Verification of Specfem3D against Emod3d

Problem Statement
To date, ground motion simulations of the Canterbury earthquakes have been carried out using the Graves and Pitarka (2010) hybrid broadband ground motion simulation methodology which combined deterministic finite di must be employed to integrate seismic waveform data to improve the Canterbury Velocity Model (CantVM). Specfem3D is a spectral element-based method which has tomographic waveform inversion capabilties which car In order to verify that our installation and usage of the Specfem3D software is correct, results from Specfem3D are compared against results from the deterministic low frequency simulations from Graves and Pitarka (2010)

Project Members

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Description (Objectives / Outcomes)

1. Produce equivalent inputs for the Specfem3D and Emod3D simulation methodologies.
2. Run Specfem3D and Emod3D simulations for the test scenarios.
3. Verify that Specfem3D and Emod3D produce matching output within numerical expectations.

Tasks

Produce the following inputs for Specfem3D and Emod3D:

- Source description.
- Velocity model.
- Station list.

Run the Specfem3D and Emod3D simulations while varying the following parameters:

- Velocity model:

    a. Homogeneous halfspace (1.00)
    b. 1D velocity model (1.02)
    c. Tomography only (1.11)
    d. Tomography + 1D basin (1.21)
    e. Tomography + 3D basin (1.65)

- Attenuation:

    a. Without attenuation
    b. With attenuation

- Sources:

    a. 19th October 2010

Compare the output from Specfem3D and Emod3D by examining:

- Waveforms directly.
- Fourier spectra.
- Intensity measures (PGV?)
- Goodness of fit?

Schedule

This project is currently ongoing, the provided schedule is a rough outline of what has been completed to date and what is expected in the foreseeable future:

June - Installation of Specfem3D on local machine and HPC (Fitzroy).

July - Learning to use Specfem3D and running the test case examples.

August - Producing inputs for Specfem3D, running real cases for Specfem3D.

September - Learning to run Emod3D, producing inputs consistent with Specfem3D, improving post-processing.

October - Comparison of Specfem3D and Emod3D outputs through waveform comparisons, Fourier spectra, Intensity measures and goodness of fit.

November - Finalize comparisons and properly document results.

Verification

As the Specfem3D and Emod3D methodologies have different formulations of the wave propagation problem, and hence take different inputs, the methods have some inherent differences which can lead to differences in th

The following two sections documents the specific details of the Specfem3D and Emod3D simulations carried out and the controls taken to ensure as much consistency between how the two methods are utilized. The presc

Specfem3D Simulation Details

- Specfem is run on a cartesian coordinate grid where the locations of features have been converted from geographic coordinates (longitude and latitude) using the ll2xy function.
- Specfem is run on a mesh with 400m spacing between nodes and with velocities prescribed at 200m spacing. Ideally specfem would be run on a mesh with 200m grid spacing but currently limitations and issues are
- The earthquake source is defined as a point source centroid moment tensor solution.
- Station locations are co-located with the station file used for Emod3D (as the stations must exist on a grid point in Emod3D).
- Simulation time step of 0.005s.
- Stacey absorbing boundary conditions.

Emod3D Simulation Details

- Emod3D is run on a cartesian coordinate grid where the locations of features have been converted from geographic coordinates using the ll2xy function.
- Emod3D is run on a grid with 200m spacing where the velocities are prescribed.
- The source is defined as a point source by its focal mechanism (strike, dip and rake).
- Station locations are located on the nearest grid point to the actual station location.
- Simulation time step of 0.005s.
- Some kind of absorbing boundary condition where the boundaries are set with a very high attenuation.

Simulation Domain

The domain of interest for the verification is a rectangular subregion of the Canterbury region spanning longitudes [172.25° 172.75°] and latitudes [-43.8° -43.4°] as shown in Figure 1. 7 sites of varying azimuth from the sou different physical phenomena observed from the simulations.

