Simulation of Earthquake Generation Process in a Complex System of Faults

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The Pacific and the Philippine Sea plates subduct westwards and northwestwards along the Japan trench and the Nankai trough in northeast and southwest Japan, respectively, and produce great interplate earthquakes with a recurrence time of a hundred years. In inland regions, there are a number of active faults and inland earthquakes occur with a recurrence time of thousands years. We construct regional 3-D heterogeneous viscoelastic FEM models in northeast and southwest Japan, respectively, and aim at simulating generation processes of such earthquakes in a complex system of interactive faults of interplate and intraplate earthquakes. For this purpose, the module of earthquake cycle simulation in a parallel FEM code, GeoFEM, which has been developed for solving large-scale problems in solid earth physics, has been installed in Earth Simulator and tuned. Since GeoFEM has been originally developed as a parallel software, we execute the vectorization of GeoFEM. In this year, we vectorize the elastic loop in GeoFEM earthquake cycle simulation module. As test models, we construct large-scale northeast FEM model with different resolution of 2.3 and 5.0 million nodes, and execute quasi-static earthquake cycle simulations, as contact problems, with three asperities of higher friction than that in the surrounding plate boundary. We successfully model the earthquakes corresponding to the friction releases after interseismic plate subduction. Next, we successfully simulate dynamic fault rupture in a northeast FEM model with 230 million nodes. In Earth Simulator, we successfully execute the largest scale simulation of quasi-static earthquake cycle and dynamic rupture propagation in the world.

Keywords: GeoFEM, plate, 3-D heterogeneous viscoelastic medium, quasi-static earthquake cycle, dynamic fault rupture, contact analysis

Report of our result:

Two source codes of earthquake generation module in GeoFEM have been installed into Earth Simulator and the following tuning has been done. One is to simulate quasi-static earthquake cycle and the other is to simulate dynamic rupture propagation. The dynamic rupture propagation analysis code starts the computation after the stress accumulation in the interseismic period calculated in the quasi-static earthquake cycle simulation code. For testing the programs, 3-D elastic FEM models in northeast Japan, where the Pacific slab is subducting along the Japan trench, are constructed. In the model, are included the laterally heterogeneous crust and the mantle wedge portion. The Pacific plate is assumed to subduct with a rate of 10 cm/yr. Two FEM models with different sizes have the total number of 2.3 and 5 million nodes, respectively.

(1) Program ST1,2

This code simulates quasi-static earthquake cycle with contact analysis. At present, this code in ES (Earth Simulator) treats only elastic materials. First, we apply gravitational force to make contact the plate interface and the overriding material. We assume three asperities with higher frictional coefficients than those in surrounding plate interface during the 100 interseismic period when the plate subducts by 10 m. During 100-year interseismic period, the asperity portions are locked and there appear slips in the surrounding plate interface. Then we drop the frictional coefficient for one asperity by 1%. Correspondingly, the asperity breaks and the fault ruptures, releasing stress for the asperity but increasing that for other asperities. After next 100 years, the friction for the second asperity is decreased and the asperity breaks, and so on.

The processes in program of FEM (Finite Element method) whose computations are the most time-consuming are production of stiffness matrix, calculation of stress and nodal forces and solving process of linear equations. In FEM, since the unconstructed or irregular structure is treated, unbalancing is easily produced. Therefore, with re-ordering, we reduce the unbalance to realize the highly parallel computational processing. And the high vectorization is realized by using continuous memory accessing and long loop. Though it takes 97.5 % time of the whole computational time to execute the process in computation of stiffness matrix, stress, and nodal forces, and of solving the linear equations in SR-8000, the vectorization reduces the computational time to 46 % of the whole one. In SR-8000, it takes only 1.7 % cpu time to execute the contact analysis process, but it takes 48 % of the whole cpu time after vectorization in ES.

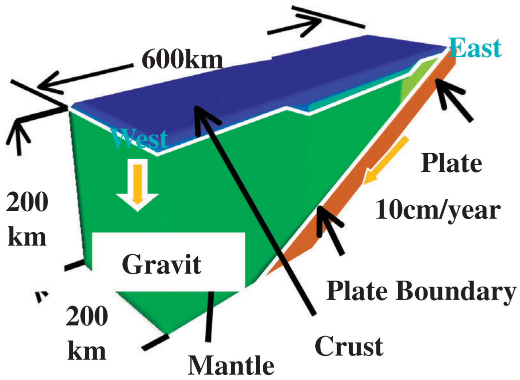
The above tuning of the code realizes the vectorization of 97.86 % and the parallelization of 99.64 % using 256 PEs in 5,000,000 nodes (15,000,000 freedom) problem. With this code, was executed the quasi-static fault analysis in the largest scale problems in the world.

