Predictive Simulation for Crustal Activity in and around Japan

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The aim of our program (CAMP; Crustal Activity Modelling Program) is to develop a physics-based predictive computer simulation system for the long-term crustal deformation and the entire earthquake generation cycles in and around Japan. The total simulation system consists of a crust-mantle structure model, a tectonic loading model, a dynamic rupture model, and a data assimilation software. In 2002, by using the Earth Simulator, we have carried out the following works: (1) optimization and scale-enlargement of a simulation code for quasi-static earthquake cycles at a transcurrent plate boundary and numerical simulation of tectonic loading on the 1200 km-long San Andreas fault system with it, (2) construction of a 3D standard model of plate interfaces in and around Japan and optimization of the computation algorithm of viscoelastic slip-response for this structure model, (3) development and optimization of a BIEM code for dynamic rupture propagation on a 3-D curved fault system, and (4) development of an efficient parallel iterative solver for symmetric multiprocessor (SMP) cluster architectures with vector processors.

Keywords: Plate subduction zones, earthquake generarion cycles, crustal deformation, predictive simulation, parallel iterative solvers.

1. The aim of CAMP

Japanese Islands are in a very complex tectonic setting. In the northeastern part the Pacific plate is descending beneath the North American plate, in the southwestern part the Philippine Sea plate is descending beneath the Eurasian plate, and in the central Kanto area these four plates are interacting with each other in a very complicated way. Interaction between the oceanic and the continental plates at subduction zones produces the periodic occurrence of large earthquakes, coseismic, postseismic and interseismic crustal movements, and long-term crustal deformation of the island arc-trench system. The aim of our program (CAMP: Crustal Activity Modelling Program) is to develop a physics-based predictive computer simulation system for the long-term crustal deformation and the entire earthquake generation cycles in and around Japan.

2. The total system for crustal activity simulation

In general, the earthquake generation cycle consists of tectonic loading due to relative plate motion, quasi-static rupture nucleation, dynamic rupture propagation and stop, stress redistribution due to viscous relaxation in the asthenosphere, and restoration of fault strength. The basic equations governing the entire process of earthquake generation cycles consists of an elastic/viscoelastic slip-response function that relates fault slip to shear stress change and a constitutive law that prescribes change in fault strength with slip and contact time. The driving force of this system is observed relative plate motion. In our modeling we use the slip- and time-dependent fault constitutive law, which consistently explains the slip weakening in high-speed slip, the log *t* strengthening in stationary contact, and the slip-velocity weakening in steady-state slip [1]. Figure 1 shows the total system of CAMP, which is divided into four main components: a crust-mantle structure model, a quasi-static earthquake cycle model, a dynamic rupture propagation model, and a data assimilation software. The complete earthquake generation cycle model is constructed by combining the quasi-static model and the dynamic model developed on the same structure model.

