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ADVANCING SEISMIC WAVE SIMULATION: THE APPLICATION OF THE SPECTRAL ELEMENT METHOD IN DIFFERENT GEOLOGICAL SETTINGS

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Abstract

Accurately simulating seismic wave propagation remains one of the core challenges in computational seismology, largely driven by the need to represent complex geological structures with high fidelity. Although traditional approaches such as the Finite Difference Method (FDM) and Finite Element Method (FEM) have long served as the backbone of seismic modelling, they struggle to efficiently capture realistic geological geometries and deliver high numerical accuracy. This review examines the pivotal role of the Spectral Element Method (SEM) in overcoming these constraints. By merging the geometric flexibility of FEM with the exponential accuracy of spectral techniques, SEM provides a powerful framework for high-fidelity seismic modelling. We detail the methodological strengths of SEM and systematically evaluate its transformative applications across a spectrum of geometrical settings, from intricate sedimentary basins like Kathmandu to continental-scale models of the Indian Peninsula, concluding with an analysis of future trajectories in the exascale computing era.

Keywords: Physics based simulation; Spectral Element Method; Wavefield; Basin amplification

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1. Introduction

The numerical simulation of seismic waves is an indispensable tool for understanding earthquake physics, assessing seismic hazard, and imaging the Earth's interior (Bijukchhen et al., 2017). The core challenge lies in solving the elastic wave equation in media that are highly heterogeneous and geometrically complex. The efficacy of any numerical method is judged by its accuracy, computational efficiency, and ability to handle realistic Earth structures (Komatitsch and Tromp, 1999).

For decades, two methods have dominated the field. The Finite Difference Method (FDM) (Graves et al., 1998; Olsen and Schuster, 1995; Olsen, 2000; Satoh et al., 2001; S. Lee et al., 2008a; Lyu et al., 2024) is renowned for its computational efficiency and straightforward implementation on structured grids. However, this structured grid is its primary weakness, causing struggles with irregular internal interfaces and complex free-surface topography. Conversely, the Finite Element Method (FEM) (Bao et al., 1998; Aagaard et al., 2001; Bielak et al., 2005; Chen et al., 2015; Li et al., 2024) excels at handling geometric complexity through unstructured meshes. Yet, traditional low-order FEM often suffers from numerical dispersion and high computational cost for large-scale, high-frequency wave propagation.

The Spectral Element Method (SEM), implementation on computational seismology by Komatitsch and Tromp (1999), emerged as a hybrid solution that synthesizes the most desirable properties of its predecessors. Numerous studies have applied the Spectral Element Method (SEM) to seismic wave simulation across major basins worldwide, including the Los Angeles Basin (Komatitsch et al., 2004), Kathmandu Basin (Shen et al., 2022), Taipei Basin (Lee et al., 2008), Sichuan Basin (Yu et al., 2017), Shidian Basin (Liu et al., 2015), Indo-Gangetic Basin (Sreejaya et al., 2023), Weihe Basin (Liu et al., 2018), and the Kutch Basin (Vijaya et al., 2020). Building on this foundation, this paper highlights how SEM especially through open-source platforms like SPECFEM (CIG, 2025) is advancing the modelling of diverse and complex geometrical settings that

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are central to modern seismological simulation and analysis.

2. Spectral Element Method: A Theoretical Overview

The SEM can be viewed as a high-order variant of the FEM, discretizing the computational domain into a mesh of deformable elements (Komatitsch and Tromp, 1999). Its key distinctions provide significant advantages:

- Spectral Accuracy: SEM uses high-degree Lagrange polynomials interpolated at Gauss-Lobatto-Legendre (GLL) nodes, enabling exponential convergence of the numerical error as the polynomial degree increases. This ”spectral accuracy” minimizes numerical dispersion, allowing for precise simulations with fewer grid points per wavelength than low-order methods.
- Diagonal Mass Matrix: The integration of the mass matrix using the GLL quadrature rule results in a diagonal mass matrix by construction. This critical feature eliminates the need to solve large linear systems at each time step, making the method explicit and computationally efficient.
- Unstructured Meshing: SEM utilizes unstructured meshes (typically hexahedral in 3D), providing the necessary flexibility to model complex geological interfaces and topography accurately

This unique combination of geometric flexibility, high accuracy, and computational efficiency makes SEM well-suited for large-scale, high-fidelity seismic wave propagation problems (Tromp et al., 2008).

