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.

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.

Keywords: high performance computing, earthquake hazard, earthquake disaster

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.

Keywords: Traffic simulator

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

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In the field of geodetic inversion, estimation of the coseismic/postseismic slip using postseismic deformation observation data is an important topic. Such estimation is expected to be improved by an inverse analysis method using numerical simulation (e.g. finite element (FE) method) of viscoelastic deformation, whose model is of high-fidelity to the available high-resolution crustal data. The authors had been developing a large-scale simulation method using such FE high-fidelity models (HFM), assuming use of a large scale computation environment such as the K computer in Japan. In this study, we developed an inverse analysis method incorporating HFM, in which fault slip and asthenosphere viscosity are estimated simultaneously, since the value of viscosity in the simulation is not trivial.We carried out numerical experiments using synthetic crustal deformation data. We constructed an HFM in the domain of 2048x1536x850 km, which includes the Tohoku region in northeast Japan based on Ichimura et al. (2013). We used the model geometry data set of JTOPO30 (2003), Koketsu et al. (2008) and CAMP standard model (Hashimoto et al. 2004). The HFM is currently in 2km resolution, resulting in 1.4 billion degrees-of-freedom. Coseimic slip based on Suzuki et al. (2011) and afterslips originally set by the authors based on Yamagiwa et al. (2014) were used as the inputted fault slips. Synthetic crustal deformation data of one and a half years after an earthquake in the location of GEONET, GPS/A observation points, and S-net were used. Inverse analysis was formulated as minimization of L2 norm of the difference between the FE simulation results and the observation data with respect to viscosity and fault slip, combining the quasi-Newton algorithm with the adjoint method. Use of this combination decreases the necessary number of forward analyses in the optimization calculation. As a result, we are now able to finish the estimation using 1/20 of entire resource of the K computer for 10 hours and a few. In the future, we would like to apply the method to the actual data.

Keywords: finite element method, adjoint method, inverse analysis, crustal deformation, viscosity estimation, fault slip estimation

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.).

Keywords: SPH, DEM, dynamic load balancing

Failure Mechanism of Breakwaters at Kamaishi Bay by using K computer

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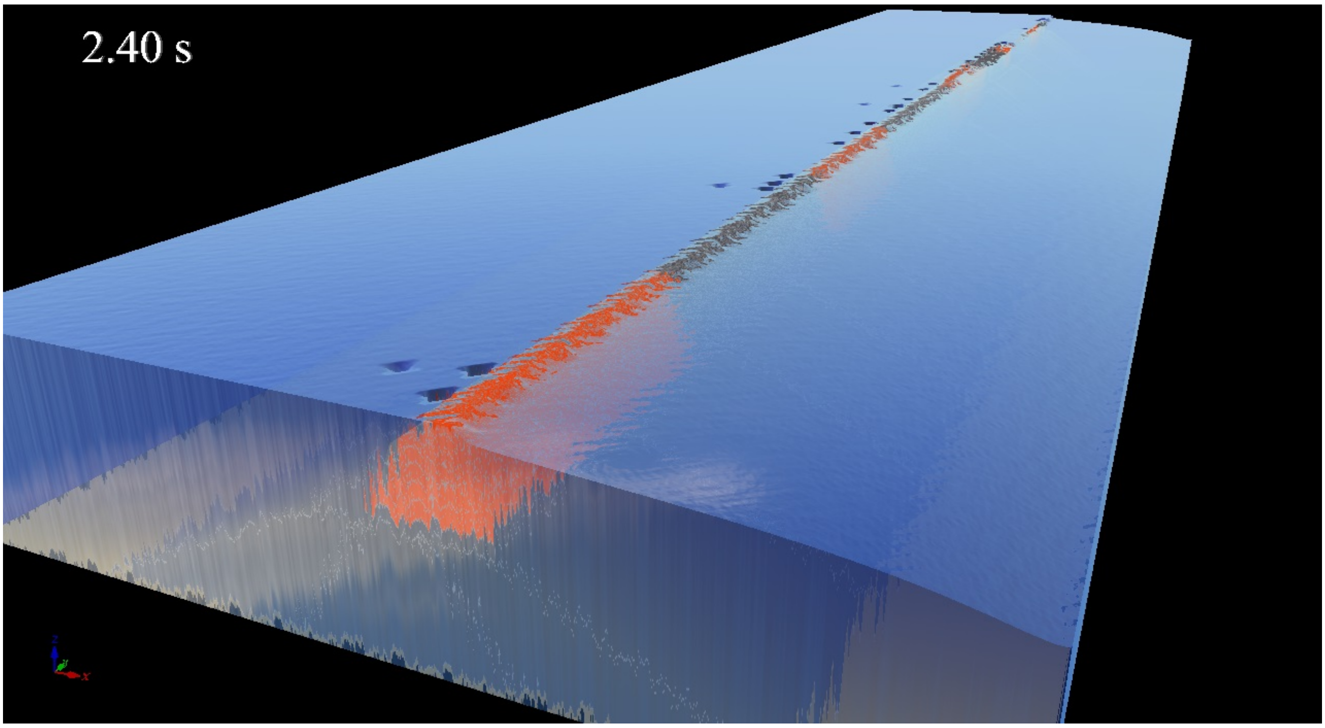
A lot of breakwaters were damaged by the 2011 off the Pacific coast of Tohoku Earthquake Tsunami that had been caused on March 11, 2011. Because a lot of tsunami exceeded the crown of the breakwater, there were a lot of cases where a breakwater was damaged when the tsunami overflowed it. The stability in the breakwater under the tsunami overflow has not been researched up to now, and the mechanism is not clear. The Kamaishi bay mouth breakwaters were presumed to have been destroyed when the tsunami overflowed from the physical experimental analysis.In the present study, the tsunami situation around the Kamaishi breakwaters was calculated by K computer based on STOC-CADMAS system, which is the Multi scale simulator, and verify the failure mechanism of breakwaters by using CADMAS-STR system, which is the coupling system with the structure analysis.

