The APEC Cooperation for Earthquake Simulation (ACES)

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Overview

ACES aims to develop realistic supercomputer simulation models for the complete earthquake generation process and to assimilate observations into such models. This capability provides a powerful "virtual laboratory" to probe earthquake behaviour and the earthquake cycle. Hence, it offers a new opportunity to gain the understanding of the earthquake nucleation process, precursory phenomena, and space-time seismicity patterns needed for breakthrough advances in earthquake forecasting and hazard quantification. The simulation approach can be compared to that of the successful Global Climate Models that are used to understand and predict long-term climatic conditions. The project represents a grand scientific challenge because of the complexity of phenomena and range of scales from microscopic to global involved in the earthquake generation process. It is a coordinated international effort linking complementary national programs, centres and research teams.

Objectives

- To develop realistic numerical simulation models for the physics and dynamics of the complete earthquake generation process and to assimilate new earthquake observations into such models,
- to foster collaboration between the relevant complementary national programs of participating member economies, and
- to foster development of the required research infrastructure and research programs.

Motivation

Earthquakes are one of the most costly and deadly natural disasters with the vast majority striking Member Economies of the Asia-Pacific Economic Cooperation (APEC) – Figure 1. The scientific method relies on development of a theoretical framework or simulation model describing nature. While no such model exists for the complete earthquake generation

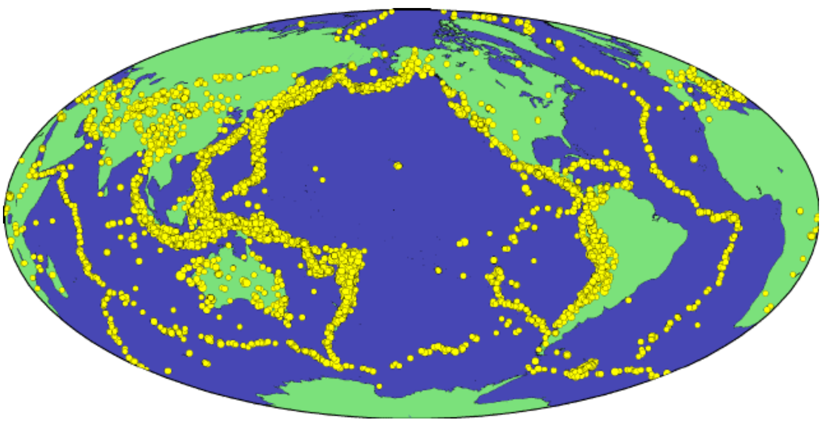

Figure 1: Distribution of earthquakes from 1900-1997 with magnitude greater than 5 (reprinted from [1]).

process, conceptual developments in understanding earthquake physics, numerical simulation methodology and advances in High Performance Computing offer the possibility to develop such models. After several years of discussions between scientists of Australia, China, Japan and USA starting in 1995, The APEC Cooperation for Earthquake Simulation (ACES) was established under APEC to capitalize on this new opportunity and the complementary strengths of the different national earthquake research programs. It aims to develop numerical simulation models for the complete earthquake generation process. This task represents a grand scientific challenge because of the complexity of phenomena and range of scales involved from microscopic to global (Figure 2). The models will provide powerful new tools for studying earthquake precursory phenomena and the earthquake cycle. They have direct application to earthquake hazard studies and earthquake engineering, and the potential to yield spin-offs in industrial sectors such as mining, geophysical exploration, high performance computing applications, material science, engineering and geotechnical.

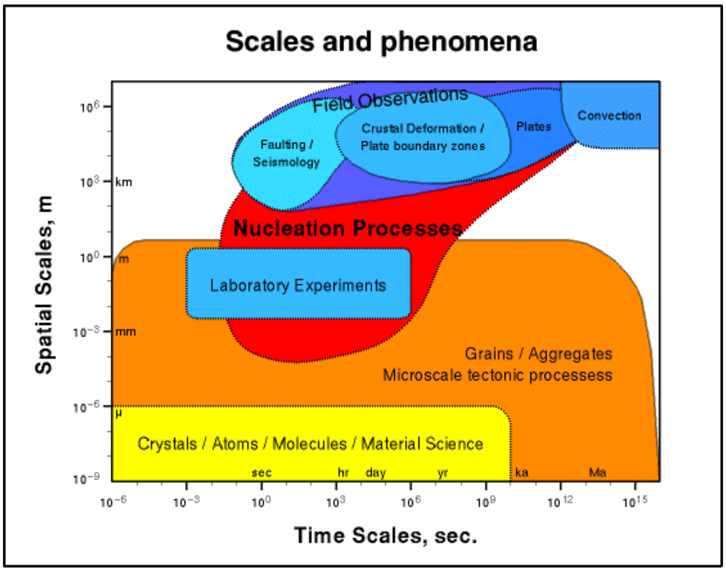

Figure 2: Scales and phenomena involved in the earthquake generation process (reprinted from [1]).

