

HIGH PERFORMANCE COMPUTING METHODS FOR EARTHQUAKE
CYCLE SIMULATIONS

by

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DISSERTATION ABSTRACT

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Title: High Performance Computing Methods for Earthquake Cycle Simulations

Earthquakes often occur on complex faults of multiscale physical features, with different time scales between seismic slips and interseismic periods for multiple events. Single event, dynamic rupture simulations have been extensively studied to explore earthquake behaviors on complex faults, however, these simulations are limited by artificial prestress conditions and earthquake nucleations. Over the past decade, significant progress has been made in studying and modeling multiple cycles of earthquakes through collaborations in code comparison and verification. Numerical simulations for such earthquakes lead to large-scale linear systems that are difficult to solve using traditional methods in this field of study. These challenges include increased computation and memory demands. In addition, numerical stability for simulations over multiple earthquake cycles requires new numerical methods. Developments in High performance computing (HPC) provide tools to tackle some of these challenges. HPC is nothing new in geophysics since it has been applied in earthquake-related research including seismic imaging and dynamic rupture simulations for decades in both research and industry. However, there's little work in applying HPC to earthquake cycle modeling. This dissertation presents a novel approach to applying the latest advancements in HPC

and numerical methods to solving computational challenges in earthquake cycle simulations.

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Here is an acknowledgment

To so-and-so...

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CHAPTER I
INTRODUCTION

1.1 Chapter One Section One

1.1.1 Chapter one section one sub-section one.

Test: including section 1.1 into the file

$$y = a * x + b \nabla \tag{1.1}$$

This is a sample citation: Schwartz (2012).

1.1.1.1 Chapter one section one sub-section one sub-sub-section one.

CHAPTER II

METHODOLOGY

2.1 Chapter Two Section One

Computational modeling of the natural world involves pervasive material and geometric complexities that are hard to understand, incorporate, and analyze. The partial differential equations (PDEs) governing many of these systems are subject to boundary and interface conditions, and all numerical methods share the fundamental challenge of how to enforce these conditions in a stable manner. Additionally, applications involving elliptic PDEs or implicit time-stepping require efficient solution strategies for linear systems of equations.

Most applications in the natural sciences are characterized by multiscale features in both space and time which can lead to huge linear systems of equations after discretization. Our work is motivated by large-scale (\sim hundreds of kilometers) earthquake cycle simulations where frictional faults are idealized as geometrically complex interfaces within a 3D material volume and are characterized by much smaller-scale features (\sim microns) Erickson and Dunham (2014); Kozdon, Dunham, and Nordström (2012). In contrast to the single-event simulations, e.g. Roten et al. (2016), where the computational work at each time step is a single matrix-vector product, earthquake cycle simulations must integrate with adaptive time-steps through the slow periods between earthquakes, and are tasked with a much more costly linear solve. For example, even with upscaled parameters so that larger grid spacing can be used, the 2D simulations in Erickson and Dunham (2014) generated matrices of size $\sim 10^6$, and improved resolution and 3D domains would increase the system size to $\sim 10^9$ or greater. Because iterative schemes

are most often implemented for the linear solve (since direct methods require a matrix factorization that is often too large to store in memory), it is no surprise that the sparse matrix-vector product (SpMV) arises as the main computational workhorse. The matrix sparsity and condition number depend on several physical and numerical factors including the material heterogeneity of the Earth’s material properties, order of accuracy, the coordinate transformation (for irregular grids), and the mesh size. For large-scale problems, matrix-free (on-the-fly) techniques for the SpMV are fundamental when the matrix cannot be stored explicitly.

In this work, we use summation-by-parts (SBP) finite difference methods Kreiss and Scherer (1974); Mattsson and Nordström (2004); Strand (1994); Svård and Nordström (2014), which are distinct from traditional finite difference methods in their use of specific one-sided approximations at domain boundaries that enable the highly valuable proof of stability, a necessity for numerical convergence. Weak enforcement of boundary conditions has additional superior properties over traditional methods, for example, the simultaneous-approximation-term (SAT) technique, which relaxes continuity requirements (of the grid and the solution) across physical or geometrical interfaces, with low communication overhead for efficient parallel algorithms Del Rey Fernández, Hicken, and Zingg (2014).

For these reasons SBP-SAT methods are widely used in many areas of scientific computing, from the flow over airplane wings to biological membranes to earthquakes and tsunamigenesis Erickson and Day (2016); Lotto and Dunham (2015); Nordström and Eriksson (2010); Petersson and Sjögren (2012); Swim et al. (2011); Ying and Henriquez (2007); these studies, however, have not been developed for linear solves or were limited to small-scale simulations.

