A Software Ecosystem for Earthquake System Science

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This white paper is in response to NSF DCL 20-036 which asks for input on NSF plans to support an earthquake research center. The DCL expresses particular interest in responses that focus on three specific issues: (1) the aspects of earthquake science that a center would coordinate, (2) potential center capabilities and infrastructure, and (3) possible center organizational structures.

(1) Aspects of Earthquake Science that a Center Would Coordinate

While earthquake science involves a broad range of phenomena across many space-time scales, a future earthquake research center should produce results that can meaningfully improve the national welfare. The earthquake science research most directly relevant to the national welfare involves efforts to accurately forecast ground motions across time scales from seconds to centuries. Such research aims to provide prospective information for reducing seismic risks and preparing for the inevitable natural disasters. This type of research is integrative and collaborative. To successfully perform such research an earthquake center must coordinate the activities of multiple communities including geoscientific specialists needed to model earthquake processes, software, computing, and data management groups needed to support the computational research, and ground motion forecast stakeholders including civil engineers, government agencies, and emergency response planners.

Broad impact seismic hazard projects often involve community-based model integration and synthesis. Many earthquake forecast methods are complex and difficult to perform, develop, or modify. An NSF earthquake research center will be one of the few research groups with the scientific breadth to develop, evaluate, and apply community-based seismic hazard models. A future earthquake research center should enable the national geoscientific community to integrate their latest research advances into socially relevant earthquake ground motion forecasting information. As one example of how such research could improve the national welfare, a future earthquake research center could have an immediate positive national impact by coordinating a research activity in which probabilistic seismic hazard methods developed for California are applied nationally.

(2) Potential Center Capabilities and Cyber-Infrastructure

A center designed to conduct the earthquake science research described above will require a broad range of capabilities and cyber-infrastructure. The center should be a world leader in earthquake system science research. The center should emphasize research that integrates advances from multiple earthquake science fields into physics-based predictive models of earthquake processes. The center scientific leadership should identify new geoscience research and computing technologies that can contribute significant improvements to ground motion forecasts and should prioritize center research in the most productive areas. The center should have the capability to convene scientific coordination meetings, to attract the participation of the academic geoscientific research community including graduate students and postdoctoral scholars, and to lead research activities that involve academic, governmental, and commercial organizations. The center should have a close working relationship with the U.S. Geological Survey Earthquake Hazards Group, with a shared goal of migrating best available geoscience research into existing, or new, seismic hazard products.

Concerning the cyber-infrastructure required for the center, a future research center with earthquake ground motion forecasting as one of its primary goals will require highly accurate earth structure models and a wide range of earthquake-related, physics-based, software modeling tools. **Table 1** contains a list of software components in a modern earthquake system science software ecosystem, showing the breadth of research capabilities needed, with more than 20 researcher-developed scientific software programs currently used in SCEC earthquake system science research. We believe a collection of well-tested and well-verified software, like SCEC's existing software ecosystem, will be critical to future earthquake system science research. A future research center could extend the SCEC software ecosystem to produce immediate results for new regions, at higher resolutions, on larger scales.