Science Plan

The ACES Science Plan is to develop physically based numerical simulation models for the complete earthquake generation process and to assimilate observations into these models. The models aim to simulate all physical and chemical processes in the solid earth at all time and space scales relevant to the earthquake cycle. The final goal is to develop a unified simulation model for the earthquake generation process and earthquake cycles. This model will consist of regional models in each of the different tectonic settings:

- Transcurrent regimes or transform plate boundaries (e.g. California, New Zealand),
- Subduction zones (e.g. Chile, Mexico, Alaska, Kurils, Japan, Indonesia),
- Intraplate regions or continental plates (e.g. Australia, China, central and eastern USA).

The simulation models will provide a new means to probe earthquake behaviour and the associated physical processes. They will allow theoretical forecasts of the earthquake cycle and related processes to be computed. This predictive modelling capability for solid earth phenomena represents a powerful tool for the development of new model applications and improved earthquake data analysis systems. The Science Plan will be achieved through the activities of seven Science Working Groups termed WG1 through WG7 consisting of multi-institutional international research teams. WGs 1-5 aim to develop physically based numerical simulation models, WG6 aims to assimilate data observations into the models and WG7 aims to develop new applications such as earthquake and catastrophic failure forecasting. Figure 3 illustrates the feedback process that will ensure the simulation models are developed such that their theoretical forecasts (e.g. of the earthquake cycle) are compatible with, and constrained by, the observed data. Figure 4 illustrates how ACES adds to, and is complementary with, pre-existing earthquake prediction and/or hazard quantification programs and systems based on data gathering and analysis.

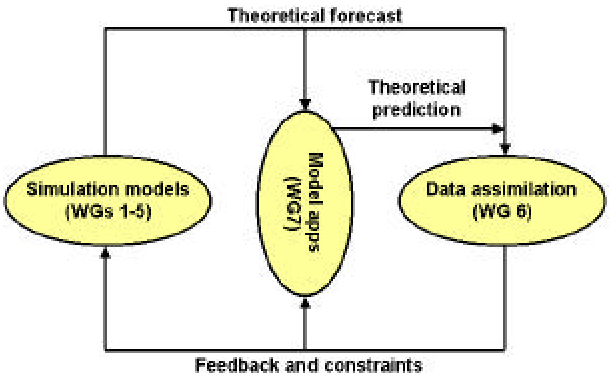

Figure 3. The ACES Science Plan involves a feedback process to ensure simulation models are developed which yield theoretical forecasts compatible with, and constrained, by the observed data. The theoretical forecasts are used to develop new applications or forecasting methods which are also refined through a similar feedback process.

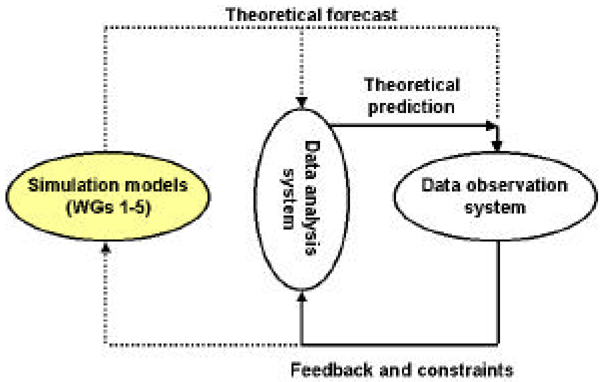

Figure 4. Illustration of how ACES adds to, and is complementary with, pre-existing earthquake prediction and/or hazard quantification programs and systems, which are based on data observation and analysis (shown in white).

