地震津波の防災減災のための京コンピュータを用いたシミュレーション研究（その２）
Advanced Disaster Simulation Researches on Earthquakes and Tsunamis using High Performance Computing System ‘Kei’ Part2

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Advanced Disaster Simulation Researches on Earthquakes and Tsunamis using High Performance Computing System ‘Kei’ Part2
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Using ‘Kei’ computer, we are performing the advanced simulation for Disaster mitigation by Earthquakes and Tsunamis. In this simulation research project, we have three part of research fields such as Earthquake simulation research field, Tsunami research filed and Damage estimation research field. In Earthquake simulation research field, we are developing the scenario simulations of earthquake recurrences on the subducting plate around Japan. We are simulating seismic waves based on the scenarios, and the underground structures using seismographs from networks. The second simulation research field on Tsunami hazard, we are developing applications for the simulating tsunami damages at East Japan earthquake 2011. In this research field, not only damage simulations, we are developing the early tsunami detection system using simulation and real time data. Finally, we will applied these research results to the Nankai trough seismogenic zone and etc. The third simulation research field on Damage estimation in cities is the civil engineering research as the adavanced civil engineering structural analyses, seismic response analyses on large scale cities, and advanced agent simulation for more precise and practical evacuations. Finally, in this project, we will integrate these simulation research results in each field as the Earthquake simulator for disaster mitigation. We will present advanced results in each field and propose the new concept of Post Kei project.

‘Kei’ computer is one of the highest computing system in the world. Using ‘Kei’ computer, we are performing the advanced simulation for disaster mitigation by earthquakes and tsunamis in a project ‘Study for Advancement of Prediction Accuracy on Earthquake and Tsunami’. In this research project, we have three research fields as Earthquake simulation research field, Tsunami research filed and Damage estimation research field.

In Earthquake simulation research field, we are developing the scenario simulations of earthquake recurrences on the subduct- ing plate around Japan. As other earthquake simulation researches, we are simulating seismic waves based on the scenarios, and the underground structures using seismographs.

The second research simulation research field on Tsunami hazard, we are developing applications for the simulating tsunami damages at East Japan earthquake 2011. In this research field, not only damage simulations, but also we are developing the early tsunami detection system using simulation and real time data. Finally, we will apply it to the Nankai trough seismogenic zone and etc.

The third research field is the civil engineering research as the adavanced civil engineering structural analyses, seismic re- sponse analyses on large scale cities, and agent simulation for more precise and practical evacuations.

Finally, we will integrate these research fields in this project for the seismic simulator on disaster mitigation.

高性能計算を使った地震災害・被害シミュレーション
Application of High Performance Computing to Earthquake Hazard and Disaster Simulation

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The utilization of high performance computing (HPC) is a key issue for more rational prediction of earthquake hazard and disaster. In principle, all physical processes of the seismic wave propagation and the resulting structural seismic responses are described in terms of sold wave equations, and it is a solution to numerically solve the equations using an analysis model of high fidelity. High performance computing solves uncertainty of material properties that appear in the solid wave equations by considering a suitable stochastic distribution and using ensemble computing.

This presentation explains recent achievement of applying HPC to earthquake hazard and disaster simulation. Explained are two targets, namely, the seismic structural response of an important structure and the urban earthquake disaster simulation. K computer, the supercomputer in Japan, is used to solve the wave equations of these two targets.

As for the seismic structural response analysis, the numerical treatment of non-linear material properties that include the occurrence and propagation of multiple-cracks is a bottleneck of applying HPC. A new discretization scheme is developed for crack which is discontinuity of displacement function. General purpose numerical analysis methods are being developed which are applicable to structures.

Urban disaster simulation is a challenge for HPC, because an analysis model is an urban area of a few kilometer dimension, which requires large-scale computation and automated model construction. In particular, a fast solver is implemented into a finite element method to solve the wave equation for a model of 100,000,000,000 degree-of-freedom, and a robust and flexible system is developed so that various digital data of an urban area are converted to a set of analysis models.

