Seismic imaging of marine crustal structure with high resolution and uncertainty quantification and utilization of the structural information

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1. Nankai subduction zone high resolution full waveform tomography

The Nankai subduction zone has hosted both many devastating earthquakes, such as 1944 Tonankai and 1946 Nankai earthquakes, and various slow earthquakes like tremors and low-frequency earthquakes. The physical properties of the subsurface structure, especially along the plate interface, are key to understand the factor controlling the occurrence of the wide-range of the subduction zone earthquakes.

An active source seismic survey using ocean bottom seismometers (OBSs) is an effective tool to reveal physical properties of the subsurface structure in the seismogenic subduction zones. Conventionally, the active source OBS data have been processed by the traditional ray-based methods such as first-arrival travel time (FAT) tomography [1]. However, the spatial resolution of the FAT tomographic results is not sufficiently high to discuss the physical properties controlling the wide-range of the earthquakes along the plate boundary faults. The full waveform inversion (FWI) that utilizes observed waveform itself is expected to be a good solution to overcome the limits of the FAT tomography.

FWI has been widely used in industry to investigate oil and gas reservoirs. In contrast, FWI has been rarely applied on academic lithospheric scale seismic explorations because the imaging targets of the academic studies are generally much bigger and deeper than those of the industry exploration. The first crust-scale waveform imaging was implemented in the Tokai area of the Eastern Nankai Trough [2][3], but their results were not clear because the imaging techniques was not enough matured to apply the actual data sets. Later, with the updating of inversion techniques, the resolution and accuracy are greatly improved in the subsequent FWI applications in the Kumano basin [4] and in the Tokai area [5].

These former results adopted the FWI method implemented in the frequency domain, although the frequency-domain FWI has some shortcomings. Therefore, we perform the time-domain FWI, which could be more efficiency to deal with different frequency contents. However, the time-domain FWI requires much more computing resources than the frequency-domain FWI. And it remains various issues in applying the method to the actual data sets of the lithospheric-scale studies.

In this study, we first aim to establish correct and robust procedures for the FWI. Then, we will apply the FWI to the actual data set. The data set was obtained in 2019 using 100 OBSs deployed at a spacing of 1-km along a 2-D survey line in the central Nankai Trough off the Cape Shiono, Kii Peninsula. Our final goal is to discuss controlling factors on the various fault slip behaviors from the megathrust to the slow slips in this subduction zone.

Building on the starting model obtained through FAT tomography [6], I completed the time domain FWI computations last year by selecting the preferred parameters. This year, my primary focus shifted to analyzing the results from these computations and drafting manuscripts for publication. Consequently, the computational usage of the ES4 cluster was relatively low compared to the previous year.

Leveraging the achievements of 2023, I revisited the outputs from FWI and conducted in depth analyses to evaluate the consistency of the inverted models, the influence of starting models, and other related factors. These efforts also included uncertainty quantification to ensure robustness and reliability in interpreting the findings.

Furthermore, I conducted many forward modeling simulations aimed at validating the various outcomes and providing additional supporting materials for interpretation (e.g. Fig. 1). These simulations supported the preferred result and focused on enhancing our understanding of the physical parameters associated with deep crustal behaviors within the specific subduction zone. The initial findings have already offered valuable insights and are currently being integrated into a manuscript under preparation.

To build on the progress made this year, I plan to expand the scope of modeling to cover additional scenarios and parameter configurations. The goal is to enhance our ability to relate the inverted models to physical processes governing fault slip behaviors in the shallower depths. These findings also can be used to investigate variations in seismic characteristics and their