History and establishment of ACES

- **1995:** *Discussions commence* on an international initiative to simulate the physics of earthquakes on supercomputers and establishment of a major parallel supercomputer facility in Australia for this purpose.
- **1996:** *Draft proposal circulated* within the international community for simulating the physics of earthquakes.
- **August, 1997:** *Project Planning Meeting held* in Brisbane with representation from Australia, China, Japan and USA to develop a formal proposal to APEC for establishment of the international cooperation for earthquake simulation.
- **October, 1997:** *Formal endorsement of The APEC Cooperation for Earthquake* at the Singapore Meeting of the APEC Industrial Science and Technology Working Group with sponsorship by Australia (the originating economy), China, Japan and USA.
- **December, 1997:** *International Science Board (ISB) nominated* by each of the four founding member economies of ACES (Australia, China, Japan and USA).
- **May, 1998:** *Inaugural ISB meeting held to develop detailed framework for cooperation*. Key outcomes include development of By-Laws, agreement of structure and voting in of ACES Executive Director.
- **August, 1998:** *Executive Office for ACES established at QUAKES*, The University of Queensland to act as ACES HQ and a focal point for a visitors program. The Executive office commenced organization of the Inaugural ACES workshop to initiate scientific co-operative activities.
- **January, 1999:** *Commencement of Activities* – Inaugural workshop held in Brisbane and Noosa, Queensland Australia.

Management structure

The management structure is summarised by Figure 5 with key components detailed below.

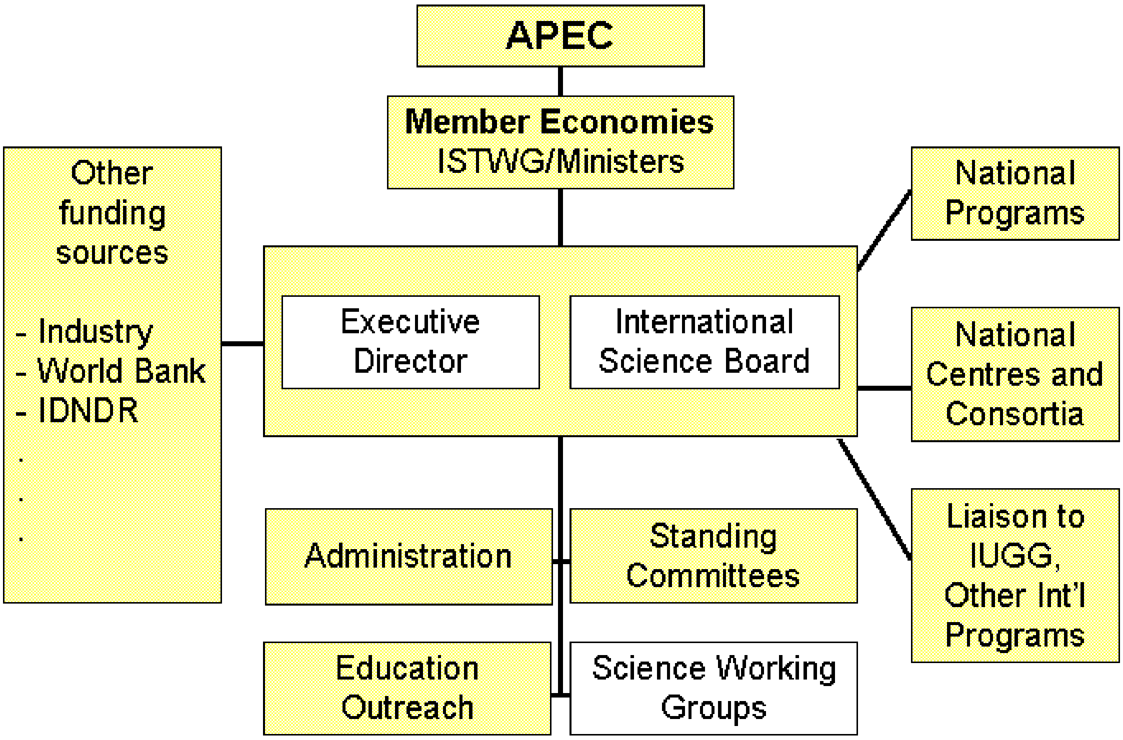

Figure 5: Management diagram for ACES.

The Executive Director is responsible for the management of the Project including implementation of the strategic goals and resource management. The Executive Director reports to the APEC ISTWG and through that, to Regional S&T Ministers on progress of The Project. Executive powers are specified in the By-Laws established by the International Science Board.