Keywords: Tsunami, K computer, Breakwater, Kamaishi Bay, Failure Mechanism



Development of large-scale particle simulations for fluid and granular dynamics

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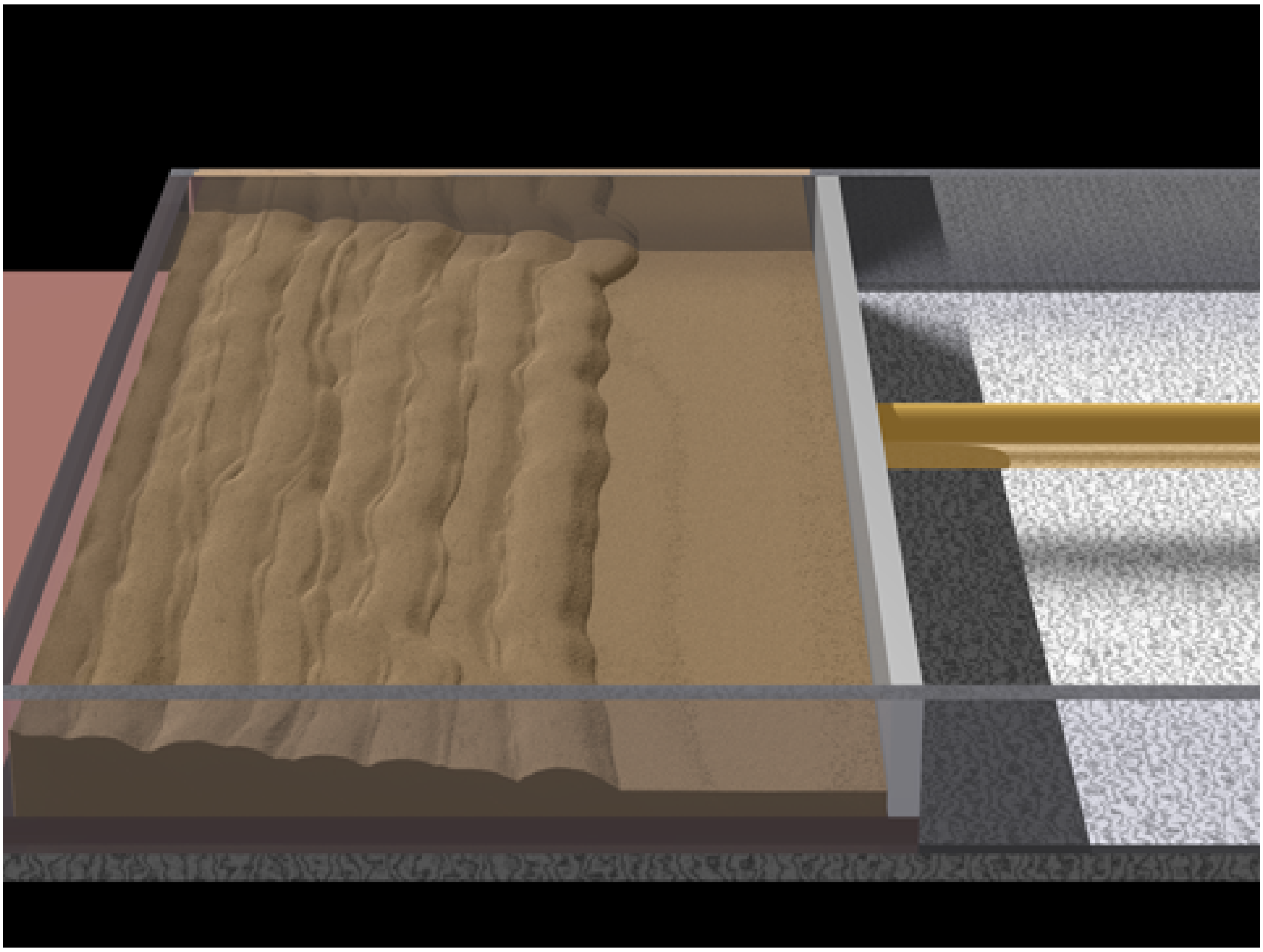
Large-scale parallel computing is important for numerically reproducing actual measurement results and dynamics of phenomena in various science and engineering areas, such as civil engineering, bioengineering, and earth sciences. The computational performance of parallelized software tools plays a critical 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.

