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Simulation of Strong Ground Motions During the 2024 Noto Earthquake Using the Spectral Element Method on an Unstructured Mesh that Precisely Matches the Sedimentary Basin

〇Kirill A. SEMENTSOV, Percy B. GALVEZ, Kazuhiro SOMEI, Anatoly G. PETUKHIN

We performed numerical simulations of the strong ground motions caused by the Noto-Hanto earthquake on 1 January 2024. The modelling was performed using the spectral element method with the world-renowned SPECFEM3D simulation environment [e.g. Komatitsch & Tromp 2002]. Our main focus was on investigating the effect of various types of input data on the simulation results. The calculation domain had dimensions of 120 × 116 km along latitude and longitude, respectively, and 24 km deep into the Earth. The JIVSM model [Koketsu et al. 2012] was used in all simulations.

The most important initial stage of the simulation is the creation of a mesh. For this purpose, we used (1) the internal mesher MESHFEM3D, which is integrated into the SPECFEM3D simulation environment, and (2) the advanced external mesher CUBIT, which allows us to create more complex unstructured meshes. The rupture process was described by a kinematic source [Somei et al. 2024], which was created using the empirical Green's Functions method (EGF). The kinematic source [Somei et al. 2024] contains five strong motion generation areas (SMGA) occupying approximately 22% of the total area of the fault plane. Kinematic simulation for the EGF model requires additional setup for the slip-rate functions (SRF). We tested two different SRFs: SRF1 – the traditional Gaussian bell and SRF2 – Kostrov's type SRF proposed by [Graves & Pitarka 2004]. The simulation results were output at the locations of the K-NET stations [NIED 2019].

We conducted three comparative numerical experiments (Table 1). In the first numerical experiment, we compared calculations performed on two meshes created using the internal mesher MESHFEM3D. The geometry of Mesh 1 consists of two volumes — a sedimentary basin and a basement. The mesh is adjusted to the curvature of the interface between these volumes, as well as to the topography of the land surface and the bathymetry of the seabed. The upper volume (sedimentary basin) contains four layers of elements, the vertical size of which varies horizontally depending on the thickness of the basin. The lower volume (basement) contains 24 layers, the vertical size of the elements averages about 1 km. The geometry of Mesh 2 is a parallelepiped obtained by "pushing" downwards/upwards all layers of the sedimentary basin by an amount corresponding to the topography/bathymetry. This geometry is divided into a regular grid with elements of 1 km size. Strong motions were modelled on both Meshes using SRF1. The results show that the effect of topography is noticeable only near local irregularities (mountains, steep slopes, etc.). For the other stations located on a flat surface, the results of calculations on Mesh 1 and Mesh 2 are almost identical.

In the second numerical experiment, we performed two calculations on Mesh 1 using SRF1 and SRF2. SRF2 more accurately reflects the actual process of propagation of the rupture front. However, due to the short duration of both slip-rate functions (<2 s), there is almost no difference between the obtained seismograms in the investigated period range of 3-10 seconds.

In the third numerical experiment, we investigated the capabilities of the advanced external mesher CUBIT. As we mentioned in the description of numerical experiment №1, the internal mesher MESHFEM3D allows us to create only meshes with a fixed number of vertical layers across the entire volume. As a result, due to a varying thickness of the sedimentary basin, we obtain a significant difference between the maximum vertical size of the element in the deep part of the basin (Δz_{max}) and the minimum vertical size of the element in the shallow part of the basin (Δz_{min}). Because of this difference, the intention to reduce Δz_{max} (to reduce the minimum resolved period of the model) inevitably leads to a reduction in Δz_{min} and, consequently, a noticeable increase in calculation time. To solve this problem, we decided to use the external mesher CUBIT. Our main simulation environment SPECFEM3D can only perform calculations on hexagonal meshes. CUBIT does not allow the creation of an unstructured hexagonal mesh with fixed element sizes using a single built-in command. In this regard, various scientific groups have developed various complex and time-consuming strategies to create an unstructured hexagonal meshes using CUBIT (e.g. Casarotti et al. 2007). We have developed our own strategy, which, as far as we know, has not been published previously in seismological papers. Calculation on an unstructured mesh requires significantly more computational resources. In this regard, to create an unstructured Mesh 3, we limited our simulation domain to an area in close vicinity to the earthquake source. Four K-NET stations are located within this area. A comparison of the calculations for these four stations on Mesh 3 with the results obtained on Mesh 1 showed that both approaches give almost the same result, especially in close vicinity to the earthquake source.

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Table 1. Brief description of our numerical experiments.

Number of experiment	Mesh	Slip-rate function
№1	Mesh 1, Mesh 2	SRF 1
№2	Mesh 1	SRF 1, SRF 2
№3	Mesh 1, Mesh 3	SRF 1