Executive Office: The Executive Office acts as ACES Headquarters and plays the role of coordinating ACES activities and acting as a central point for scientific interchange via a Visitors Program. The Executive Office operates through a combination of pooled resources obtained from Participant Economy contributions, funding for specific events and activities supplied by ACES participants, and other funds raised by the Executive Office.

The International Science Board (ISB) consists of one representative nominated by each participating member economy and is responsible for developing the program of activities. Each ISB Member is responsible for coordinating between The Project and the relevant research programs, centres and consortia of the member economy being represented.

Science Working Groups established by the International Science Board conduct scientific research to address the different components of the scientific problem.

Standing Committees are established as the need arises to address non-scientific issues that may need to be resolved to achieve the goals of The Project.

Participant economies are responsible for nominating a representative to the International Science Board who would be the liaison between ACES and the activities of the member economy associated with The Project.

Core participants or members are APEC Member Economies, Countries, Institutions, Research Centres or Research Groups who make a major commitment to participate in, and contribute to, ACES. The ISB will vote on whether new members participation constitutes core participation. Core participants will have a voting seat on the ISB. The mode and level of participation is flexible such as cash contributions to the pooled operating funds or other significant commitments. Yearly cash contributions to the pooled operating funds by an amount comparable to those of other core participants (approx $US 21,000 in 2000) ensures full membership and core participant recognition, and is the preferred mode of participation. For such full members, ACES will fund attendance of ISB representatives at International Science Board meetings and core participation of key researchers at workshops and working group meetings. The number of full member researchers funded by ACES depends on the pooled funding resources available to the Executive Office and costs of attendance. During 1999 and 2000, ACES funded full member's participation of 8-10 researchers at major workshops and 2-3 researchers at WG meetings. A similar level of support for full member's core participation at future meeetings is expected to continue.

Associate participants are APEC Member Economies, Countries, Institutions, Research Centres or Research Groups who are interested in participating in ACES. The mode and level of participation is totally flexible. Associate participants receive a non-voting seat on the ISB.

Process to join ACES: Economies or countries that wish to join ACES as a participant Economy must express their wish in writing to the International Science Board through the Executive Director, and agree to comply with the By-Laws and any related understandings between the relevant government agencies. Participating member economies are responsible for nominating a representative to the International Science Board who would be the liaison between ACES and the activities of the member economy associated with The Project.

Science Working Groups

Seven Science Working Groups (WGs) have been established with five relating to construction of physically based numerical simulation models for the earthquake generation process and the remaining two respectively for data assimilation and model applications. Working group leaders are nominated by each participating economy. The role of WG leaders is to coordinate and animate interaction and collaboration within their Working Group, including identification of WG goals & activities and organisation of WG sessions at ACES workshops.

WG1: Microscopic simulation
WG2: Scaling physics
WG3: Macroscale simulation/Earthquake generation and cycles
WG4: Macroscale simulation/Dynamic rupture and wave propagation
WG5: Computational environment and algorithms
WG6: Data assimilation and understanding
WG7: Model applications to space-time earthquake hazard quantification

WG1: Microscopic simulation working group

WG leaders: Peter Mora (QUAKES, Australia), Yilong Bai (LNM, China), Terry Tullis (Brown University, USA), Teruo Yamashita (ERI, University of Tokyo, Japan)

Aims:

- Development of microscopic numerical simulation models for the elementary physical and chemical processes and study of fault rheological properties and constitutive relations.
- Gain understanding of scaling from microscopic to larger scales.

Functions:

Micro-model construction (physical/chemical processes). Study of micro-mechanisms and emergent behaviour, fault zone constitutive laws, damage mechanisms, rupture nucleation, granular mechanics (fault gouge), and the frictional instability.

WG 2: Scaling physics

WG leaders: Miti Ohnaka (ERI, University of Tokyo, Japan), Bill Klein (Boston University, USA), Meng-Fen Xia (Peking University, China)

Aim:

- Develop theory and understanding of emergent behaviours resulting from the underlying physics and nonlinear dynamics of fault zones and crustal fault systems.

Functions:

Study of scaling domains, emergent behaviors, role of fluctuations & fundamental physics, field theories, multi-scale, and multi-resolution physics.

