

Seismic Traveltime Inversion with Quantum Annealing

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ABSTRACT

This study demonstrates the application of quantum computing based quantum annealing to seismic traveltime inversion, a critical approach for inverting highly accurate velocity models. The seismic inversion problem is first converted into a Quadratic Unconstrained Binary Optimization problem, which the quantum annealer is specifically designed to solve. We then solve the problem via quantum annealing method. The inversion is applied on a synthetic velocity model, presenting a carbon storage scenario at depths of 1000-1300 meters. As an application example, we also show the capacity of quantum computing to handle complex, noisy data environments. This work highlights the emerging potential of quantum computing in geophysical applications, providing a foundation for future developments in high-precision seismic imaging.

Introduction

Quantum computing is an emerging field with significant promise for various scientific and engineering disciplines. As we stand at the frontier of this technological revolution, early-stage research in quantum computing is crucial for the advancement of geophysics. Numerous studies have begun to explore the integration of quantum computing within this field, highlighting its immense and revolutionary potential¹. For instance, quantum annealers can perform well in solving tomography optimization problems². The quantum computing is applied for binary-value full waveform inversion, addressing issues related to velocity variations³. In the frequency domain, the seismic wave equation can be reduced to a system of linear equations, allowing for the application of quantum annealing⁴. Furthermore, it has been shown that quantum annealing impedance inversion with L1 norm regularization can dramatically enhance accuracy and anti-noise capabilities⁵.

A quantum annealer is a specific type of quantum computer designed to solve optimization problems⁶. The quantum annealing process in quantum annealers can find the minimum energy state of a system, corresponding to the optimal solution of a given problem⁷. This process is achieved by utilizing quantum fluctuations, allowing the system to tunnel through energy barriers⁸. While there are various types of models in quantum computing^{9,10}, this particular feature allows quantum annealing to efficiently explore complex energy landscapes, making them particularly well-suited for solving optimization problems.

Most previous attempts to address seismic problems using quantum annealers have primarily involved relatively simple models^{11,12}. For conventional approach by classical computers, the cross-well seismic inversion between boreholes can be computationally expensive¹³, necessitating the development of new methods to tackle these challenges. Therefore, in this study, we aim to advance this line of research by applying quantum annealing to a complex problem: Seismic traveltime inversion of the velocity model between two boreholes. Our focus is on developing an inversion strategy that can accurately invert the velocity model with noisy data despite the limitation of the quantum hardware, specifically targeting carbon storage scenarios at depths of 1000-1300 meters. We use quantum annealer at D-Wave Advantage System, which has at least 5000 qubits¹⁴. Clearly, this travel-time inversion method can be applied to other acquisition geometries and data such as surface seismic, vertical seismic profile (VSP), earthquake or micro seismic data.

Results

We start the quantum annealing inversion process with exact traveltime data without noise and constant initial velocity model v_{init} of 3475 m/s. The initial model and the results of the inverted model v_{inv} at each iteration obtained after the first 9 iterations indicate rapid convergence (Fig. 1). Notably, in the first iteration, the carbon storage area is immediately identified with high precision.

The component-wise relative errors e_{ij} between the true $v_{\text{true},ij}$ and final inverted velocity model $v_{\text{final},ij}$ after 10 iterations is shown in Fig. 2. The component-wise relative errors are calculated by $e_{ij} = [v_{\text{inv},ij} - v_{\text{true},ij}] / |v_{\text{true},ij}|$. The most significant errors occurs in the shallow and deep regions with weakest constraints, yielding a maximum relative error value of about 0.326%. In contrast, the carbon storage area, spanning depths from 1100 to 1200 m, demonstrates exceptionally low errors due

Seismic Traveltime Inversion

Edward Leigh Salo

A red circular graphic with a gradient, appearing as a semi-circle or a partial circle, located to the right of the author's name.

Seismic Traveltime Inversion:

