China Seismic Experimental Site (CSES): Challenges of Deep Earth Exploration and Practice (DEEP)

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Since May 2018, the planning, construction and functioning of China Seismic Experimental Site (CSES) has attracted much attention in earthquake science (CSES, 2020a, b, c; Wu, 2020; Li et al., 2021). Different from traditional earthquake prediction experiment projects, such as the Parkfield earthquake prediction experiment (Roeloffs, 2000), the Turkish dilatancy project (TDP, Evans et al., 1987), the Tokai earthquake prediction experiment (Mogi, 2004), and the induced seismicity experiments in Koyna (Gupta, 2018), CSES emphasizes the 'broad spectra' of scientific problems from the tectonics and physics of earthquakes and faulting to the engineering countermeasures for disaster risk reduction to much extent. CSES focuses on not only earthquake system science as those done by the Southern California Earthquake Center (SCEC, Jordan, 2006), but also the systems engineering which deals with the designing, integrating, and management of the 'system of systems' over their life cycles (Wu and Li, 2021).

Location of CSES is within the range 97.5°–105.5°E; 21.0°–32.0°N, bordered in the south by the territory of China. Since 1965, on average there have been 14 $M \geq 6.0$ (including 3 $M \geq 7.0$) earthquakes for every 10 years, which provides earthquake science experiments with unique opportunity to carry out close-in observations of earthquake phenomenology and verify scientific hypotheses based on the exchange and cooperation of in-house physical experiments, numerical experiments, and field experiments. CSES aims to construct a natural laboratory to facilitate interdisciplinary, multi-institutional, and international studies on earthquakes and associated natural disasters (Fig. 1). The mission of such a natural laboratory is to provide worldwide colleagues with the backbone (observational facilities), background (information for further studies), and baseline (for testing the variations with a shorter time scale). Apparently Deep Earth Exploration and Practice (DEEP), as well as its theoretical framework, plays an essential role in CSES.

Based on a 'community discussion', the priorities to be considered in CSES include (CSES, 2020a): 1) What is the relation between the distribution of major earthquakes and lithospheric structure? 2) Are there any observable structural variation associated with earthquake preparation process? 3) What control the segmentation and cascading rupture of the fault systems in the Sichuan-Yunnan region? 4) How to enhance the resolution of the characterization of a fault system? 5) What is the current state of movement of the fault systems in the Sichuan-Yunnan region? How to constrain the creeps by observation? 6) What useful information could be provided by paleo-seismology of a fault system? 7) How to construct the numerical stress-strain model? What is the effect of the subduction of the Burmese arc on the stress state of the Sichuan–Yunnan region? 8) Are there any low-frequency earthquakes and/or non-volcanic tremors in the continental environment? 9) How to constrain the nucleation of earthquake rupture by observations? 10) Are there any direct evidence to constrain the Coulomb failure stress (CFS) changes, calculated indirectly by earthquake models? 11) What is the relation between the measurements of stress (variation) by seismological, geodetic, and other methods, respectively? 12) What is the relation between the precursory variation of the geochemistry of ground fluid/gas and the pre-earthquake process of stress variation? 13) What are the key ingredients of the numerical models of the geodynamics of earthquakes? What is the roadmap to implement 'numerical earthquake forecast'? 14) What is the role of earthquake disaster scenario in the reduction of seismic disaster risk? 15) What are the special and general characteristics of the seismic destruction to civil engineering in the Sichuan-Yunnan region? How to evaluate the performance of the engineering countermeasures? 16) How to prevent the secondary disasters of major earthquakes associated with the along-stream series reservoirs? 17) What are the key factors and critical countermeasures determining the seismic disaster resilience of urban areas? 18) What is the relation between artificial engineering activities and induced/triggered seismicity?

One of the goals of CSES is to establish a cyber-environment of earthquake simulation and forecast, similar to the Uniform California Earthquake Rupture Forecast (UCERF) system (Field et al., 2014). But the basis of such a system relies on the results and capabilities of DEEP.

Current challenges of DEEP in CSES include, but are not limited to:

1) Community models of fault systems, Earth

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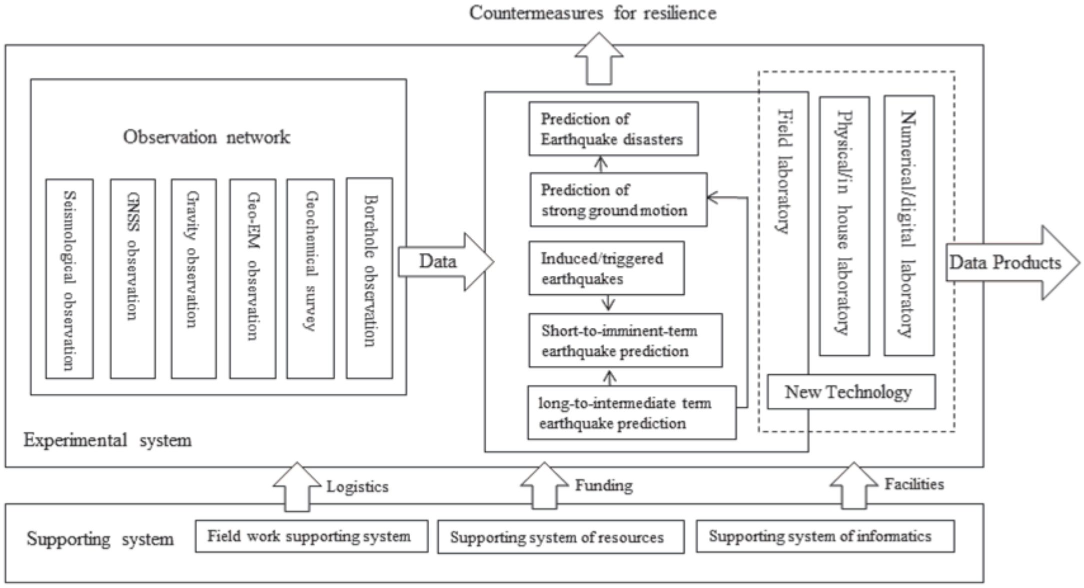