キーワード：高性能計算、地震災害、地震被害
Keywords: high performance computing, earthquake hazard, earthquake disaster

交通障害マルチスケールシミュレーション：開発の展望と課題
Multi-scale simulation of damaged transport systems: prospects and tasks of the development

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This presentation proposes an outline of the multi-scale simulation of damaged transport systems and discusses its prospects and tasks of the development. Damages on buildings and infrastructure by a major disaster will influence both performances and demand patterns of transport systems in a damaged area. The combination of degraded performances and a demand pattern that is significantly different from a normal demand can cause severe congestion, creating a major impact on the social systems of a damaged area. The multi-scale simulation of damaged transport systems aims to reproduce such situations using a traffic flow simulator and a transport demand model for a disaster situation combined with an estimated physical damages on buildings and infrastructure. Two issues should be mentioned to develop the simulation system. First, in a major disaster, an affected area should be substantially large and hence the scale of the problem (i.e. the number of links of a network and agents moving in it) must be very large. Second, the demand pattern after a disaster should be completely different from that of normal days and cannot be precisely estimated beforehand, implying that a huge number of demand patterns needs to be evaluated in the simulation. These two issues certainly arise computation burden that is very huge compared to typical problems that have been dealt with in past transport studies. The high-performance computing is useful to overcome these issues. In this presentation, the following technical topics will be introduced with a few tentative result: (1) How a traffic flow simulator is to be parallelised, (2) How travellers' behaviour in a post-disaster network can be mathematically modelled, (3) How numerous patterns of the demands are to be sampled so that practically important cases are effectively evaluated.

キーワード：交通シミュレーション
Keywords: Traffic simulator

余効変動の大規模有限要素シミュレーションを用いた断層すべり量とアセノフェア粘性率同時推定手法の開発

Simultaneous Estimation of Fault Slip and Asthenosphere Viscosity Using Large Scale Finite Element Simulation of Postseismic Deformation

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地殻変動データを用いた地震時・余効すべりの推定は，測地逆解析上重要な研究課題である．このような逆解析は，入手可能な高分解能プレート形状データと同分解能の有限要素モデルを用いた，粘弾性変形の有限要素シミュレーションを適用することで高度化することができると考えられる．著者らは，京コンピュータなどの大規模計算機環境上で，このような高分解能有限要素モデル（以下高詳細モデル）を用いた大規模シミュレーションを行うための手法を開発してきた．本研究では，シミュレーションに必要なアセノスフェアの粘性率の設定が自明でないことを踏まえ，高詳細モデルを用いた，粘性率と断層すべり量の同時推定手法を開発した．現在は人工観測データを用いた数値実験により開発した手法の有効性を検証している段階である．Ichimura et al. (2013)の手法に基づき，東北地方および東北地方太平洋沖地震震源域を含む2048x1536x850 kmの領域に高詳細モデルを生成した．プレート形状データとしては，JTOPO30 (2003), Koketsu et al. (2008), CAMPモデル(Hashimoto et al. 2004)を用いた．高詳細モデルは現在のところプレート形状分解能2kmで生成され，モデルの自由度は14億程度となっている．入力する断層すべりとして，Suzuki et al. (2011)を基にした地震時すべりと，Yamagiwa et al. (2014)を参考に便宜的に設定した余効すべりを用いた．地震発生から1.5年間の人工観測データをGEONET，GPS/A観測点， S-netの設置地点において生成した．逆解析は有限要素解と観測データの差の二乗和からなる評価関数を，粘性率と断層すべり量について最小化することにより行った．これは非線形最適化問題となるため，準ニュートン法とアジョイント法を組み合わせることにより少ない順解析数で最適化計算を行えるようにした．結果的に，京コンピュータの計算機の1/20を十数時間占有する程度の計算資源で，最適解を得られるようになっている．現在の数値実験設定においては，良好な推定結果を得ている．将来的には本手法の実観測データ解析や，観測点位置の評価などへの適用を考えている．