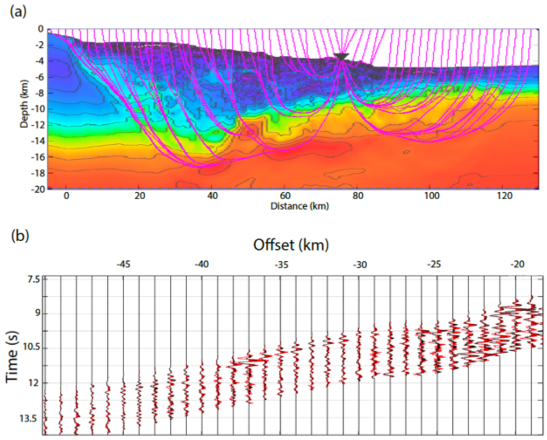

Fig.1 Ray tracing for one OBS gather and synthetic residual comparison using the FWI velocity model and a modified velocity model with the high-velocity crustal anomaly removed.

implications for hazard assessments in subduction zones.

Continued efforts will focus on preparing results for publication and presenting them at scientific conferences.

2. Development of FWI software and its application to OBS dataset in Nankai trough

Full waveform inversion (FWI) is one of the seismic tomography methods that estimates elastic/acoustic properties of the Earth. Because of its less approximation about seismic wave propagation than other methods such as first-arrival tomography, the FWI has been estimated subsurface models with better resolution and accuracy.

A critical factor influencing the quality of subsurface models derived from FWI is the accuracy of forward modeling in seismic wave propagation. To achieve better forward modeling, it is essential to incorporate realistic environmental features, such as topography, fluid columns, and geological boundaries, into the simulations.

However, many current FWI applications rely on strong approximations of wave propagation. For example, FWI applied to ocean-bottom seismometer (OBS) seismic reflection data often approximates wave propagation using acoustic wave equations. This approach fails to model S-waves, leading to discrepancies between simulated and actual wave propagation. Consequently, the accuracy of the estimated subsurface models is compromised.

To address these limitations, this study aimed to develop a new FWI framework capable of solving the coupled acoustic-elastic wave equations for applications in oceanic environments. The goal was to improve subsurface imaging by incorporating a more realistic wave propagation.

We developed the FWI software called SEM-SWS (Spectral Element Method based Seismic Wave Simulator). As its name suggests, SEM-SWS solves wave equations—including acoustic, elastic, and coupled equations—using the spectral element method (SEM), a high-order finite element approach. This methodology allows for an explicit representation of seafloor topography through an appropriate computational mesh. In oceanic environments, SEM-SWS solves the acoustic wave equation in the fluid domain and the elastic wave equation in the solid domain, applying appropriate boundary conditions at the seafloor. To enable efficient large-scale simulations, the software employs a hybrid parallelization strategy combining domain decomposition and source decomposition techniques.

We applied FWI using SEM-SWS to acoustic-elastic coupled domains with OBS seismic refraction data from the Nankai Trough. The computations were performed on the Earth Simulator using 5,504 processing cores. The resulting subsurface model reveals previously unreported heterogeneous structures within the oceanic plate, which may be linked to seismicity and very low-frequency earthquakes.

3. Development of "HypoNet Nankai": a rapid hypocenter determination tool for the Nankai Trough subduction zone using physics-informed neural networks"

Accurate hypocenter determination in the Nankai Trough, where a major earthquake is predicted to occur, is crucial for both hazard prediction and enhancing scientific understanding of seismic phenomena. Improving the accuracy of hypocenter determination largely depends on accurate calculation of travel times from the hypocenter to surface observation points. Traditionally, methods using simple velocity structure models, such as one-dimensional structures, have been widely applied for travel time calculations in hypocenter determinations. However, in areas like subduction zones where the subsurface structure is expected to exhibit complex spatial variations, incorporating more realistic three-dimensional (3D) velocity structures can significantly impact the accuracy of hypocenter determination. Research on establishing 3D velocity structure models has progressed in the Nankai Trough region by researchers in JAMSTEC [7]. 3D travel time calculations can be performed using grid-based finite difference numerical perform based on such models. However, the fact that many studies still rely on hypocenter determinations based on simple structures suggests that the practical computational costs and efforts required for 3D travel time calculations remain substantial. To advance the application of 3D velocity structure models in hypocenter determination, it is considered effective to release a user-friendly hypocenter determination tool that do not require such computational costs and efforts. Machine learning models, such as deep learning model, offer a modern approach by generating rapid and data-efficient models that can approximate nonlinear relationships between inputs and outputs. Physics-informed neural networks (PINNs) [8] can incorporate physical laws described by partial differential equations into their training process, enabling the construction of deep learning models for