Seismic Traveltime Inversion Sergei Vasil'evich Gol'din, 1986 **Seismic Traveltime Inversion in Three-dimensional Heterogeneous Media** Christopher Jude Finn, 1990 The measured traveltimes of specular reflection events are inverted to obtain a low spatial frequency three dimensional model of the reflector geometry and the compressional wave propagation speed B spline functions are used to describe the shapes of the interfaces and the lateral variations in velocity The inversion is performed by optimizing a maximum likelihood criterion using a Newton based iteration Model updates are obtained by iterative forward modeling and solution of the linearized equation set derived from the maximum likelihood criterion In the forward problem the ray tracing equations are solved as a two point boundary value problem with appropriate internal boundary conditions at velocity discontinuities Analytic expressions for the Frechet derivatives necessary to obtain the model updates are given Conventional methods are compared to the traveltime inversion technique using synthetic examples For a relatively simple earth model containing only moderate lateral velocity variations hyperbolic moveout analysis followed by a Dix inversion produces a biased estimate of the velocity and depth This is a consequence of the simplifying assumptions of the method In this case the more general traveltime analysis provides a better result This is also true for a more complex earth model containing lateral velocity variations and interfaces with large dips and curvatures where the conventional methods fail badly Picked traveltimes are used as the data in the inversion although the use of the data semblance or the stack power along the predicted traveltime trajectory is also explored These criterion are shown to be more nonlinear than the least squares data residual measure Thus it is difficult to converge to a global minimum using these criterion and more accurate initial guesses are necessary An application of the traveltime inversion technique to a 3D marine data set is presented In this application the effects of the seismic source and the recording system on the measured traveltimes are estimated The time delay between the first break and the main pulse of the minimum phase source wavelet and the effect of the ghost reflections from the free surface are compensated for in the prediction of the measured traveltimes **An Algorithm for Implementing Traveltime Inversion for 2-D Seismic Models** Baocang Jia, 1992 Traveltime Inversion and Migration of Offset Vertical Seismic Profiling Data Edward Leigh Salo, 1989

Traveltime Inversion for a 3-D Near Surface Velocity Model James Layton Simmons, 1987 The near surface environment is often the source of the most severe lateral velocity variations present in the seismic section Near surface lateral velocity variations distort the traveltimes of deeper events and are the most serious limitation in achieving accurate structural maps This work discusses the development of a near surface velocity model for a shallow marine data set The near surface model consists of three components The first is a model of the laterally variable seafloor depth and topography Below the seafloor the model consists of the compressional wave velocity as a function of depth which reaches a maximum depth of approximately 500 meters The presence of vertical and lateral velocity gradients is recognized Embedded within this slowly

varying background velocity field are a number of local lens like velocity anomalies The lens anomalies represent the major lateral velocity variations present in the near surface Autocorrelograms of the deeper pre stack data are used to obtain the seafloor model The period of the first water layer reverberation is used to estimate the water depth These data are enhanced by a deconvolution algorithm which improves the agreement at the line intersections Measured first arrival times from the pre stack data are used to develop the subseafloor velocity model A multichannel filter algorithm is devised to estimate the traveltimes deviations produced by the lens anomalies and the common shot statics These traveltimes deviations are the higher spatial frequency components of the first arrival times and are produced by the higher spatial frequency components of the velocity model The output from the algorithm consists of a sixteen layer traveltimes velocity perturbation model The estimates of the lens anomaly and shot static produced traveltimes deviations are subtracted from the first arrival times to isolate the slowly varying background components These data are then inverted using the Generalized Linear Inversion and Tausum algorithms to obtain the laterally varying background velocity model **Library of Congress Subject Headings** Library of Congress,2002 Processing and Traveltimes Inversion of Seismic Diffractions in Anisotropic Media Yogesh Arora,2020

Introduction to Seismic Inversion Methods Brian H. Russell,1988 Inversion is defined as mapping the physical structure and properties of the subsurface of the earth using measurements made on the surface creating a model of the earth using seismic data as input In Introduction to Seismic Inversion Methods an overview of techniques used in the inversion of seismic data is provided **Library of Congress Subject Headings** Library of Congress. Cataloging Policy and Support Office,2009 **Ray Theoretical Traveltimes Inversion of Seismic Data in Two Dimensional Plane Dipping**

Layers Yeadong Kim,1987 Abstract *Recent Developments in Using Seismic Waves as a Probe for Subsurface Investigations* Rajib Biswas,2022-09-30 Seismology has come a long way Being the scientific study of seismic waves and their allied phenomena it has entered a multidisciplinary realm As the main tool it provides a wealth of information when applied systematically to dig inside the Earth structure Notwithstanding the utility of seismic waves has increased manifold Starting from knowing the epicenter of seismic events it has influenced mapping of civil engineering structures such as dams and bridges as well as huge constructions Although there is no dearth of technical papers in the area of seismic waves there is an absence of synchronized and recent coherent contents in the direction of seismic waves The book will be a unique contribution to the field of seismology with the aim of assimilating theory and practices It will provide a comprehensive glimpse of recent advancements in this area with a strong unification of theory and practices The main objective of the book is to present an in depth analysis of the theory and real implementations of seismic waves as versatile probes that would be integrated with modern and future perspectives The current and the future strategies to be discussed in the relevant areas of seismic waves will be another boon for readers This book will cater to the needs of novices researchers and practitioners Additionally the contents of the book will be useful for undergraduate as well as postgraduate students of earth science