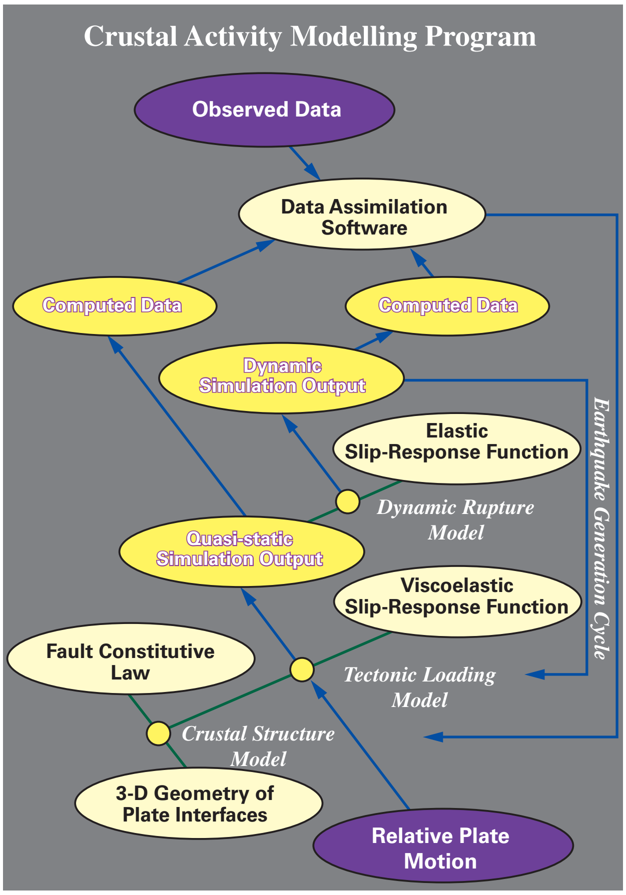

Fig. 1 Composition of the total system for predictive crustal activity simulation (M. Matsu'ura).

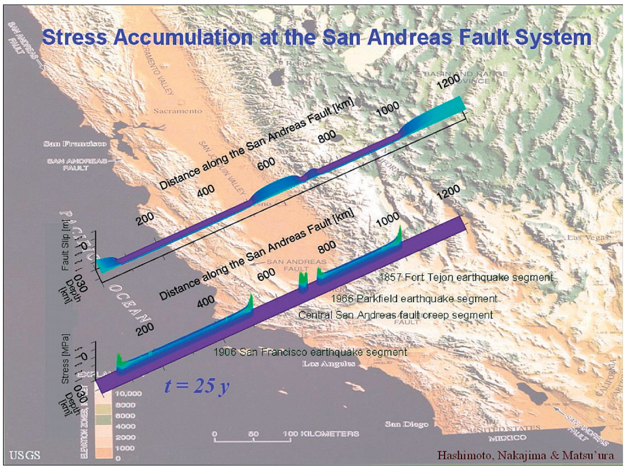

Fig. 2 The snapshots showing the distributions of fault slip and shear stress along the simplified San Andreas Fault system at t = 25 yr (K. Nakajima, C. Hashimoto & M. Matsu'ura).

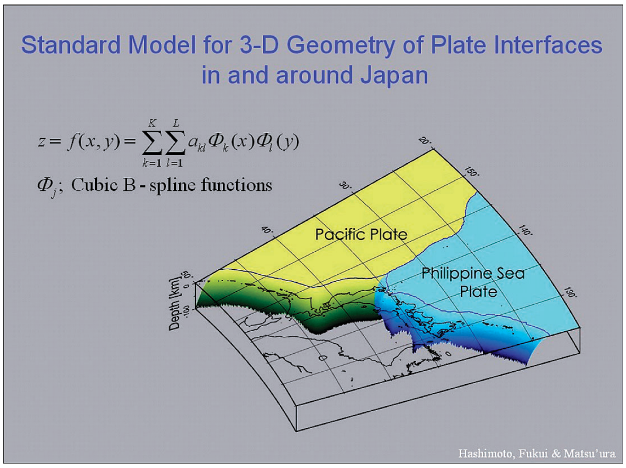

Fig. 3 The 3D standard model of plate interfaces in and around Japan. The plate interfaces are represented by the superposition of about 50,000 bi-cubic B-splines (C. Hashimoto, K. Fukui & M. Matsu'ura).

3. Numerical simulation of tectonic loading at the San Andreas Fault system

For transcurrent plate boundaries we have already developed the small-scale (L < 120 km) simulation models of quasi-static earthquake cycles [2] and dynamic rupture propagation, and succeeded in simulating the complete earthquake generation cycle by combining them [3]. In 2002 the simulation code of quasi-static earthquake cycles at a transcurrent plate boundary was vectorized and parallelized by MPI. Matrix assembly and inversion processes were highly optimized for parallel computing, and 2-way parallelization was developed for local operations for parameter points and data/integral points. Computations with this code for the tectonic loading on a 1200 km-long transcurrent plate boundary demonstrated good scalability on the Earth Simulator with up to 64 processors [4]. The snapshots in Fig. 2 show the distributions of fault slip and shear stress along the simplified San Andreas Fault system at t = 25 yr (just before the occurrence of the Parkfield earthquake).