3. Application of SEM in diverse Geological Settings

3.1. Irregular Sedimentary Basin

Sedimentary basins with their strong velocity contrasts and deep, irregular shapes are a classic example of where SEM's advanced meshing capabilities become essential. The Kathmandu Basin, shown in Figure 1, illustrates this well. After the 2015 Gorkha earthquake, SEM-based simulations successfully reproduced the observed ground-motion amplification and extended shaking duration. By accurately capturing the basin's deep, bowl-shaped structure, the models revealed how seismic energy became trapped, producing multi-path reverberations that aligned with the natural frequencies of multi-story buildings and intensified structural damage (Galetzka et al., 2015; Bijukchhen et al., 2017; Tiwari and Bhandary, 2021).

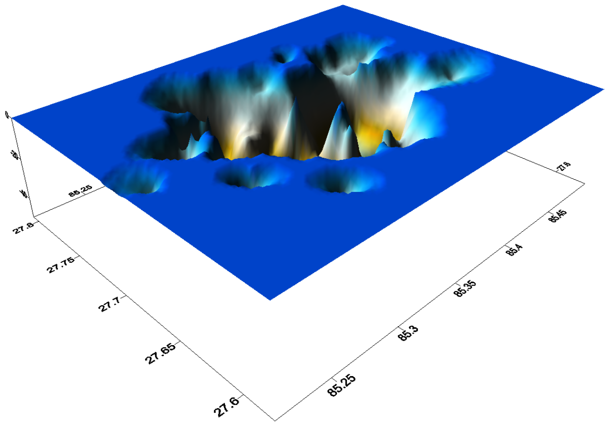

Figure 1. Vs profile of Kathmandu basin (Bijukchhen, 2018)

The Los Angeles Basin is among the most extensively studied sedimentary basins worldwide. Its deep and highly irregular structure produces strong amplification, wave-guiding effects, and significant basin-edge generated surface waves. SPECFEM, an open-source software suite (CIG, 2025) has been used for simulation of ground motions from past earthquake such as the 1994 Northridge earthquake, as well as scenario ruptures on the San Andreas Fault. These simulations reveal how seismic energy is channelled through the basin, resulting in severe shaking in downtown Los Angeles even from distant sources. They also capture the conversion of body waves into damaging surface waves (Love and Rayleigh) at basin boundaries (Komatitsch et al., 2004; Ma et al., 2007; E.-J. Lee et al., 2014).

The Taipei Basin simulation utilizes the spectral-element method (SEM) to model seismic wave propagation, which inherently accounts for topography and is well-suited for representing the intricate surface terrain and variable low-velocity sedimentary basins in Taiwan. The details of the Taipei Basin Mesh Adjustment describe the integration of the basin model, noting that the mesh for the shallow sedimentary structure is refined to accommodate its complicated geometry, strong lateral wave-speed variations, and comparatively shallow depth. Furthermore, the incorporation of the 3D Basin Model specifies that the high-resolution, small-scale 3D velocity structure for the Taipei Basin is embedded into the SEM simulations, and its form depicted in the finest-resolution mesh (S. J. Lee et al., 2008, 2014, 2008a).

3.2. Rugged Topography and Mountainous Regions

The interaction of seismic waves with complex topography leads to pronounced wave focusing, scattering, and localized amplification. SEM's ability to generate unstructured meshes that accurately follow digital elevation models enables the realistic incorporation of rugged surface features. Research in the Grenoble Valley, France (Stupazzini et al., 2009; Chaljub et al., 2010), the European

Alps (Beller et al., 2018), the Chile Basin (Pilz et al., 2011), and the Andes (Ward et al., 2016) has shown that SEM effectively captures how topography shapes ground-motion behaviour. These studies reveal phenomena such as the production of damaging surface waves at mountain fronts and the intensified shaking on ridge crests effects that are often missed by approaches assuming simplified, flat topographic surfaces.

