Comment to NSF on upcoming earthquake center

“Earthquake simulators in studies of earthquake physics and hazard”

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Summary

Earthquake simulators are poised to play a transformative role in future integrative earthquake science studies. They are ready to contribute in three major ways. One, they provide a platform for bringing together different disciplinary elements and examining the compatibility and implications of these ingredients. Two, they provide a platform for testing our physical understanding of the system, and a tool to examine emergent aspects of these ingredients. Three, they provide a tool for exploring, estimating, refining, and mitigating seismic hazard, a core task of broad societal significance. An earthquake center can provide key support for the full range of integrative interdisciplinary activities which can foster the development of and take advantage of these capabilities. We discuss these points in more detail in what follows.

Earthquake simulators

Earthquake simulators provide a central integrative platform for testing our understanding of earthquake physics, simplifications and approximations of the physics, and its implications. A key goal of earthquake simulators is to reproduce the full suite of complex earthquake behaviors from a deterministic representation of earthquake physics over a wide range of length and time scales. This is a different, but complementary set of questions, than those being asked by efforts aimed at modeling the range of earthquake source processes [see “Modeling earthquake source processes in California: building on SCEC success in integrating numerical, field, and laboratory studies” (Lapusta and Dunham)].

A central challenge in the simulator effort is that finite computational resources preclude a straightforward simulation of the elastodynamic equations if we are to reach the broad range of space and time scales relevant to long term hazard. Thus approximations are needed. Much as climate models do not support the full spectrum of inertial waves in weather models, earthquake simulators make approximations which are aimed to retain the essential dynamical character while allowing for a vast speedup computationally. The test of the validity of the approximations, and the sufficiency of the included physics, is in a large array of tests of behaviors against observations. A series of Turing tests are used to validate the models against earthquake observations. If we can pass a gauntlet of tests, the simulator output can be useful in a number of ways.

Platform for integration and testing of earthquake physics.

Earthquake simulators provide a setting where we can combine many of the key anticipated ingredients of the system, including the faults, deformation, and dynamics, and examine the interactions and implications of the different ingredients. In California where we have the best observational foundation, the ingredeints have been developed through a broad coordinated community effort spearheaded by the SCEC center. Finding a model which can reproduce the full suite of earthquake behaviors from a deterministic dynamics means a number of things. One, we have a possible sufficient description of the underlying processes. This does not mean it's the only one, but even finding one is hugely valuable. Two, if we have the ability to simulate complex synthetic catalogs which reproduce the richness of earthquake behaviors, there are a variety of uses for them. Among them are:

- Testing and honing algorithms for analyzing real earthquakes in a setting where limited statistics and noise do not limit things.
- Extrapolating from regions which are observationally well constrained to regions with poor statistical constraints (e.g. large earthquake's close in, and multiple cycles).
- Tesing sensitivity and robustness of results to physical parameters.

Advantages of a center

A center can help foster earthquake simulator development in a number of ways that smaller scale efforts are less suited to support. Vertical and horizontal integration are two ways. Vertical integration involves taking the wide array of input ingredients, feeding it through the simulators, and then connecting the simulator output onwards through a series of processes to connect to downstream ground motions, hazards, and risk. Each layer requires multidisciplinary efforts, and is hard to span at the typical scales of individual PI and small collaboration networks. A center provides an excellent setting for fostering these wide ranging collaborations. Additionally, many of these applications require High Performance Computing (HPC). SCEC has been a tremendously valuable partner in developing a sophisticated nationally recognized team tackling these problems. Support for HPC capabilities should be part of any future center with the ambitions to contribute to these societally significant areas.

Horizontal integration, through comparisons and combination across different models is another aspect a center is especially well-suited to cultivate. Again climate modeling provides a good reference point, where we see model inter-comparison and ensemble model forecasts have pushed the science and applications forward. Horizontal integration is an extension, and in many ways an even more difficult challenge then the highly successful code validation exercises initiated and nurtured by the SCEC center already, where precise agreement was the goal and measure of the comparisons. Here, where approximations are essential, and different ones desirable, and the goal is to reproduce a variety of complex behaviors, statistical comparisons become essential. How to do this, which problems, phenomena, and measures to use, what constitutes agreement and range of valid differences, would benefit from broad community participation and coordination. A center can provide the support and focus that would be difficult to cultivate in a more dispersed individual organizational model. Having a broad range of models participating in inter-comparison projects helps improve the models, and provides a setting for ensemble combinations of models, which typically perform better than individual models.

Earthquake simulators and Hazard

Finally I would like to speak to simulators and hazard. In an unanticipated leap forward, deterministic simulators have been shown to replicate hazard estimates from the best current statistical models [Shaw et al., *Science Advances*, 2018]. This agreement has been found across a wide range of hazard measures of central engineering interest. This is an important result for a number of reasons. Current statistical methods rely on a series of linked uncertain empirical scaling relations and assumptions, with different logic tree branches aiming to catch the range of epistemic uncertainties at each level. A proliferation of branches (more than a thousand in the latest UCERF3 California model), and a construction which does not take into account correlations of parameters at different branch levels adds uncertainties to the approach. Replicating the hazard results using a completely different method, a form of triangulation, provides a strongly increased confidence in the hazard estimates. It also gives a new method for estimating hazard needing fewer inputs and assumptions. This opens up a new avenue for ensemble forecasting using a variety of approaches, something expected to better span epistemic uncertainty space. If this approach is to be used in next generation hazard maps, it will need broad community scrutiny, debate, and hopefully consensus. A center can provide an excellent setting where a wide range of voices can come together and grapple with this challenge and opportunity.

A center would also provide a strong community and infrastructure for further developing and testing the ingredients and implications and applications of these results. These types of activities bring together multidisciplinary adaptive collaborations which are uniquely served by a center structure and would be hindered by more traditional smaller scale collaborations under more typical defined participant defined timescale funding arrangements. We often hear of a desire to foster multidisciplinary research and research of broader societal significance. The SCEC center has provided a tremendously productive beacon of success in precisely these hard to realize ways. I urge the NSF to find ways to continute to support this fertile thriving ecosystem.