based on multidisciplinary collaboration.

A plan for the future.

Individual research projects are important to scientific advances and often foster very creative thinking. By integrating such research ideas into broader research activities driven by practical problems, multidisciplinary teams working in collaboration enable larger impacts. This integration often involves the development of open-source software implementations, a trend that is only expected to grow as we grapple with increasingly complex data-rich problems. We have shown examples for which software being developed for science became and continue to be engines for new science, especially when used by multidisciplinary teams. The allocation of resources to support this type of work, including its computing activities, as part of a longer-termed earthquake research center will be an important foundation for the types of integrative activities discussed above, especially as we aim to tackle seismic hazard and risk at regional scales, for interconnected and complex systems.

In summary, to be successful and to sustain scientific growth and societal relevance, the next earthquake center(s) must coordinate research programs that span multiple disciplines. And more importantly, the future center(s) must provide a diverse pool of researchers a framework and resources for solving problems that transcend each of their disciplines. To that end, NSF's EAR should consider partnering with other relevant NSF directorates, such as ENG and CISE, to provide the required resources to the next center(s). As shown in the few selected examples above, the multidisciplinary model leads to new research ideas, new tools that enable research, and broader societal impacts. We are convinced that such an endeavor, anchored in deep collaboration and interdisciplinary research, will lead to the largest benefit to science, and to society as a whole.