With this work, we contribute a novel iterative scheme for linear systems based on SBP-SAT discretizations where nontrivial computations arise due to boundary treatment. These methods are integrated into our existing, public software for simulations of earthquake sequences. Specifically, we make the following contributions:

- Since preconditioning of iterative methods is a hugely consequential step towards improving convergence rates, we develop a custom geometric multigrid preconditioned conjugate gradient (MGCG) algorithm which shows a near-constant number of iterations with increasing system size. The required iterations (and time-to-solution) are much lower compared to several off-the-shelf preconditioners offered by the PETSc library Balay et al. (2023), a state-of-the-art library for scientific computing.
- We develop custom, matrix-free GPU kernels (specifically for SBP-SAT methods) for computations in the volume and boundaries, which show improved performance as compared to the native, matrix-explicit implementation while requiring only a fraction of memory.
- GPU-acceleration of our resulting matrix-free, preconditioned iterative scheme shows superior performance compared to state-of-the-art methods offered by NVIDIA.

Furthermore, the ubiquity of SBP-SAT methods in modern scientific computing applications means our work has the propensity to advance scientific studies currently limited to small-scale problems.

CHAPTER III

SCIENTIFIC COMPUTING LIBRARIES AND LANGUAGES

3.1 PETSc

PETSc, which stands for Portable, Extensible Toolkit for Scientific Computation, is a software library developed primarily by Argonne National Library to facilitate the development of high-performance parallel numerical code written in C/C++, Fortran and Python. It provides a wide range of functionality for solving linear and nonlinear algebraic equations, ordinary and partial differential equations, and also optimization problems (provided by TAO) on parallel computing architectures. In addition, PETSc includes support for managing parallel PDE discretizations including parallel matrix and vector assembly routines.

Key features of PETSc include:

- Parallelism: PETSc is designed for parallel computing, especially distributed-memory parallel computing architectures. It is intended to run efficiently on parallel computing systems where multiple processors or nodes communicate over the network via a message passing interface (MPI). These architectures include clusters, supercomputers, and other HPC platforms.
- Modularity and Extensibility: PETSc is highly modular and extensible, allowing users to combine different numerical techniques and algorithms to solve complex problems efficiently. It provides a flexible framework for implementing new algorithms and incorporating external libraries. It mainly contains the following objects

- * Algebraic objects

- Vectors (Vec) containers for simulation solutions, right-hand sides of linear systems
- Matrices (Mat) containers for Jacobians and operators that define linear systems
- * Solvers
 - Linear solvers based on preconditioners (PC) and Krylov subspace methods (KSP)
 - Nonlinear solvers (SNES) that use data-structure-neutral implementations of Newton-like methods
 - Time integrators (TS) for ODE/PDE, explicit, implicit, IMEX
 - Optimization (TAO) with equality and inequality constraints, first and second order Newton methods
 - Eigenvalue/Eigenvectors (SLEPc) and related algorithms
- Efficiency and Performance: PETSc is optimized for performance, with algorithms and data structures designed to minimize memory usage and maximize computational efficiency. It supports parallel matrix and vector operations as well as efficient iterative solvers and preconditioners via the objects mentioned previously
- Flexibility: PETSc supports a wide range of numerical methods and algorithms and has built-in discretization tools. It provides interfaces for solving problems in various scientific and engineering disciplines, including computational fluid dynamics (CFD), solid mechanics, etc with documented examples and tutorials for researchers.

- PETSc is portable across different computing platforms and operating systems, including UNIX/Linux, macOS, and Windows. It provides a consistent interface and functionalities across different architectures, making it easy to develop and deploy simulation code across multiple platforms.

3.2 AmgX

AmgX is a proprietary software library developed by NVIDIA to accelerate the solution of large-scale linear systems arising from finite element and finite volume discretizations typically found in computational fluid dynamics (CFD) and computational mechanics simulations on NVIDIA GPUs. AmgX stands for Algebraic Multigrid Accelerated. It provides wrappers to work with other libraries like PETSc and programming languages like Julia.

Key features of AMGX include:

- Preconditioning: AmgX offers a variety of advanced preconditioning techniques, including algebraic multigrid (AMG), smoothed aggregation and hybrid methods to accelerate the convergence of iterative solvers for sparse linear systems. These preconditioners are designed for and tested in real-world engineering problems in collaboration with companies like ANSYS, a provider of leading CFD software Fluent.
- Parallelism: AmgX is optimized for NVIDIA GPUs and provides support for OpenMP to allow acceleration via heterogeneous computing and MPI to run large simulations across multiple GPUs and clusters.
- Flexibility and Customization: AmgX offers a flexible and extensible framework for configuring and customizing the solver algorithms via JSON files.