キーワード：有限要素法、アジョイント法、逆解析、地殻変動、粘性率推定、断層すベリ推定
Keywords: finite element method, adjoint method, inverse analysis, crustal deformation, viscosity estimation, fault slip estimation

粒子法計算における動的負荷分散技術の開発：津波等の混相流問題の大規模計算にむけて

Parallel implementation of the particle simulation method with dynamic load balancing: Toward large scale simulation of geophysical system of mutiphase flow

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Fully Lagrangian methods such as Smoothed Particle Hydrodynamics (SPH) and Discrete Element Method (DEM) have been widely used to solve the continuum and particles motions in the computational geodynamics field. These mesh-free methods are suitable for the problems with the complex geometry and boundary. Moreover, their Lagrangian nature allows non-diffusive advection useful for tracking history dependent properties (e.g. chemical evolution) of the material. These potential advantages over the mesh-based methods offer effective numerical applications to the geophysical flow and tectonic processes, which are for example, tsunami with free surface and entrainment of sand, magma intrusion within a fracture of rock with crystals, and shear zone pattern generation of granular deformation.

In order to investigate such geodynamical problems with the particle based methods, over millions to billion particles are required for the realistic simulation. Parallel computing is therefore important for handling their huge computational cost. An efficient parallel implementation of SPH and DEM methods is however known to be difficult especially for the distributed-memory architecture. Lagrangian methods inherently have workload imbalance problem for parallelization with the fixed domain in space, because particles move around and change workloads during the simulation run. Therefore, dynamic load balance is key technique to perform the large scale SPH or DEM simulation.

In this presentation, we introduce the parallel implementation technique of SPH and DEM method utilizing dynamic load balancing algorithms toward the high resolution simulation over large domain using the massively parallel super computer system. Our method utilizes the imbalances of the executed time of each MPI process as the nonlinear term of parallel domain decomposition and minimizes them with the Newton like iteration. In order to perform flexible domain decomposition in space, the slice-grid algorithm is used. Numerical tests show that our approach is suitable for solving the particles with different calculation costs (e.g. boundary particles) as well as the heterogeneous computer architecture. We analyze the parallel efficiency and scalability on the super computer systems (K-computer, Earth simulator 3, etc.).

キーワード：粒子法、動的負荷分散、津波
Keywords: SPH, DEM, dynamic load balancing

京コンピュータを用いた釜石の湾口防波堤の被災メカニズムの検討
Failure Mechanism of Breakwaters at Kamaishi Bay by using K computer