WG3: Macro-scale simulation/Earthquake generation and cycles

WG leaders: Kazuro Hirahara (Nagoya University, Japan), Steve Day (San Diego State University, USA), Yong-Xian Zhang (CAP, CSB, China)

Aims:

- Develop macroscopic domain numerical simulation models for the earthquake generation process (based on continuum mechanics) including the complete cycle from tectonic loading, quasi-static rupture nucleation, to dynamic rupture, to fault lithification and healing.
- Gain understanding of: (i) the earthquake cycle & crustal movement, and (ii) seismicity & spatio-temporal patterns of interacting fault systems.

Functions:

Construction of macroscopic domain numerical simulation models for long time scale processes and the earthquake cycle. Study of macro-phenomena including stress transfer, long range interactions in fault systems, effective constitutive laws (consequences), dynamic rupture processes, and the earthquake cycle.

WG4: Macro-scale simulation/Dynamic rupture and wave propagation

WG leaders : Kim Olsen (UCSB, USA), Takasi Furumura (ERI, University of Tokyo, Japan)

Aims:

- Develop macroscopic domain numerical simulation models for short time scale dynamic processes including dynamic rupture, wave propagation and strong ground motion.

- Definition of standard models in different tectonic settings.

Functions:

Construction of macroscopic domain simulation models for short time scale processes and wave propagation. Definition of standards including "standard earth models" in different tectonic settings, code standards, data repositories, data formats, and attenuation functions.

WG 5: Computational Environment and Algorithms

WG leaders: Geoffrey Fox (Syracuse University, USA), David Place (QUAKES, Australia), Hiroshi Okuda (University of Tokyo, Japan), David Yuen (Minnesota supercomputer center, USA), Nai-Gang Liang (CAP, CSB, China)

Aim:

- Development of computational methods and algorithms for the simulation models, and common tools/routines for their computation on super-parallel computer systems.

Functions:

Development of numerical algorithms, algorithms catalog & handbook, computational environment…distributed computing, collaboratories, XML, CORBA, objects, web-based computing, parallel computing and visualization technologies.

WG 6: Data assimilation and understanding

WG leaders: Andrea Donnellan (NASA JPL, USA), Takeshi Sagiya (Geographical Survey Institute, Japan), Sheng-kui Zhou (CAP, CSP, China)

Aim:

- Compare theoretical forecasts of numerical simulation models to data observations and use these comparisons as a basis to gain insight into the earthquake cycle and earthquake behaviour. Provide feedback to the Simulation Working Groups needed for the model refinement process. Data may include "real-time data" and "static data". Examples include seismicity, laboratory/rock physics, crustal deformation/GPS, geo-elasto-magnetic, electro-magnetic emissions, groundwater, and earth structure.

Functions:

Data inversion, pattern processing, data mining tools development and application.

WG 7: Model applications

WG leaders: Xiang-chu Yin (CAP, CSB, China), Hans Mühlhaus (CSIRO, Australia), Dave Jackson (UCLA, USA), Naoshi Hirata (ERI, University of Tokyo, Japan)

Aims:

Development of applications using new simulation capabilities such as earthquake forecasting, space-time hazard quantification, strong ground motion prediction, scenario modelling, and industrial applications.

Functions:

Strong ground motion studies, earthquake forecast tests and evaluations, benchmarks – model "shoot-outs", define set of standard problems, industrial/engineering applications …dams, buildings, structures, built environment, geophysical exploration, mining, geomechanics, materials engineering etc.

Activities

Key ACES activities are major workshops, smaller working group meetings, a visitors program, target/goal related activities identified by Science Working Groups, ISB meetings, publicity, and fundraising and infrastructure development. Reports consisting of a compilation of research papers documents progress (normally published as a workshop proceedings). Additional activities envisaged may include education (eg. development of a regular summer school) and organization of symposia during international conferences.

International Science Board (ISB) meetings

ISB meetings will be held at least once per year to plan future activities and identify strategic goals. These will normally be held during major workshops and smaller working group meetings.

Major workshops and working group meetings

ACES workshops are the principal forum for international scientists of the cooperation to interact and smaller working group meetings allow for more focused interactions on specific themes and issues. During the 1-st workshop, the ISB agreed on the following schedule of major workshops and smaller working group meetings between 2000-2004.

When	What	Host country	Internet address

2/1999	1-st ACES Workshop	Australia	http://quakes.earth.uq.edu.au/ACES_WS
2/2000	WG Meeting	Japan	No home page developed
10/2000	2-nd ACES Workshop	Japan	http://www.tokyo.rist.or.jp/ACES_WS2
2001	WG Meeting	USA	
2002	3-rd ACES Workshop	USA	
2003	WG Meeting	Australia	
2004	4-th ACES Workshop	China	

Workshop proceedings are published immediately after major workshops[5] and full-length peer reviewed papers are subsequently published in an international journal[6] and in book form[7].