The limitation of AmgX is due to its link with NVIDIA. It can not run on GPUs from other vendors, such as AMD and Intel. Some of the latest exascale supercomputers are built with CPUs and GPUs from AMD and Intel.

3.3 HYPRE

HYPRE is a software library of high performance numerical algorithms including preconditioners and solvers for large, sparse linear systems of equations on massively parallel computers Falgout, Jones, and Yang (2006b). The HYPRE library was created to provide users with advanced parallel preconditioners. It features parallel multigrid solvers for both structured and unstructured grid problems. These solvers are called from application code via HYPRE’s conceptual linear system interfaces Falgout, Jones, and Yang (2006a), which allow a variety of natural problem descriptions.

Key features of PETSc include:

- Scalable preconditioners: HYPRE contains several families of preconditioners focused on scalable solutions of very large linear systems. HYPRE includes ”grey box” algorithms including structured multigrid that use more than just the matrix to solve certain classes of problems more efficiently.
- Common iterative methods: HYPRE provides several common Krylov-based iterative methods in conjunction with scalable preconditioners. This includes methods for symmetric matrices such as Conjugate Gradient (CG) and nonsymmetric matrices such as GMRES.
- Grid-centric interfaces for complicated data structures and advanced solvers: HYPRE has improved usability from earlier generations of sparse linear solver libraries in that users do not have to learn complicated sparse matrix data

structures. HYPRE builds these data structures for users through a variety of conceptual interfaces for different classes of users. These include stencil-based structured/semi-structured interfaces most suitable for finite difference methods, unstructured interfaces for finite element methods, and linear algebra based interfaces for general applications. Each conceptual interface provides access to several solvers without the need to manually write code for new interfaces.

- User options for beginners through experts: HYPRE allows users with various levels of expertise to write their code easily. The beginner users can set up runnable code with a minimal amount of effort. Expert users can take further control of the solution process through various parameters
- Configuration options for different platforms: HYPRE allows a simple and flexible installation on various computing platforms. Users have options to configure for different platforms during the installation. Additional options include debug mode which offers more info and optimized mode for better performance. It also allows users to change different libraries such as MPI and BLAS.
- Interfaces to multiple languages: HYPRE is written in C, but it also provides an interface for Fortran users.

3.4 Fortran

There are many languages designed for high performance computing. Traditionally, Fortran has been used to write high performance numerical code. It is short for "Formula Translation". As the name suggest, it is one of the oldest and most enduring programming languages in scientific computing. Developed in the

1950s by IBM, it was designed to facilitate numerical and scientific computations, particularly for high-performance computing on mainframe computers.

Fortran was specifically designed for efficient numerical and scientific computing, with optimized operations handling mathematical operations, arrays, and complex computations. It provides a rich set of built-in functions and libraries for numerical analysis, linear algebra, differential equations, and other mathematical tasks. It is a statically typed language, meaning that variable types are declared explicitly at compile time and do not change during runtime. This allows compilers to perform extensive type checking and optimization to generate efficient code for execution.

Fortran codes are also highly portable across different computing platforms. While early versions of Fortran (66, 77) were designed for specific hardware architectures, modern Fortran standards, such as Fortran 90, 95, 2003, 2008, and 2018 (formerly 2015) have introduced features that enhance portability and interoperability with other languages and systems. Fortran is also known for its excellent backward compatibility, with newer language standards preserving compatibility with older databases. This allows legacy Fortran programs to continue running without modification on modern compilers and systems, ensuring long-term viability and support for existing applications, which is very important in scientific research where many simulation codes are built on top of decades of previous work.

Because of these reasons, despite its age, Fortran remains widely used in scientific and engineering computing.

3.5 C++

CHAPTER IV
PROBLEMS AND FORMULATIONS

CHAPTER V

RESULTS

5.1 Chapter Three Section One

5.1.1 Chapter three section one sub-section one.

5.1.1.1 *Chapter three section one sub-section one sub-sub-section one.*

CHAPTER VI

CONCLUSION

6.1 Chapter Four Section One

6.1.1 Chapter four section one sub-section one.

6.1.1.1 Chapter four section one sub-section one sub-sub-section one. This is a sample citation: Schwartz (2012).

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