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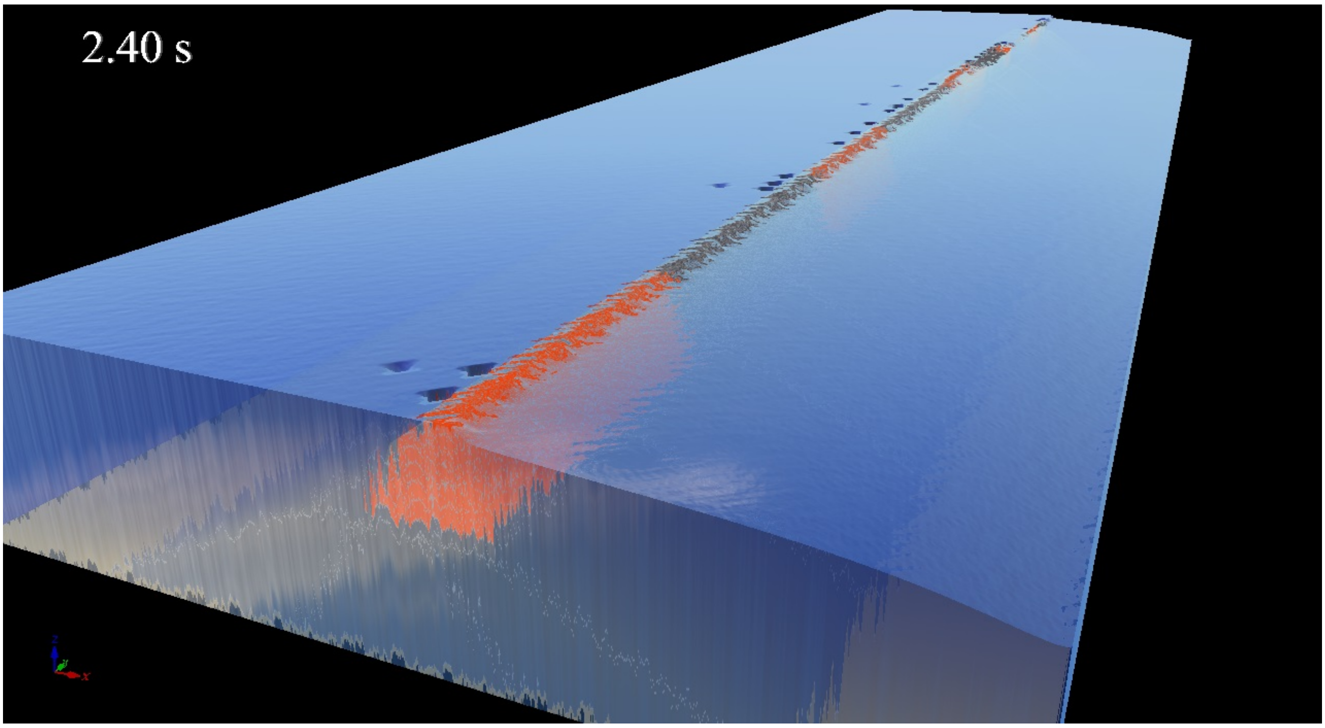
2011年3月11日に生じた東北地方太平洋沖地震津波によって多くの防波堤が被災した．被災形態は様々あるが，今次津波は，その多くが防波堤の天端を超えていたため，津波が越流した際に被災した事例が多かったのではないかと考えられている．釜石湾口防波堤は，今次津波により半分以上の防波堤が被災を受けたが，水理実験などから越流後に破壊されたと推定される．そこで，本研究では，波源域から遡上域までを階層的に解くことのできるSTOC-CADMASシステムを用いた、京コンピュータによる釜石の湾口防波堤の被災時の状況再現を行い、また、構造物との連成計算システムである、CADMAS-STRによって、その被災メカニズムの検討を行うものである。

キーワード：津波、京コンピュータ、防波堤、釜石湾、被災メカニズム
Keywords: Tsunami, K computer, Breakwater, Kamaishi Bay, Failure Mechanism



流体と粒状体の大規模粒子法シミュレーション開発
Development of large-scale particle simulations for fluid and granular dynamics