3.3. Complex Fault Systems and Subduction Zones

The geometry of fault systems, particularly the non-planar, curved interfaces in subduction zones, is crucial for simulating realistic ground motions. SEM allows representation of these faults within the mesh. Simulations of megathrust earthquakes in the Japan Trench (Galvez et al., 2014; Miyoshi et al., 2017; Parla et al., 2025) use SEM to incorporate the precise geometry of the subducting Pacific Plate, enabling more accurate modelling of the resulting wavefield, including the effects of dipping slabs on energy directivity.

3.4. Multi-Scale Geometries: From Local to Global

SEM's scalability enables simulations to span a wide range of geometrical scales. At the continental level, SEM-based models of the Indian Peninsula have been used to study wave propagation from intraplate earthquakes, incorporating the complex structure of the crust–mantle boundary and major sedimentary basins (Sreejaya and Raghukanth, 2024). At the global scale, SPECFEM3D_GLOBE a member of the SPECFEM family of open-source spectral element codes (Komatitsch and Tromp, 1999) employs a cubed-sphere mesh to represent Earth's spherical geometry with high fidelity, enabling realistic simulations of seismic wavefields generated by large earthquakes that travel across the entire planet (Sawade et al., 2025).

4. SPECFEM Software Suite: Implementation and Workflow

SPECFEM, an open-source software suite is the leading implementation of spectral element method for computational seismology (CIG, 2025). Its workflow for a typical basin study involves:

- Model Construction: Building a 3D geologic/velocity model from seismic, geological, and geotechnical data.
- Mesh Generation: Generating an unstructured mesh that conforms to major interfaces using tools like CUBIT (Casarotti et al., 2008).
- Source Definition: Defining the seismic source, from a simple point source to a complex finite-fault rupture ehich depends upon the magnitude (S. J. Lee et al., 2014)
- Parallel Simulation: Running the large-scale simulation on high-performance computing (HPC) systems using MPI for domain decomposition.
- Post-processing: Analysing the synthetic seismograms to extract ground motion parameters and visualize wave propagation.

5. Challenges and Future Directions

Despite its strengths, challenges remain. The generation of high-quality, conforming hexahedral meshes for extremely complex geometries is a non-trivial task. Furthermore, the computational cost for high-frequency simulations of large domains, while managed through parallelization, remains immense.

Future efforts are focused on several key areas:

- Advanced Mesh Generation: Developing more automated and robust mesh generation tools to alleviate the pre-processing bottleneck.
- Exascale Computing: Porting SEM codes to GPU-based exascale platforms to achieve unprecedented resolution and scale.
- Coupled Multi-Physics: Integrating SEM with models for soil-structure interaction, poroelasticity, and tsunami generation.
- Data Integration and Inversion: Leveraging SEM's accuracy for full-waveform inversion (FWI) to iteratively improve Earth models.
- Machine Learning: Using SPECFEM simulations to generate training datasets for machine learning emulators, which could provide rapid ground motion predictions and assist in automating mesh generation.

6. Conclusion

The Spectral Element Method, as embodied in the SPECFEM software suite, has fundamentally transformed our capacity to simulate seismic wave propagation in geometrically complex Earth models. By transcending the limitations of FDM and FEM, SEM provides a unique combination of geometric flexibility, high numerical accuracy, and computational efficiency that is essential for modern seismology. Its successful application across a diverse range of settings from local basins to global models has made it an indispensable tool for physics-based seismic hazard assessment. As computational power grows and geological models become more refined, SEM will continue to be central to efforts aimed at unravelling the complexities of seismic wave phenomena and building a more resilient future.

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