Fig. 1. Conceptual diagram of China Seismic Experimental Site (CSES).

structures, and engineering sites;

2) Characterization of stress state and its spatio-temporal variations;

3) Physics and chemistry varieties of earthquake fault from kilometer scale to nanometer scale;

4) Co-seismic and pre-seismic structural variations;

5) Relation between resource engineering and triggered/induced seismicity.

The showcase first generation CSES community models (CSES, 2020b, c) may be a manifestation of the role of DEEP in CSES, and a basis for DEEP to further contribute:

-Community velocity model (DOI:10.12093/02md.02.2019.01.v1), by the team of China University of Science and Technology, including 3-D Vp and Vs structure in the crust, with vertical resolution better than 10km and horizontal resolution better than 50 km above 40 km depth, and vertical resolution better than 10-15km and horizontal resolution better than 70km below 40 km depth;

-Community fault model (DOI:10.12093/04md.02.2019.02.v1), by the team of the Institute of Geology of China Earthquake Administration (CEA), including surface faults, reflection profiles, focal mechanisms, relocated micro-earthquakes, MT sounding images, and borehole measurements, from geological maps, remote sensing images, geophysical survey, and field investigation of earthquakes.

-Community deformation model (DOI:10.12093/03md.02.2019.04.v1), by the Team of Guangdong Institute of Technology, including velocity and strain rate, based on the GPS measurements at about 500 stations;

-Community rheology model (DOI:10.12093/04md.02.2019.03.v1), by the joint team of the Institute of Earthquake Forecasting of China Earthquake Administration (CEA) and the Second Center for Monitoring and Survey of CEA, including the viscous coefficients at depths 20, 40, 60, and 80 km, and the cross sections crossing the eastern border of the 'Sichuan–Yunnan diamond', considering both deformation measurements and geothermal constraints.

Scientific field investigation of significant earthquakes opens the window to the close-in study on what happens before, during and after the earthquakes, in which DEEP is one of the important components. Traditional organization of DEEP in the scientific field investigation can be developed into a 'modernized' way with better efficiency, with the ideas of 'scenario-earthquake-rupture and planning' as a reference. That is, even if an earthquake has not occurred, exploration of its 'seismogenic' fault can still be conducted with the reference of the 'scenario-earthquake-rupture'. Most importantly, if the earthquake occurs at last, the comparison between the pre-earthquake measurement and the post-earthquake survey will provide useful information about the whole process of the preparation and occurrence of the earthquake. This is a significant weak point of earthquake science at present time, which leads to the difficulties of earthquake prediction to much extent.

Working on scientific problems, CSES also acts as a test site of new instruments and observation/detection systems to finish their 'last mile' to be put into practice, which means the enhancement of their technical readiness level (TRL) from 7 to 9. This implies that the cooperation between CSES and DEEP has broad space to be explored.

But the more important agenda for CSES and DEEP to cooperate lies in that, as pointed out by Prof. DONG Shuwen, PI of SinoProb (personal communication, 2018), in the environment of deep Earth with high pressure and high temperature, properties of materials are very different from what to be known in the environment of 'normal' pressure and 'normal' temperature. Deep within the Earth, iron and water are no longer the same as we are familiar with, and similarly, an earthquake rupture is probably different from the rock failure experiment in our laboratory. This calls for the conducting of field experiments in the natural laboratory, and calls for the in-depth exchange and collaboration between CSES and DEEP.

Last but not the least, selecting a region with active seismicity and carrying out observations and earthquake prediction experiments does not mean the establishment of a seismic experimental site, which is proved by the lessons of earthquake prediction experimental sites in the past decades. As a matter of fact, just consider the duration of an earthquake cycle being much longer than the lifetime of human, experiments of earthquake science have the feature of game-playing (in the sense of game theory) between human being and earthquakes. This indicates that the design, construction, operating, and upgrading of an experimental site in earthquake science has to consider the necessary attributes which make the concept for natural laboratory (Box.1). Such a consideration is also useful when dealing with not only one but also several seismic experimental sites to meet the challenge of earthquake studies. The first challenge is the dearth of large earthquakes in a specific place of experiments, which is to be solved by considering more places to compensate our limit of time. The second challenge is that too many factors affect the preparation and occurrence of earthquakes, which is to be solved by considering a kind of coordinated distributed experiments (CDEs, Fraser et al., 2012; Wu et al., 2019).

Box 1 The '$C5^2$ model': Attributes of a seismic experimental site

Community Scientific Problems List (CSPL)
Community X Models (CXM)
X = Structure, Stress, Deformation, Rheology, Thermal, etc.
Community Earthquake Models (CEM)
Community Scientific Forecast for Falsification (CSF^3)
Community Accepted Technical Test (CATT)

Coordinated Distributed Capacity-Building Plan (CDCP)
Coordinated Distributed Data Centers (CDDC)
Coordinated Distributed Computational Bases (CDCB)
Coordinated Distributed Project 'Ecology' (CDPE)
Coordinated Distributed Experiments Proposal (CDEsP)

Key words: Deep Earth Exploration and Practice, community models, China Seismic Experimental Site

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