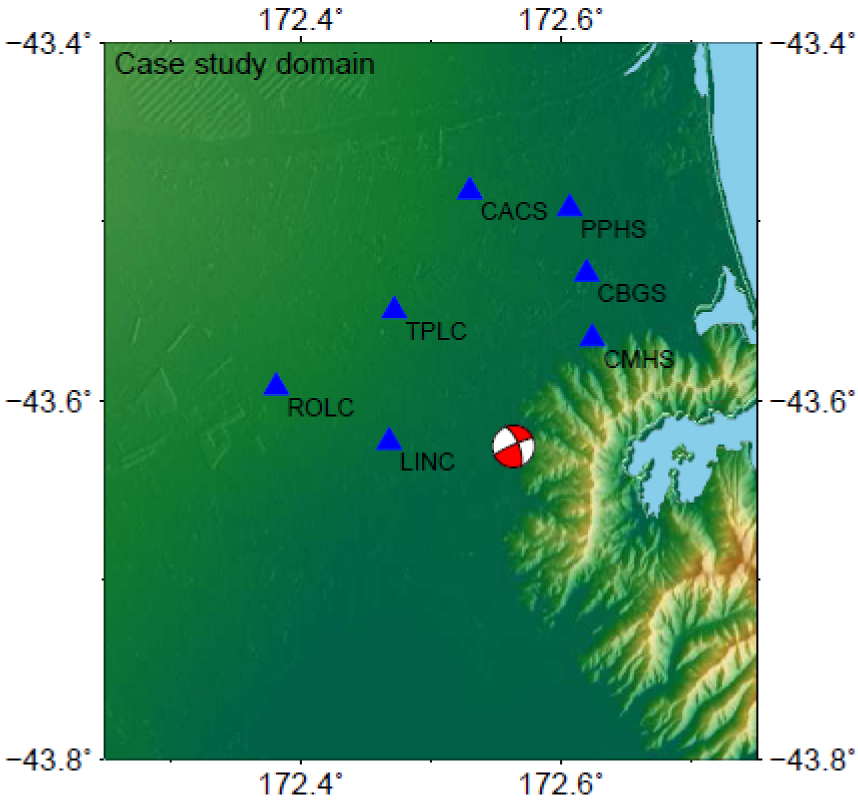


Figure 1. Verification domain for the 19th October 2010 earthquake including the source and station locations.

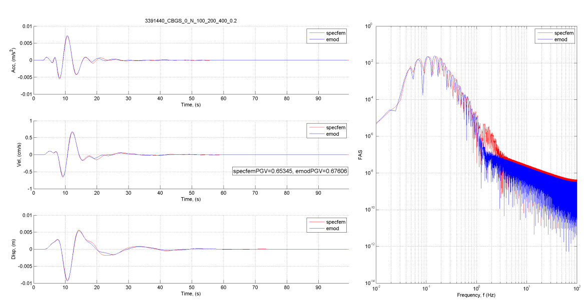
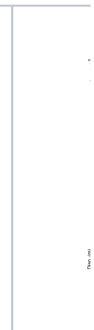
Both Specfem3D and Emod3D will be run as equivalently as possible for several scenarios (as shown in Table 1 of the Results section) provided the inherent differences in the numerical methods (and current limitations an

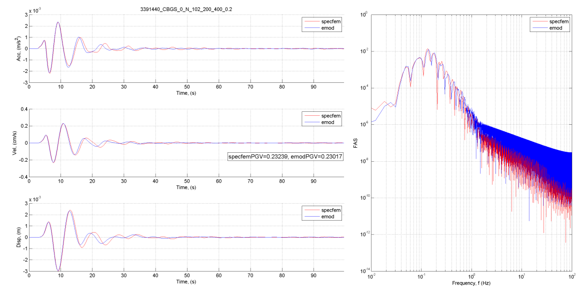
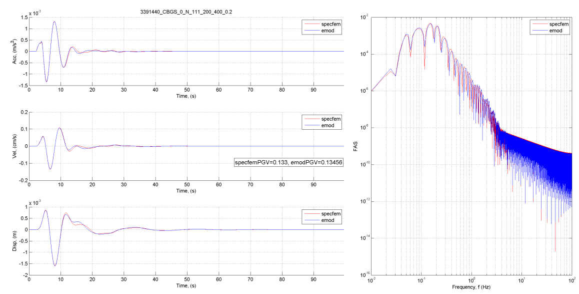
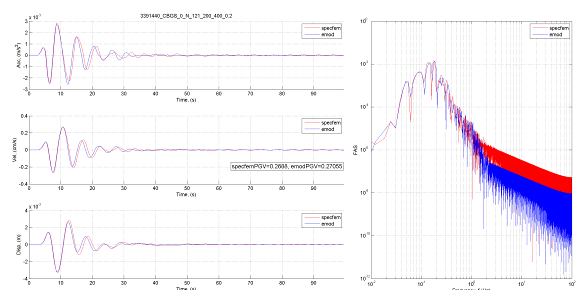
The output from Specfem3D and Emod3D are filtered at various frequencies to determine their similarities and differences within different frequency bands, highlighting in particular the difference between frequencies which resolved should be roughly 0.5Hz (considering 5 nodes per wavelength). Hence the frequency band of 0.05-0.2Hz highlights the well resolved components of the output, the frequency band of 0.05-0.5Hz highlights what is determining the verdict of the verification, followed by the frequency band of 0.05-0.5Hz, and lastly the frequency band of 0.05-1Hz is provided to solely show the effect of including unresolved frequencies.