Visitors Program

The scientific Visitors Program enables development of collaborative research projects between participants. The visitors program commenced in 2000 funded by Australia (IREX), China (NSFC, LNM and CAP), Japan (JSPS and RIST), and USA (USGS and NSF project funding).

Visitors program supercomputer infrastructure

In 2000, Australia established the Australian Solid Earth Simulator (ASES) parallel supercomputer facility to serve its national groups participating in ACES and ACES visitors. In its final configuration early in 2001, the main node of the facility located at the ACES HQ will consist of a 40 processor (Itanium) SGI Origin 3800 supercomputer capable of up to 256 GFlops.

Figure 6: ASES supercomputer facility.

Visitors to Australia during year 1

Dr J. Dieterich, US Geological Survey; Prof. M. Matsu'ura, Department of Earth and Planetary Science, University of Tokkyo; Prof. X.C. Yin, Centre for Analysis and Prediction, China Seismological Bureau; Dr. K. Olsen, University of California at Santa Barbara; Dr. Y. Wang, Laboratory of Nonlinear Mechanics, Chinese Academy of Sciences, China; Mr Y. Fujii, University of Tokyo; Mr O. Hazama, Yokohama National University; Professor H. Okuda, Yokohama National University; Dr. M. Iizuka, Research Organisation for Information Science and Technology; Dr. B. Shaw, Lamont-Doherty Earth Institure; Prof. M-F. Xia, Peking University; Prof. K. Peng, Centre for Analysis and Prediction, China Seismological Bureau; Professor K. Hirahara[1], Nagoya University; Mr M. Hyodo[1], Nagoya University; Mr H. Suito[1], Nagoya University.

Visitors to Japan during year 1

Prof. P. Mora, Director, QUAKES; Dr. D. Place, QUAKES; Dr. H. Mühlhaus, CSIRO; Mr S. Abe, QUAKES.

[1] Rescheduled to early 2001.

Collaborative projects initiated during 2000

Transition from the stable to catastrophic regime

Description: Study of statistical features of earthquake rupture and the transition from the stable to catastrophic regime, multi-scale effects, trans-scale sensitivity, and the characteristics of critical state and precursors of rupture.

Participants: Australia (QUAKES), China (Peking University & Laboratory of Nonlinear Mechanics, Chinese Academy of Sciences).

Mesoscopic mechanism for the LURR earthquake prediction method and the relationship between LURR, accelerating moment release and criticality

Description: Simulation studies using the lattice solid model developed at QUAKES to study the mesoscopic mechanism underlying the LURR earthquake prediction model developed in China, and simulation studies to probe the relation between LURR and the proximity to a critical point.

Participants: Australia (QUAKES), China (Centre for Analysis and Prediction, State Seismological Bureau & Laboratory of Nonlinear Mechanics, CAS).

LURR model studies in Australia and the critical scaling region

Description: Observational studies using the LURR model to forecast the future seismic tendency in Australia and Accelerating Moment Release (AMR) observations. Comparison of the critical scaling region for AMR and LURR. This project aims at providing feedback with simulation studies of the underlying mechanism for LURR and AMR using the lattice solid model.

Participants: Australia (QUAKES), China (Centre for Analysis and Prediction, CSB).

Scaling laws and fault zone evolution

Description: Studies of scaling laws for large earthquakes of the evolution process of fault zones and time history of seismic activity using the lattice solid model developed at QUAKES.

Participants: Australia (QUAKES), Japan (University of Tokyo).

Micro-mechanics underlying macroscopic friction laws

Research on numerical simulation of the laboratory derived rate-and-state friction law using the Lattice Solid micro-model aiming in the long-term to extend knowledge of how to scale the laboratory results of rock friction to derive the effective behaviour of complex fault gouge zones.

Participants: Australia (QUAKES), USA (US Geological Survey).

Ground motion studies

Description: Macroscopic scenario modelling using methods developed at SCEC and comparisons with teleseismic methodologies to estimate site amplification developed in Australia.

Participants: Australia (QUAKES), USA (UC Santa Barbara).