Keywords: DEM, SPH, Parallel computing, Tsunami, Sandbox, Accretion prism



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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Real-time tsunami forecasting based on source inversion of offshore tsunami data is effective for update of tsunami early warnings. We developed tsunami forecasting method based on inversion of offshore tsunami data for initial sea-surface height distribution, named tFISH (Tsushima et al., 2009). The purpose in this study is improvement of tsunami-waveform Green’s function database (DB) that is one of key elements of tFISH algorithm. In tFISH algorithm, tsunami forecasting calculation is based on linear superposition of Green functions. Therefore, error in the functions directly affects tsunami-forecasting error. The present DB is prepared by using tsunami simulations based on linear long wave (LLW) theory. Generally, tsunamis have lone-wave length, and thus this approximation is valid. When a tsunami source is abundant in short-wave length component, however, the resultant tsunami waveforms become dispersive even at the near-field observing point (Saito et al., 2009). In such situation, use of LLW Green function degrades source-estimation accuracy (Saito et al., 2010). To overcome this problem, we have to prepare Green’s function DB based on linear dispersive-wave (DSP) theory, instead of LLW. However, the cost of the DSP calculation is much higher than that of LLW simulation. In addition, we have to conduct DSP simulations for more than 3000 cases to construct DB, and thus total computation cost is extremely huge. To overcome this difficulty, we implemented functions to accomplish these huge calculations in realistic calculation time by using K computer and then constructed DSP DB for Nankai-trough region (Tsushima et al., 2015, JpGU). In this presentation, we introduce construction of DSP DB for Kuril-Japan trench region and results of numerical simulations to show effectiveness of DSP Green functions in real-time tsunami forecasting.

In numerical simulations of tsunami forecasting, we assumed the 1933 Sanriku earthquake (magnitude 8.4) as a target event. This earthquake is an outer-rise normal-faulting event. Since the seafloor deformation is abundant in short wavelength and water depth in the source is great, the resultant tsunami waveforms are dispersive. To produce synthetic observation, we assumed earthquake faulting model proposed by Kanamori (1971) and then calculate the tsunami propagation based on nonlinear dispersive-wave theory. Then, we estimated initial tsunami height distribution using the synthetic data at offshore stations to forecast coastal tsunami waveforms. In tFISH inversion with LLW DB, significant source artifact appeared, while the artifact disappeared by applying our DSP DB. At coastal points around which offshore tsunami stations are few, better forecasting results were obtained with DSP Green functions than with LLW ones. This indicates that use of DSP Green functions is important to improve tsunami source estimation and tsunami prediction for dispersive event. Next, we assumed one of the huge Nankai-trough earthquakes proposed by the Cabinet Office: an earthquake with huge slip off Kochi Prefecture. To simplify situation, we neglect finiteness of rupture velocity in production of synthetic observations. It is noteworthy that the resulting synthetic data are less dispersive. Then, we compared the predicted tsunami waveforms at coastal points based on DSP DB and those based on LLW DB. As a result, these show good agreement. This result indicates the possibility that DSP DB works well for both dispersive and non-dispersive events. To clarify this point, we will perform more performance tests in future.

This research used computational resources of the K computer provided by the RIKEN Advanced Institute for Computational Science through the HPCI System Research project (Project ID: hp150216).

Keywords: K computer, Real-time tsunami forecasting, Database, Linear dispersive-wave theory, Disaster mitigation

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.