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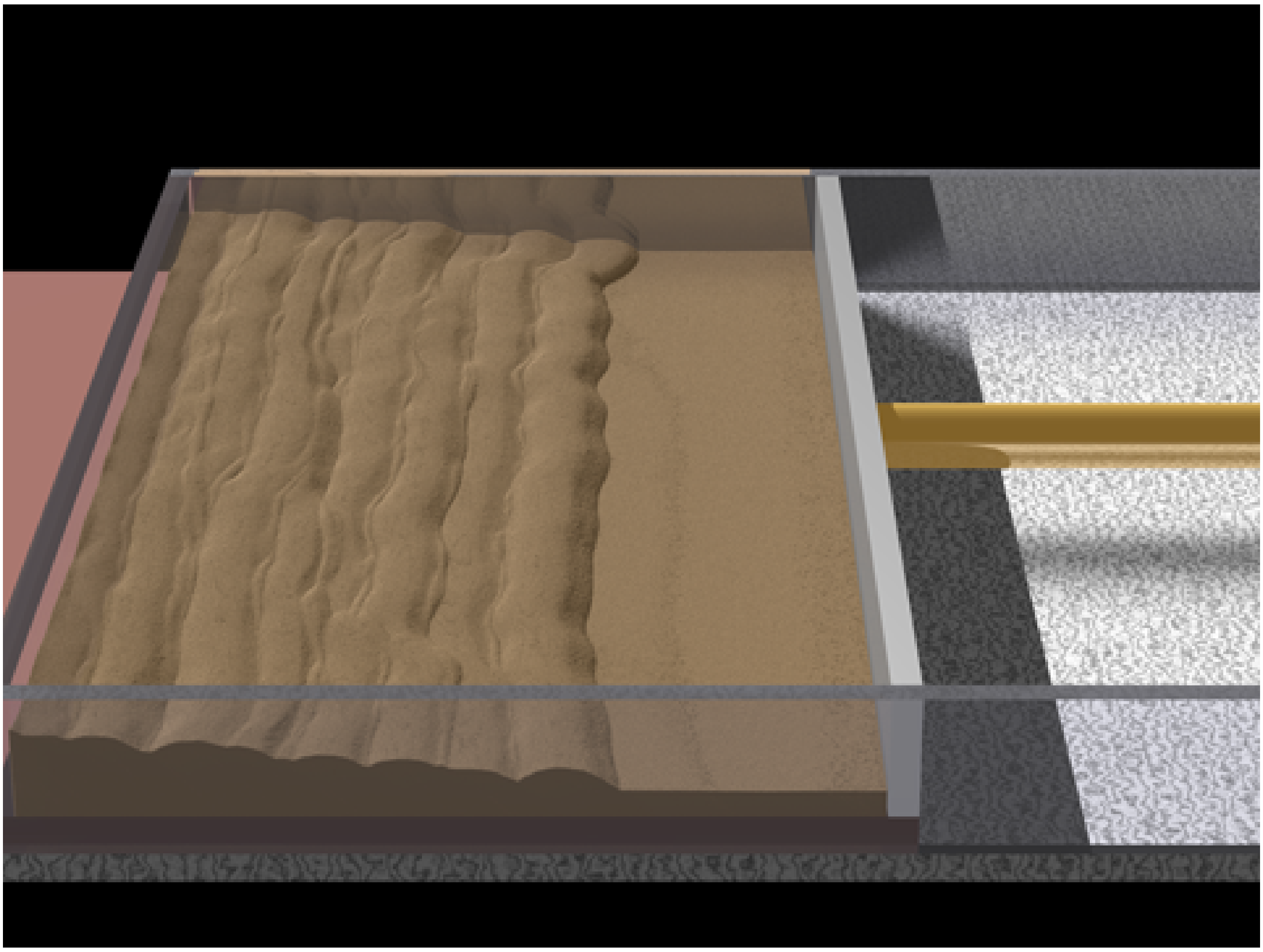
Large-scale parallel computing is important for numerically reproducing actual measurement results and dynamics of phenomena in various science and engineering areas, such as civil engineering, bioengineering, and earth sciences. The computational performance of parallelized software tools plays a critical role in such simulation studies, as these improve the computational accuracy relative to the simulation resolution within a limited computation time. Recent massively parallel computer systems based on shared- and distributed-memory architectures employ various types of arithmetic processors. Current processor designs are known to exhibit totally different computational performance depending on the numerical algorithms and implementation methods employed. Currently, parallel computing generally uses either a multi-core CPU, graphics processing unit (GPU), or many integrated core (MIC) processor. Multi-core CPUs have traditionally been used in high-performance computing, whereas GPUs were originally designed for computer graphics with many arithmetic cores. The common progress of current processor designs is the increase in the number of cores using vector operations such as single-instruction–multiple-data (SIMD). In such a situation, the shared-memory parallelization plays a basic but critical role in dealing with the increasing number of arithmetic cores in an efficient manner.

Particle simulation method (PSM) has a benefit of being mesh-free, allowing the computation of large-scale deformations and fractures of a continuum body without expensive remeshing tasks. As a PSM, smoothed particle hydrodynamics (SPH) is often used for tsunami disaster simulations because of its robustness in free-surface fluid dynamics. The discrete element method (DEM) is one popular PSM for granular dynamics in which geometrical size and shape attributes are provided for each particle. Therefore, the DEM is attractive to simulate granular materials such as sand, pebbles, and other grains.