It is, however, not so easy to vecorize the code, because the code itself is highly complex due to the strong nonlinearity in contact analysis. Further, the computational unbalancing occurs due to local contact analysis. These problems are to be solved.

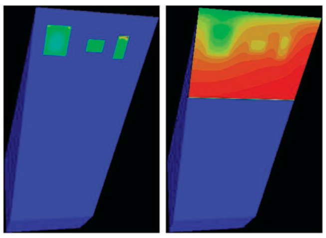
(2) Program ST_dyn

This code adds the dynamic analysis part to the quasi-static contact analysis code, ST1,2. Following the quasi-static analysis, which includes gravity loading, plate motions, and quasi-static stress accumulation in one asperity, we execute the fault rupture. As fault constitutive law, we adopt the slip-weakening friction law in this dynamic contact analysis code. We vectorize the part of the calculation of the mass matrix in the code for dynamic contact analysis.

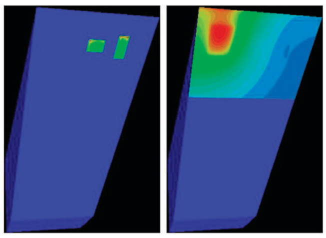
After the above tuning, we realize the vectorization of 97.3 % and the parallelization of 99.66 % using 128 PEs in the dynamic problem of 2,300,000 nodes (6,900,000 freedom). This analysis is the largest scale analysis of dynamic fault rupture in the world.



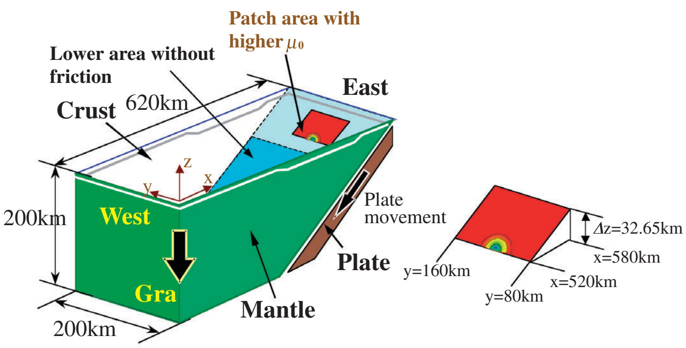
Model

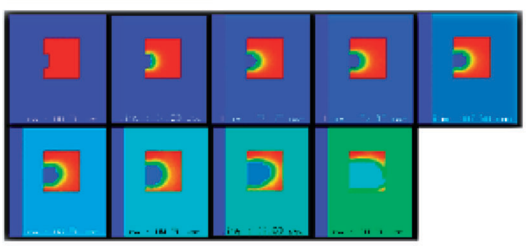


Friction & Slip after 100 years



Friction & Slip for the asperity berak





Snapshot of dynamic fault rupture

複雑断層系の地震発生過程シミュレーション

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東北日本および西南日本といった領域における3次元不均質粘弾性媒質中の複雑断層系における巨大地震の発生過程のシミュレーションを行うGeoFEMの(1)準静的地震発生サイクルシミュレーションモジュールおよび(2)動的破壊伝播シミュレーションモジュールを地球シミュレータに移植し、以下のチューニングを行ないテストモデルを解析した。
(1) プログラムST1,2
有限要素法では不規則なデータを扱うため，依存性が生じやすいが，Re-Orderingによって依存性を回避し，並列性の高い計算プロセスを実現した。また、連続メモリアクセス，充分に長いループ長を実現することによって高いベクトル性能を達成した。以上の結果、最大規模 5,000,000節点(15,000,000自由度)モデルで、ベクトル化率、97.86%、並列化率　99.64%(256PEs)を達成した。 このコードを用いて、世界最大規模の準静的断層解析を実施した。また、断層問題では、接触解析の強い非線形性を持ち、解析コード自体が複雑なため、ベクトル化も容易ではない。また局所的に接触解析があるため、計算の負荷バランスが悪い。次年度の課題である。
(2) プログラムST_dyn
本プログラムは、ST1,2に、動的解析部分と、断層摩擦構成則として すべり弱化則を加えたものである。動的解析のためのマスマトリクス作成部分をさらにベクトル化している。
以上より、最大規模　2,300,000節点(6,900,000自由度)モデルで、ベクトル化率、97.3%、並列化率 99.66%(128PEs)を達成した。 このコードを用いて、世界最大規模の動的断層破壊解析を実施した。

キーワード：GeoFEM、3次元粘弾性不均質媒質、プレート、準静的地震サイクル、動的断層破壊、接触解析