4. Construction of a 3D standard plate interface model and computation of viscoelastic slip-response

In the case of convergent plate boundaries, although the basic equations governing the earthquake generation cycle is essentially the same as those in the case of transcurrent plate boundaries, the practical modeling is much more difficult, because of complexity in geometry of plate interfaces. We constructed a realistic 3D standard model of plate interfaces in and around Japan by applying an inversion technique to the ISC hypocenter distribution data [5, 6].

As shown in Fig. 3, the 3D configuration of the plate interfaces is very complex in the Kanto area, where the Philippine Sea plate is descending beneath the North American plate to the northwest along the Sagami trough, and the Pacific plate is descending beneath the both plate to the west along the Japan trench. Furthermore, the Philippine Sea plate is colliding with the North American plate at the base of the Izu peninsula and running on the Pacific plate at its eastern rim. In order to construct the simulation model of quasi-static earthquake cycles on these plate interfaces, we need to compute viscoelastic stress changes due to a unit step slip for this structure model in advance, which is the most time-consuming part. For this purpose we vectorized and parallelized the computation code of viscoelastic slip-response.

5. Development of a BIEM code for dynamic rupture propagation on a 3D curved fault system

For the construction of the simulation model of spontaneous dynamic rupture propagation on the 3D curved plate interfaces, we developed a new computation code by applying the boundary integral equation method (BIEM) to triangle elements [7]. In this code a spontaneous propagation of dynamic rupture is computed under a pre-defined fault geometry, initial stress and constitutive relation. The computation code has already been parallelized by using MPI libraries and tuned for scalar processors (e.g., PC cluster). In order to run this code (tridyn) on the Earth Simulator (ES) with high performance, the code must be vectorized. Since the most time-consuming part is the subroutine named trisub, which computes the kernels and convolutions with the current slip rate. By this modification, the code runs with the vectorization ratio of 0.9973 and computation speed of 1.99 GFLOPS. Next, parallelization efficiency is measured using 1 node (8 CPUs) and 10 nodes (80 CPUs) on the ES. Since the computation times are 346 s and 45 s, respectively, the parallelization ratio and parallelization efficiency become 0.9956 and 0.742, respectively. This result is almost comparable to that obtained by the PC cluster (0.9942 for parallelization ratio). Figure 4 is an example of numerical simulation for dynamic rupture propagation on the Earth Simulator with this code. Incorporating the output of quasi-static earthquake cycle simulation into this code, a large-scale computation of dynamic rupture propagation on the curved plate interfaces in and around Japan will become possible, as was done for the transcurrent plate boundary [3]. This will be the next target for the computation on the ES.