An efficient parallel implementation of SPH and DEM methods is however known to be difficult especially for the distributed-memory architecture. Particle methods inherently have workload imbalance problem for parallelization with the fixed domain in space, because particles move around and change workloads during the simulation run. Therefore, dynamic load balance is key technique to perform the large scale SPH or DEM simulation. In this presentation, we introduce the several techniques of parallel implementation utilizing dynamic load balancing algorithms toward the high resolution simulation over large domain using the massively parallel super computer system. We will also introduce the applications of large-scale particle simulations such as Tsunami disaster simulation in consideration of structures–soil–fluid interactions and sandbox simulation for thrust dynamics of an accretion prism that require a high performance computing resources.

キーワード：離散要素法、SPH、並列計算、津波、砂箱、付加体
Keywords: DEM, SPH, Parallel computing, Tsunami, Sandbox, Accretion prism



線形分散波理論に基づく理論津波波形データベースの作成とそれを活用した津波即時予測
Development of tsunami Green’s function database based on linear dispersive-wave theory and its application to real-time tsunami forecasting

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沖合で観測される津波波形からリアルタイムに津波波源を推定し，それに基づき沿岸の津波を即時に予測して，津波警報を住民まで適切に伝達できれば，津波被害の軽減につながることが期待される．我々は，近地津波を対象として，リアルタイム波源推定に基づく津波予測手法tFISH (Tsushima et al., 2009)の高度化を進めている．本研究では，京コンピュータを活用して，tFISHの構成要素の一つである津波波形グリーン関数のデータベース(DB)を高精度化することが目的である．tFISHの津波予測は，津波波形逆解析と予測波形合成によって行われるものであり，これらの線形解析は津波波形グリーン関数の重ね合わせに基づく．そのため，グリーン関数が実際の津波現象を正しく再現できていないと，その誤差が波源推定と津波予測の誤差に直結する．既存のグリーン関数は線形長波近似によって数値計算したものである．一般に，津波の波長は水深に比べて十分長く，通常はこの近似で伝播過程を再現できるが，深海域で短波長に富む津波が発生すると，たとえ近地であっても波数分散性が強く現れるため(Saito and Furumura, 2009)，線形長波で計算した波形グリーン関数を使うと，波源の推定精度が低下する(Saito et al., 2010)．こうした波源推定および津波予測の精度低下を回避するには，線形分散波理論に基づいて津波波形グリーン関数DBを更新する必要がある．しかし，分散波理論に基づく津波計算は長波理論計算に比べて計算コストが非常に高く，しかもDB構築には3000以上の波源についての津波計算が必要であり，計算資源の総量は膨大になる．そこで本研究では，京コンピュータを活用して大量の高精度津波計算を実施し，津波波形グリーン関数DBの高精度化を図る．対馬ほか (2015, JpGU)では，京コンピュータとそれに最適化された津波計算コードJAGURS (Baba et al., 2015)を活用して現実的な時間内で大量・高精度津波波形計算を効率的に実施する計算方法の設計・実装と，南海トラフ沿い海域のDB構築について報告した．本発表では，千島・日本海溝沿い海域のDB構築と，分散波理論に基づく津波波形グリーン関数を用いることの有効性を調べるために行った津波予測実験について紹介する．