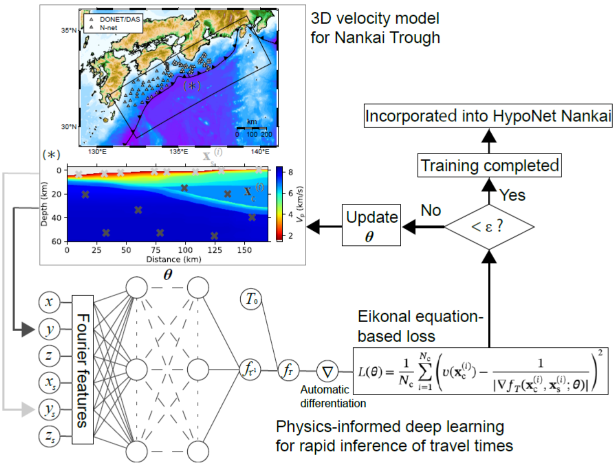

Fig.2 Schematic of PINN-based training of travel time based on the 3D P-wave velocity model of the Nankai Trough region [7].

fast travel time calculations (inference) without labeled training data.

In this study, we developed a rapid hypocenter determination tool based on a 3D velocity structure, called "HypoNet Nankai," using PINNs trained with the 3D P-wave velocity structure model of the Nankai Trough. The PINN used in HypoNet Nankai is trained to minimize the residual of the eikonal equation, which determines travel times for numerous samples of arbitrary hypocenter-receiver combinations within the analysis domain of the velocity structure model [9][10] (Fig. 2). The velocity in the eikonal equation is provided by the 3D P-wave velocity structure model constructed with emphasis on marine seismic exploration data [7]. Once trained, the PINN can quickly calculate (infer) travel times between any hypocenter and surface observation points required for hypocenter determination. Such a NN was developed for the entire region of the offshore region of the Nankai Trough subduction zone (hereafter called the global domain). Additionally, we introduced smaller, additional NNs to represent the travel time function in overlapping subdomains in addition to the NN for the global domain, aiming at higher prediction accuracy of travel time in the vicinity of the source. We generated (5 × 7 =) 35 subdomains covering the global domain. In inference, the travel time in the subdomain was inferred using the subdomain NN whose horizontal position of the central point was closest to that of the source. Those outside the subdomain were inferred using a global-domain NN. The training for the global domain used eight A100 GPUs in ES4 for 21 hours. Those for each sub-domain used two A100 GPUs for around 12 hours.

For the hypocenter determination algorithm, we adopted a method based on maximum a posteriori estimation and uncertainty quantification using Laplace (Gaussian) approximation, which is widely accepted in the community of seismological studies.

To verify the accuracy of the trained PINN and HypoNet Nankai, we conducted two validation tests by comparing them with grid-based numerical calculation methods. The results showed good agreement in travel time functions on the Earth's surface for randomly set hypocenters and were consistent with true hypocenter position within the range of estimation errors. In one hypocenter determination using first arrival travel time data from over 100 observation points, HypoNet Nankai required less than an average of 5 seconds. HypoNet Nankai has been confirmed as a promising alternative tool to grid-based 3D travel time calculations and traditional methods based on one-dimensional velocity structures for hypocenter determination in the mainly marine areas of the Nankai Trough. Currently, we are preparing to upload HypoNet Nankai to a public server. Additionally, we are working on extending the tool to include S-wave velocity structures.

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