# HIGH PERFORMANCE COMPUTING METHODS FOR EARTHQUAKE CYCLE SIMULATIONS

by

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A DISSERTATION

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DISSERTATION APPROVAL PAGE

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Title: High Performance Computing Methods for Earthquake Cycle Simulations

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DISSERTATION ABSTRACT

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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.

# CURRICULUM VITAE

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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 (∼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 (∼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); Svärd 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 Sjögreen (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

# RESULTS

## 3.1 Chapter Three Section One

### 3.1.1 Chapter three section one sub-section one.

#### *3.1.1.1 Chapter three section one sub-section one sub-sub-section one.*

# CHAPTER IV

# CONCLUSION

## 4.1 Chapter Four Section One

### 4.1.1 Chapter four section one sub-section one.

#### *4.1.1.1 Chapter four section one sub-section one sub-sub-section one.*

This is a sample citation: Schwartz (2012).

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