Ben-Zion, Y., Beroza, G. C., Bohnhoff, M., Gabriel, A.-A., Mai, P. M. (2022): A Grand Challenge International Infrastructure for Earthquake Science. - Seismological Research Letters, 93, 6, 2967-2968.

https://doi.org/10.1785/0220220266

A Grand Challenge International Infrastructure for Earthquake Science

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Seism. Res. Lett.

In press, August 2022

Scientific communities need cutting-edge collaborative observational facilities to test models and to enable ground-breaking discoveries. The acquisition of fundamental new data often leads to transformative advances in research that have significant societal and economic benefits. Grand challenges in physical sciences often require grand facilities. Several communities, not including Earthquake Science so far, have realized grand-challenge facilities. Particle physicists use very large accelerators to study properties of elementary particles. Astronomers send state-of-the-art telescopes to space to improve their observations. Space missions deploy rovers and other instrumentation on nearby planets and space probes to advance planetary sciences. Such efforts involve infrastructure with price ranges in the 10^8-10^9 US dollars or more.

While these efforts are essential to advance our understanding of space, time, and matter, the public is hardly affected in daily life by the outcome of such projects. In contrast, earthquakes and their immediate effects on humankind and the environment have been subject of myth, fascination, and terror for millennia. The same holds for volcanoes and other major geohazards, but here we focus on earthquakes. The potential loss of life and economic damage from seismic events is growing rapidly due to increasing urbanization in seismically vulnerable regions, development of high-risk utility plants, and aging critical infrastructure. The annualized direct economic losses from earthquakes in California alone is estimated at nearly 4×10^9 US dollars and the loss from a single large earthquake (e.g., the 2011 Tohoku-Oki event in Japan) can exceed hundreds of billions of dollars. These large numbers do not account for the ripple effects of direct losses through the economy. Yet, the resources invested in Earthquake Science research are a small fraction of these potential losses, and much less than those invested in the above examples. How can the Earthquake Science community receive the attention from decision makers and funding sources needed to establish grand-research infrastructure that will lead to transformative advances?

Several geophysical initiatives have been realized over the last few decades. These include national or transnational efforts resulting in densely instrumented local facilities (e.g., Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland - KTB, San Andreas Fault Observatory at Depth - SAFOD) and regional monitoring infrastructures (e.g., Hi-net, KiK-net, Plate Boundary Observatory - PBO, USArray, SinoProbe, ChinArray), each delivering key insights on Earth properties and processes. Large observational facilities generate both planned and surprise discoveries and applications. As examples, the establishment of the Hi-net and KiK-net seismic networks in Japan led to the discovery of tectonic tremor now recognized in many regions worldwide, and the continuous recording of the USArray facilitated the development of noise-based seismic imaging which has since found many global applications. Programs and organizations such as the European Plate Observing Systems - EPOS, International Continental Scientific Drilling Program - ICDP, EarthScope, and Southern/Statewide California Earthquake Center - SCEC provide venues and seed funding for international teams of scientists to develop research projects. However, far larger efforts are required to address the fundamental problems in Earthquake Science, such as the limits to the predictability of large earthquakes and the intensity of hazardous ground motions, which are essential for seismic risk mitigation.

Large earthquakes occur on time scales of a century or more even in seismically active areas, and actionable earthquake prediction has proven elusive. The cure for cancer and other diseases is also elusive but the medical establishment has ongoing research on these topics. Similarly, the Earthquake Science community should continue to address earthquake prediction and other fundamental problems of Earthquake Science. With sparsely instrumented observation systems, each new significant earthquake is not well recorded, and the Earthquake Science community does not benefit from the potential detailed information and insights necessary to make fundamental progress. Much denser and integrated observations are needed to advance research through data analyses, computation, and model development, to gain fundamental new insights into earthquake processes and significantly improve mitigation of seismic risks.

We call for an international initiative to develop a grand infrastructure that will transform the current understanding of earthquakes, their effects on nature, the built-environment, and society in general. The envisioned infrastructure would consist of 5-10 natural laboratories focused on geo-hazard hot spots involving transform fault systems in continents and oceans. In continents, earthquakes are shallow, near-field observations are most feasible, and threats to major population centers are immediate. In oceans, the geology is more homogeneous, influences on physical processes may be more easily discerned, and experiments involving deliberately triggering earthquakes of different size can be done with little risk to populations. Example locations on continents include sections of the San Andreas, North Anatolian, Alpine, and Dead Sea transforms, and in oceans the Gofar, Sea of Cortez, and Red Sea transforms. We note that subduction zones are the subject of another major initiative, Subduction Zone Hazards in 4 Dimensions - SZ4D, which will be complementary to our proposed transform fault infrastructure towards a unified global understanding of earthquakes.

Each natural laboratory of this international initiative will have dense networks of seismic and strain sensors at the surface, accompanied by several well-instrumented boreholes extending to depths of a few km at representative crustal locations. The dense surface networks will provide near- and far-field data at unprecedented resolution, while the boreholes sensors will increase the resolution of seismogenic processes and provide valuable information on properties of the top crust affecting strongly seismic ground motion. The instrumental facilities will be augmented by the development of "digital twins" that will be used to simulate evolving deformation fields, which will be tested iteratively against the data. The "big data" streams generated in the observatories will be fused, compared, and assimilated with models to better understand commonalities and variability in earthquake processes and seismic motion. These activities will utilize supercomputers worldwide, which are already used to model earthquakes and their impacts, while exploiting and contributing to exascale computing and big data.

The energy exploration industry routinely performs observational studies exceeding current capabilities of the academic community. In parallel with our efforts to obtain resources to conduct highly detailed observations, we should strengthen connections with industry to increase sharing of data for academic research. The recent data sharing from the dense industry seismic survey using thousands of seismic sensors in Long Beach, California, with academic researchers has led to numerous methodological developments and a range of important results on the structure of the Los Angeles basin and detection of small events. The (re)insurance, real-estate, and large companies relying on vast multi-faceted infrastructure in large metropolitan areas stand to gain significantly from new knowledge on earthquake processes and strong ground motion. The Earthquake Science community should increase efforts to have partners from local, state, and national government agencies, industry, utility companies, and other stakeholders to develop together, for the first time, a grand infrastructure for earthquake research on the scale accomplished by a few other communities.

The development of the envisioned grand facility will revolutionize the state of knowledge about earthquake processes, Earth and fault structures, crustal rheology, and seismic ground motions. The new level of observations and knowledge will enable many novel, data-driven and physics-based, applications for reduction of seismic risks, including advanced early warning and engineering response systems to protect critical infrastructure (e.g., nuclear and hydroelectric power plants; water, electricity, gas, and communication networks; road and rail transportation systems, air- and sea- ports, buildings and underground structures) needed to sustain communities and the economy, and most importantly save lives.

Data and Resources

The paper does not include data analysis. The estimated economic losses are from the FEMA report https://www.fema.gov/sites/default/files/2020-07/fema_earthquakes_hazus-estimated-annualized-earthquake-losses-for-the-united-states_20170401.pdf.

Acknowledgements

The text benefitted from comments by an anonymous referee and editor Allison Bent.