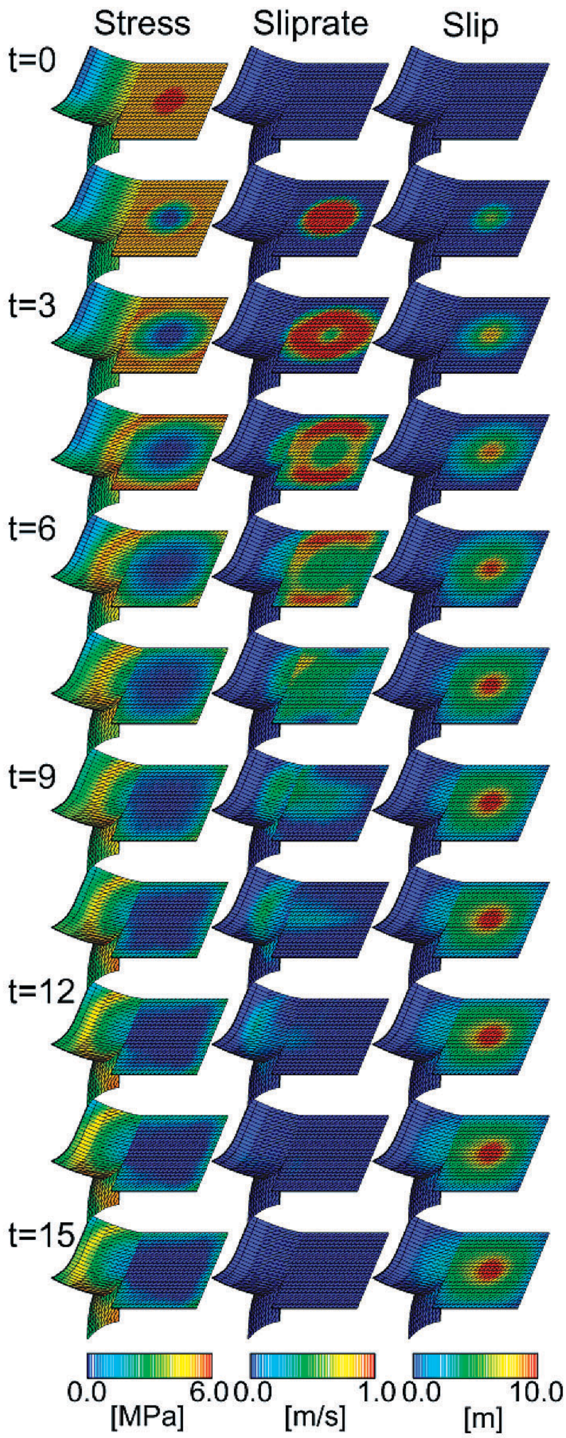

Fig. 4 A series of snapshots showing the changes in stress, slip rate and fault slip obtained by the dynamic rupture simulation on a non-planar fault with a branch (E. Fukuyama, T. Tada & B. Shibazaki).

6. Development of parallel iterative solvers for SMP cluster architectures with vector processors

An efficient parallel iterative method for unstructured grids has been developed on the GeoFEM platform for symmetric multiprocessor (SMP) cluster architectures with vector processors such as the Earth Simulator [8]. The method is based on a 3-level hybrid parallel programming model, including message passing for inter-SMP node communication, loop directives by OpenMP for intra-SMP node parallelization and vectorization for each processing element. Simple 3D linear elastic problems with more than 2.2×10^9 DOF have been solved by using a 3×3 block ICCG(0) method with additive Schwarz domain decomposition and PDJDS/CM-RCM reordering on 176 nodes of the Earth Simulator, achieving performance of 3.80 TFLOPS. The PDJDS/CM-RCM reordering method provides excellent vector and parallel performance in SMP nodes. A three-level hybrid parallel programming model outperforms flat MPI in the problems involving large numbers of SMP nodes.

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日本列島域の地殻活動予測シミュレーション

利用責任者

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本研究課題は、日本列島域を一つのシステムとしてモデル化し、プレート運動に伴う長期的地殻変形から大地震の発生まで、時間・空間スケールの異なる地殻活動現象を統一的且つ定量的に予測することを目的としている。このシミュレーション・システムは、準静的地震発生サイクルモデル、動的破壊伝播モデル、及び地殻活動データ解析・同化ソフトウェアで構成される。平成14年度には、地球シミュレータを利用して以下の成果を得た。(1)横ずれプレート境界での準静的地震発生サイクルモデルの最適化及び大規模化を行い、サン・アンドレアス断層系の応力蓄積シミュレーションを試みた。(2)日本列島域のプレート境界形状モデルを構築し、その構造モデルに対する粘弾性すべり応答の計算コードのベクトル化及び並列化を行った。(3)3次元曲面断層上の動的破壊伝播シミュレーションコードを地球シミュレータ上で動作テストし、大規模化及び最適化を行った。(4)並列反復法ソルバーを地球シミュレータ上で動作テストし、大規模線形システム解法のための最適化を行った。

キーワード：プレート沈み込み帯、地震発生サイクル、地殻変形、予測シミュレーション、並列反復法ソルバー