Table 1: Essential Components in an Earthquake System Science Software Ecosystem

	Earthquake System Science Software Component	**SCEC Community Codes**	**Software Reference**
1	Earthquake catalog processing	CSEP	Schorlemmer et al., 2018
2	Regional fault models	SCEC CFM v5.3	Shaw et al., 2015
3	Regional seismic velocity models	SCEC CVM-H v15.1 SCEC CVM-S4 SCEC CVM-S4.26	Shaw et al., 2015 Magistrale et al., 2000 Lee et al., 2014
4	3D Earth model viewers	SCEC-VDO CXM Website	Milner et al., 2016 Su et al., 2019
5	Simulation meshing tools	UCVM	Small et al., 2017
6	Ground motion prediction equations	OpenSHA	Field et al., 2003
7	Kinematic rupture models	Graves and Pitarka UCSB Method Song Method EXSIM Method Irikura Recipe	Graves et al., 2016 Crempien et al., 2015 Song, 2016 Atkinson et al., 2015 Irikura et al., 2011
8	Dynamic rupture models	AWP-ODC SORD	Olsen et al., 2008 Ely et al., 2009
9	Ground motion time series processing	ts-process Broadband Platform	github/SCECcode/ts-process Maechling et al., 2015
10	1D kinematic wave propagation codes	Graves and Pitarka UCSB Method EXSIM Irikura Recipe	Graves et al., 2010 Crempien et al., 2015 Atkinson et al., 2015 Irikura et al., 2011
11	Broadband (deterministic/stochastic) ground motion models	Graves and Pitarka BBToolbox EXSIM UCSB Method Irikura Recipe	Graves et al., 2015 Olsen et al., 2015 Atkinson et al., 2015 Crempien et al., 2015 Irikura et al., 2011
12	Non-linear site response models	SVM GP	Shi et al., 2018 Stewart et al., 2016
13	3D deterministic wave propagation	AWP-ODC Hercules 3D-EWP	Cui et al., 2010 Tu et al., 2006 Graves, 1996
14	Full 3D tomography	F3DWI	Lee et al., 2013
15	Earthquake cycle simulators	RSQSim	Richards-Dinger et al., 2012
16	Earthquake rupture forecast	UCERF3-TI UCERF3-TD	Field et al., 2014 Field et al., 2015

17	Standard PSHA	OpenSHA	Field et al., 2003
18	Physics-based PSHA	CyberShake	Graves et al., 2011
19	Short-term earthquake forecasting	OpenSHA-ETAS	Field et al., 2017
20	Earthquake forecast evaluation methods	CSEP	Savran et al., 2018
21	Hazard and risk earthquake response	OpenSHA	Porter et al., 2017

(3) Possible Center Organizational Structures

The center should be organized as a scientific and engineering research institute with expertise in physics-based earthquake research and in broad-impact seismic hazard information. The new center's organizational plans must look both outward and inward. Outward looking plans will define a role for the center within the wider scientific community, within the academic research community, with scientific computing and data facilities, with research funding organizations, and with governmental and commercial end-users of seismic hazard information. Inward looking plans will define an organizational structure that can identify productive research targets, determine research priorities, coordinate a wide range of collaborative research, communicate research results to stakeholders, develop the next generation of researchers, and attract and retain talented staff within an organizational structure that offers professional growth for both academics and non-academics.

Future earthquake center funding levels and distributions should reflect the increased importance of software in geoscientific research. The center should establish funded collaborations between geoscientists, computer scientists, and software developers to ensure that the center benefits from the specialized knowledge of these experts. Ground motion research has benefited greatly from collaborative research with high-performance computing software experts. Advanced research by a future earthquake research center is likely to require collaborations with many additional software, computing, and data experts.

The center should include a software staff that is capable of modifying, verifying, validating, and operating a software ecosystem to perform large-scale community research calculations. As the number of research codes increases, the center staff may not be able to perform all required software development. In this case, the role of the center software staff should shift from developing new software to coordinating development of the software ecosystem. The center staff can encourage contributions from external researchers by specifying the needed software, defining software evaluation criteria, and identifying validated software versions. In this approach, the center provides the scientific authority behind the applications in the software ecosystem, and the research community provides the wide-ranging scientific expertise needed to maintain, operate, and extend essential research software.

As part of a sustainability strategy, the NSF should encourage other federal agencies and commercial organizations to contribute financial resources to the center. If the center is supported by multiple funding sources, the center leadership must coordinate the interests of all contributors and maintain the appropriate balance of center activities.

To be effective, the center will need significant participation by the earth science communities that develop earth and ground motion models, by the civil engineering communities that use seismic hazard information, by high-performance computing software and data experts, and by government agencies responsible for the development, review, and release of public seismic hazard information. A research center working to improve broad impact earthquake ground motion forecast information opens possibilities for new sustainability models. A research program focused on producing well-validated seismic hazard products using best available methods could lead to new sources of financial support from ground motion forecast stakeholders including emergency response planners, civil engineers, federal agencies, and private companies.

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