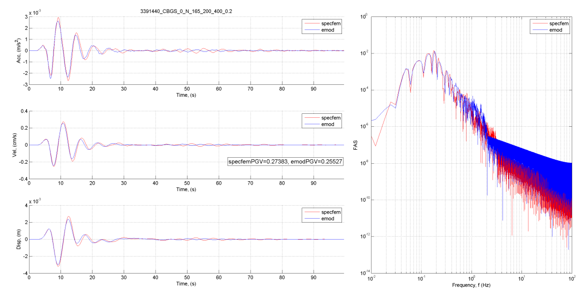
Result

The scenarios with their respective parameters are listed in Table 1 along with the results of and comments on the verification. While it is not plausible to include all results here, the CBGS site is used as an example here tc

Table 1. Results of the Specfem3D and Emod3D comparisons for the various scenarios tested.

Verification Test Number	Source Description	Crustal Model Description	Attenuation	Purpose	Pass /Fail	Notes/Figures
#1	Small Mw4.8 Pt Source (19Oct2010)	Homogeneous halfspace (1.00)	None	Wave propagation	Pass	0.2Hz: Waveforms 'exact' for all waveforms for the first 20 seconds. After 20 seconds, some waveforms remain practically exact while others begin to show devi 0.5Hz: Similar results to the 0.2Hz. 1.0Hz: Significant differences between Specfem3D and Emod3D outputs, visible in both waveforms, PGV values, and Fourier spectra.  Figure 2.1 North-South (0°) component of the CBGS site filtered at 0.2Hz for verification test number 1.  Figure 2.2 Nor

#2	Small Mw4.8 Pt Source (19Oct2010)	1D velocity model (1.02)	None	Wave propagation	Pass	0.2Hz: Waveform first arrivals are very similar, often 'exact'. However, Specfem3D waves which arrive after the first arrivals fall increasingly behind Emod3D wav 0.5Hz: Similar results to the 0.2Hz. 1.0Hz: Similar results to the 0.5Hz but slightly worse fitting.  Figure 3.1 North-South (0°) component of the CBGS site filtered at 0.2Hz for verification test number 2. Figure 3.2 Nor
#3	Small Mw4.8 Pt Source (19Oct2010)	Tomography only model (1.11)	None	Wave propagation	Pass	0.2Hz: Results mostly exact between the two methods. PGV values are extremely similar. 0.5Hz: Similar results to the 0.2Hz. 1.0Hz: Similar results to the 0.5Hz but slightly worse fitting.  Figure 4.1 North-South (0°) component of the CBGS site filtered at 0.2Hz for verification test number 3. Figure 4.2 Nor
#4	Small Mw4.8 Pt Source (19Oct2010)	Tomography + 1D basin model (1.21)	None	Wave propagation	Pass	0.2Hz: Waveform first arrivals are very similar, often 'exact'. However, Specfem3D waves which arrive after the first arrivals fall increasingly behind Emod3D wav 0.5Hz: Similar results to the 0.2Hz. 1.0Hz: Still good first arrivals but very poor comparison for later arrivals in both phase and amplitudes.  Figure 5.1 North-South (0°) component of the CBGS site filtered at 0.2Hz for verification test number 4. Figure 5.2 Nor

#5	Small Mw4.8 Pt Source (19Oct2010)	Tomography + 3D basin model (1.65)	None	Wave propagation	Pass	0.2Hz: Waveform first arrivals are very similar, often 'exact'. However, Specfem3D waves which arrive after the first arrivals fall increasingly behind Emod3D wav 0.5Hz: Mostly good first arrivals but significant differences in phase and amplitudes of later arrivals. CMHS still essentially perfect. 1.0Hz: Still good first arrivals but very poor comparison for later arrivals in both phase and amplitudes.  Figure 6.1 North-South (0°) component of the CBGS site filtered at 0.2Hz for verification test number 5. Figure 6.2 Nor

Discussion and Conclusions

The verification process has concluded that the outputs from Specfem3D and Emod3D are practically exact in some scenarios, and similar in others for the relevant frequencies. In particular, smooth velocity models (such a models) which have sharp interfaces produce increasing differences in the phase of later arrivals but match first arrivals and amplitudes in general well. The findings here are supported by work carried out by Chaljub (2015) between each method as well as the discrete representation of the velocity model input. Chaljub (2015) has presented some options to mitigate these problems. The primary solution to this problem is to create a mesh whic changes in velocities to occur within elements. However, the computational requirement to produce this kind of mesh, and also to run the simulations in 3D are beyond what is currently plausible. The second solution to this model which intrinsically smooths the velocity model. With this overarching objective in mind, it seems unreasonable to manually smooth the velocity model.

Numerical dispersion and instability is also a likely factor for the differences observed, as seen in the Fourier spectra where the low frequencies are reasonably consistent between the two methods, but significantly different Therefore results which are filtered at a lower cutoff frequency, such as 0.2Hz, are given more weight in determining the results of the verification.

Considering the overarching objective of ground motion simulations in Specfem3D, inherent differences in the two simulation methodologies, and current limitations, the verification of Specfem3D and Emod3D is considerec