数値実験では，まず断層運動を仮定し，非線形分散波理論に基づいてJAGURS (Baba et al., 2015)によって津波計算をして，得られた津波波形を観測波形とみなす．そして，沖合の観測波形を用いてtFISHで津波予測を行い，沿岸付近のFP(Forecast Point: 気象庁が津波予測で用いる沖合の仮想点)における観測波形と予測波形の比較によって予測結果を評価する．
まず，昭和三陸地震(マグニチュード8.4)を想定した．日本海溝沖よりも沖合のアウターライズ領域で発生した地震で，高角正断層の震源メカニズムを持つことと，波源域の水深が深いことから，短距離を伝播するうちに分散する．こうした分散の影響が強い津波に対して，本研究で構築したDBは威力を発揮するものと期待される．Kanamori (1971)が推定した震源断層モデルを使って観測波形を作成し，tFISHで津波予測を行った．その結果，線形長波のグリーン関数を用いると，真値にはみられない偽の隆起域が求まってしまい，結果として周辺の沖合津波計が少ないFPでは津波第一波の予測精度が低下した．一方で，分散波グリーン関数を用いると，こうした偽像が解消されるとともに，予測精度も改善した．このように，分散波グリーン関数を用いれば，波源推定と津波予測の精度改善につながりうることがわかった．
　次に，内閣府が発表した想定南海トラフ地震(高知沖大すべりモデル)を対象に実験を行った．ここでは簡単のため，破壊伝播速度は無限大として模擬観測データを生成した．試みに，非線形分散波理論と非線形長波理論に基づいて模擬観測波形を計算したところ，両者はほぼ一致した．したがって，この模擬データは分散性の影響が小さい津波といえる．先と同様，分散波と長波でそれぞれ計算したグリーン関数を用いて津波予測を行ったところ，FPの予測波形はほとんど変わらないものとなった．これは，模擬観測データに分散性が含まれ

なかったためであると解釈できる．同時に，対象とする津波の分散性の強さに関わらず，分散波理論に基づく津波波形グリーン関数を常時用いるようにすれば，予測精度を確保できる可能性があることを示唆している．今後さらなる数値実験を行うことで分散波グリーン関数の詳細な性能評価を進める予定である．

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キーワード：京コンピュータ、津波即時予測、データベース、線形分散波理論、災害軽減
Keywords: K computer, Real-time tsunami forecasting, Database, Linear dispersive-wave theory, Disaster mitigation

大規模高詳細有限要素シミュレーションコードを用いた日本列島とその周辺の地殻活動予測モニタリング・予測システムの提案

A proposal of monitoring and forecasting system for crustal activity in and around Japan using a large-scale high-fidelity finite element simulation codes

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Here we propose a system for monitoring and forecasting of crustal activity, especially great interplate earthquake generation and its preparation processes in subduction zone. Basically, we model great earthquake generation as frictional instability on the subjecting plate boundary. So, spatio-temporal variation in slip velocity on the plate interface should be monitored and forecasted. Although, we can obtain continuous dense surface deformation data on land and partly at the sea bottom, the data obtained are not fully utilized for monitoring and forecasting. It is necessary to develop a physics-based data analysis system including (1) a structural model with the 3D geometry of the plate interface and the material property such as elasticity and viscosity, (2) calculation code for crustal deformation and seismic wave propagation using (1), (3) inverse analysis or data assimilation code both for structure and fault slip using (1)&(2). To accomplish this, it is at least necessary to develop highly reliable large-scale simulation code to calculate crustal deformation and seismic wave propagation for 3D heterogeneous structure. Actually, Ichimura et al. (2014, SC14) has developed unstructured FE non-linear seismic wave simulation code, which achieved physics-based urban earthquake simulation enhanced by 10.7 BlnDOF x 30 K time-step. Ichimura et al. (2013, GJI) has developed high fidelity FEM simulation code with mesh generator to calculate crustal deformation in and around Japan with complicated surface topography and subducting plate geometry for 1km mesh. Further, for inverse analyses, Errol et al. (2012, BSSA) has developed waveform inversion code for modeling 3D crustal structure, and Agata et al. (2015, this meeting) has improved the high fidelity FEM code to apply an adjoint method for estimating fault slip and asthenosphere viscosity. Hence, we have large-scale simulation and analysis tools for monitoring. Furthermore, we are developing the methods for forecasting the slip velocity variation on the plate interface. Basic concept is given in Hori et al. (2014, Oceanography) introducing ensemble based sequential data assimilation procedure. Although the prototype described there is for elastic half space model, we will apply it for 3D heterogeneous structure with the high fidelity FE model.