Coupled macroscopic-microscopic computations

Description: Development of multi-scale simulation methodologies. Computational research to develop a hybrid approach to simulate earthquake generation integrating the lattice solid model developed at QUAKES for micro-scale phenomena in the fault zone with Finite-Element and Element-Free-Galerkin macro-models developed in Japan's Earth Simulator Project. Interfacing between the micro-scale simulation software system LSMearth developed at QUAKES (Figure 6, left) and the macro-scale software system (GeoFEM – Figure 6, right) developed under Japan's Earth Simulator national science agenda priority project.

Participants: Australia (QUAKES), Japan (University of Tokyo, Research Organisation for Information Science and Technology, Yokohama National University, Nagoya University).

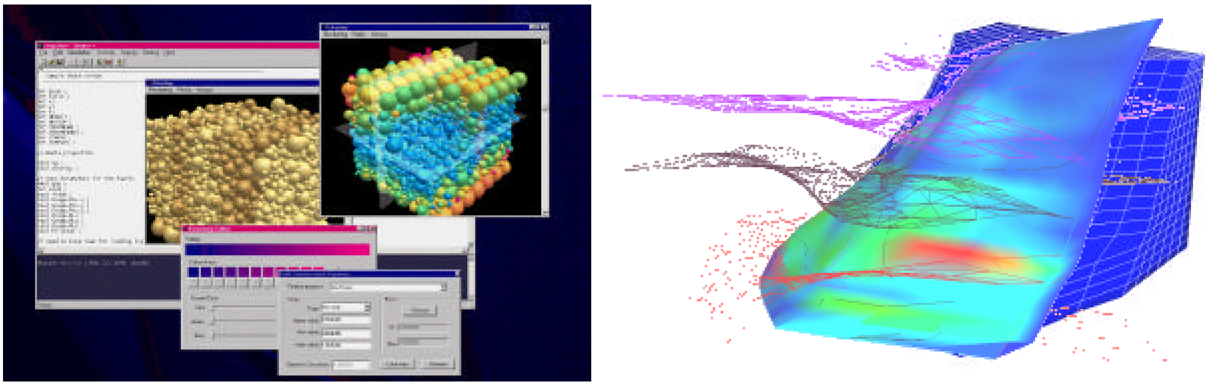

Figure 6: *Left:* The LSMearth micro-scale modelling software system developed at QUAKES showing a system of particles representing a rock structure being subjected to compression. *Right:* The GeoFEM macro-scale software system developed at RIST by the GeoFEM group showing a large scale simulation of a subduction fault zone.

Participants of ACES

Member economies

Australia (originating economy), China, Japan and USA.

Participant institutions, centres and organisations

Australia: QUAKES (Executive Office), The University of Queensland; Centre for Industrial Solid Mechanics (CSIRO/University of Western Australia), Australian Geological Survey Organisation.

China: Centre for Analysis and Prediction, China Seismological Bureau, State Science and Technology Commission; Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences; Beijing University of Aeronautics & Astronautics; Peking University.

Japan: Crustal Activity Modelling Program/Earth Simulator Project: University of Tokyo, Earthquake Research Institute, Geographical Survey of Japan, Building Research Institute, National Research Institute for Earth Science and Natural Disaster Prevention; Strong Motion Modelling Program/Earth Simulator Project: Nagoya University, Kyushu University, Hokkaido University of Education, Meteorological Research Institute, Chiba University; National GeoFEM Group: Research Organisation for Information Science & Technology (RIST), Science and Technology Agency, Yokahama National University, Institute of Physical and Chemical Research.

USA: Southern California Earthquake Center: University of Southern California, California Institute of Technology, Columbia University, Lamont-Doherty Earth Observatory, San Diego State University, UCLA, University of California San Diego, Scripps Institution of Oceanography, UC Santa Barbara, University of Nevada, US Geological Survey, NASA Jet Propulsion Laboratory, Lawrence Livermore National Laboratory; National General Earthquake Models group: Centre for Chaos and Complexity, Colorado University; University of California, Davis; Los Alamos National Labs; Stanford University; UC Santa Barbara; UCLA; USC; San Diego Supercomputer Centre; Institute for Geophysics and Planetary Physics; Centre for Advanced Computing Research, NASA JPL; LLNL; Lamont-Doherty Earth Institute; Boston University; Brown University; Cornell University; Northeast Parallel Architectures Center; Syracuse University; Worcester Polytechnic Institute; Massachusetts Institute of Technology; Harvard University.

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