disciplines Advances in Geophysics ,2011-08-09 The critically acclaimed serialized review journal for nearly fifty years Advances in Geophysics is a highly respected publication in the field of geophysics Since 1952 each volume has been eagerly awaited frequently consulted and praised by researchers and reviewers alike Now in its 49th volumes the Serial contains much material still relevant today truly an essential publication for researchers in all fields of geophysics **Library of Congress Subject Headings** Library of Congress. Office for Subject Cataloging Policy,1992 *Seismology and Structure of the Earth* Barbara Romanowicz,Adam Dziewonski,2010-04-20 Treatise on Geophysics Seismology and Structure of the Earth Volume 1 provides a comprehensive review of the state of knowledge on the Earths structure and earthquakes It addresses various aspects of structural seismology and its applications to other fields of Earth sciences The book is organized into four parts The first part principally covers theoretical developments and seismic data analysis techniques from the end of the nineteenth century until the present with the main emphasis on the development of instrumentation and its deployment The second part reviews the status of knowledge on the structure of the Earths shallow layers starting with a global review of the Earth s crustal structure The third part focuses on the Earth s deep structure divided into its main units the upper mantle the transition zone and upper mantle discontinuities the D region at the base of the mantle and the Earth s core The fourth part comprises two chapters which discuss constraints on Earth structure from fields other than seismology mineral physics and geodynamics Self contained volume starts with an overview of the subject then explores each topic with in depth detail Extensive reference lists and cross references with other volumes to facilitate further research Full color figures and tables support the text and aid in understanding Content suited for both the expert and non expert *Treatise on Geophysics* ,2015-04-17 Treatise on Geophysics Second Edition is a comprehensive and in depth study of the physics of the Earth beyond what any geophysics text has provided previously Thoroughly revised and updated it provides fundamental and state of the art discussion of all aspects of geophysics A highlight of the second edition is a new volume on Near Surface Geophysics that discusses the role of geophysics in the exploitation and conservation of natural resources and the assessment of degradation of natural systems by pollution Additional features include new material in the Planets and Moon Mantle Dynamics Core Dynamics Crustal and Lithosphere Dynamics Evolution of the Earth and Geodesy volumes New material is also presented on the uses of Earth gravity measurements This title is essential for professionals researchers professors and advanced undergraduate and graduate students in the fields of Geophysics and Earth system science Comprehensive and detailed coverage of all aspects of geophysics Fundamental and state of the art discussions of all research topics Integration of topics into a coherent whole Advances in Near-surface Seismology and Ground-penetrating Radar, Volume 15 Richard D. Miller,John H. Bradford,Klaus Holliger,Rebecca B. Latimer,2010-01-11 Advances in Near surface Seismology and Ground penetrating Radar SEG Geophysical Developments Series No 15 is a collection of original papers by renowned and respected authors from around the world Technologies used in the application of near surface seismology and ground penetrating radar

have seen significant advances in the last several years Both methods have benefited from new processing tools increased computer speeds and an expanded variety of applications This book divided into four sections Reviews Methodology Integrative Approaches and Case Studies Captures the most significant cutting edge issues in active areas of research unveiling truly pertinent studies that address fundamental applied problems This collection of manuscripts grew from a core group of papers presented at a post convention workshop Advances in Near surface Seismology and Ground penetrating Radar held during the 2009 SEG Annual Meeting in Houston Texas This is the first cooperative publication effort between the near surface communities of SEG AGU and EEGS It will appeal to a large and diverse audience that includes researchers and practitioners inside and outside the near surface geophysics community Publisher description *Crustal Structure of the Cascadia Fore Arc of Washington* Tom Parsons,2005 *Inversion of Traveltime Data for Seismic Velocity Structure in Three Dimensions* Joyce Chee Wu,1977 **Fundamentals of Geophysical Interpretation** Laurence R. Lines,Rachel Therese Newrick,2004 Fundamentals of Geophysical Interpretation SEG Geophysical Monograph Series No 13 is a practical handbook for the petroleum geophysicist Fundamental concepts are explained using heuristic descriptions of seismic modeling deconvolution depth migration and tomography Pitfalls in processing and contouring are described briefly Applications include petroleum exploration of carbonate reefs salt intrusions and overthrust faults The book includes past present and possible future developments in time lapse seismology borehole geophysics multicomponent seismology and integrated reservoir characterization **Engineering Seismology with Applications to Geotechnical Engineering** Öz Yilmaz,2015-05-20 The scope of engineering seismology includes geotechnical site investigations for buildings and engineering infrastructures such as dams levees bridges and tunnels landslide and active fault investigations seismic microzonation and geophysical investigations of historic buildings These projects require multidisciplinary participation by the geologist geophysicist and geotechnical and earthquake engineers A key objective of this book SEG Investigations in Geophysics Series No 17 by z Yilmaz is to encourage the specialists from these disciplines to apply the seismic method to solve the many challenging engineering problems they face The broader scope of engineering seismology also includes exploration of earth resources including groundwater exploration coal and mineral exploration and geothermal exploration While focusing on the application of the seismic method to geotechnical site investigations this book includes many case studies in all of the applications of engineering seismology

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