2024 SCEC Internships: "Impact of Empirical Green's Functions on Estimating Rupture Velocity with Back-Projection Across Various Rupture Scenarios"

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Abstract

Understanding rupture propagation on faults and accurately measuring source parameters are crucial for enhancing earthquake response times, potentially saving lives and minimizing damage. We developed a method to utilize waveform data from aftershocks of the 2011 Mw 9.1 Tohoku Earthquake and form Empirical Green's Functions (EGFs) to simulate a variety of rupture scenarios. Our analysis tested various parameters to assess their impact on rupture velocity estimation using back-projection (BP) techniques (e.g. Kiser and Ishii, 2017) on rupture scenarios with realistic slip distribution and variable rupture speeds. We examined data from two different seismic arrays (U.S. vs. European stations) and used the 6 aftershocks to form EGFs for each seismic array, applying three slip models (Uniform, Landers, and Izmit), and four rupture velocities (2 - 5 km/s). Results indicated significant artifacts in the BP leading to an underestimation of rupture velocity due to coda waves masking P-waves. The accuracy of velocity estimations was dependent on the receiver array and rupture scenario while moderate effects are also seen due to the choice of EGFs and slip models. This study fills a gap by providing controlled experiments on rupture propagation speed estimations based on EGF estimations, supporting the development of back-projection imaging for fault rupture analysis. Future work will employ the Incoherent Green's Function (IGFs) to mimic the earthquake data seen by EGFs allowing us to simulate earthquakes while bypassing limitations due to lack of EGF events.

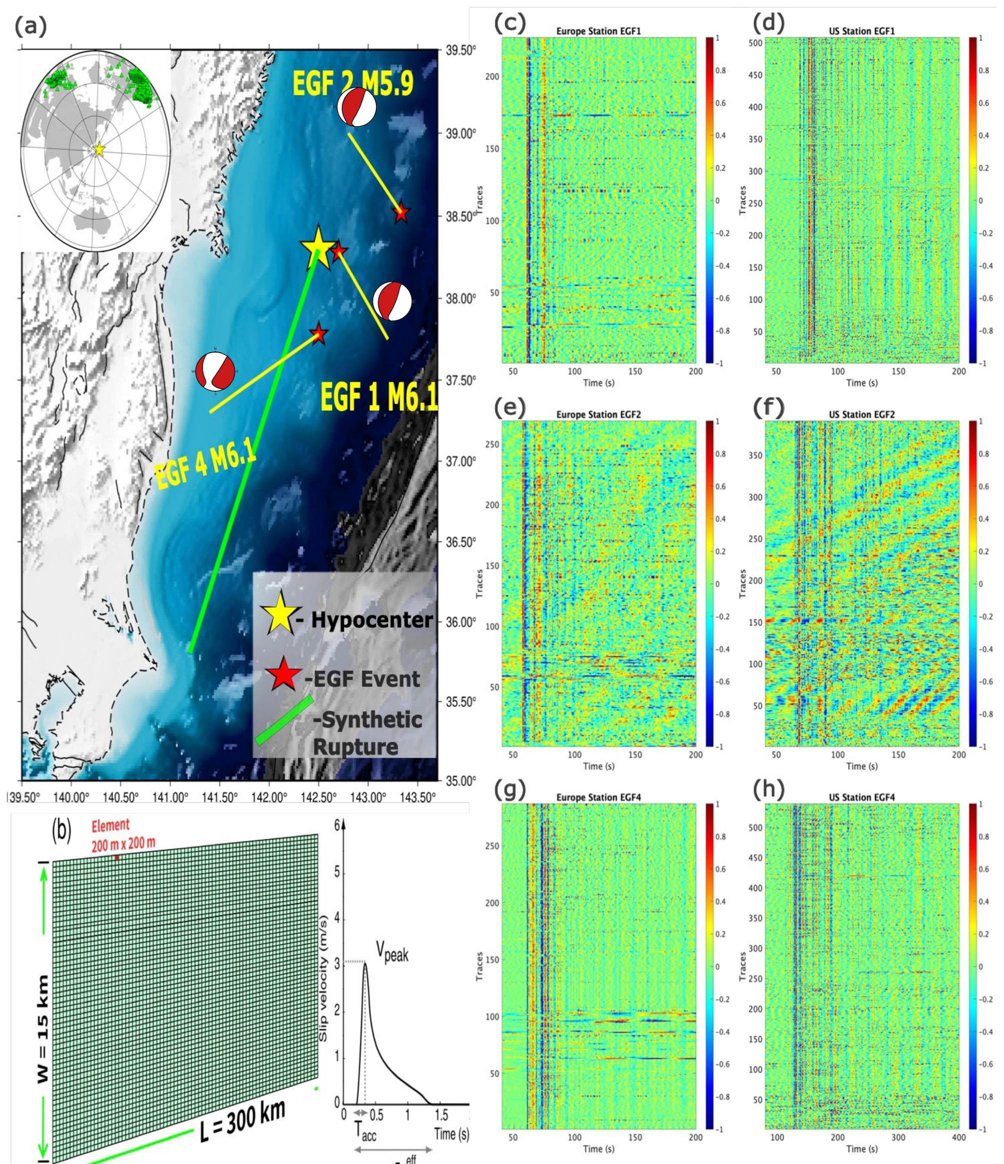

Figure 1: a) Map of main earthquake, earthquakes used for EGFs and receiver stations. b) finite fault model with slip velocity. (c-h) EGF aligned waveform plots, column 1 - Euro Station column 2 - US Station: EGFs 1, 2 and 4

Introduction

This research aims to enhance understanding of the accuracy of rupture velocity estimations by conducting synthetic BP analysis. By examining the effects of different rupture variables, we can improve the estimation of rupture propagation. Our work demonstrates the dependence of rupture velocity estimation on specific rupture scenarios as discussed in Meng (under revision BSSA 2024), by evaluating whether the findings on the 2020 M2 7.7 Cayman Trough earthquake are applicable to the Tohoku event. This study enhances our understanding of earthquake dynamics and paves the way for further testing using Incoherent Green's Function in comparison to EGF and real earthquake data. By refining these methods, we aim to improve real-time earthquake monitoring and contribute to better preparedness in seismically active regions.

Methodology

We formed EGFs by running BP codes on waveform data from six after/foreshocks from the Tohoku Earthquake recorded by a station array in the US and Europe. Developing several codes, we simulate various rupture scenarios such as uniform and realistic slips (1992 Landers Mw 7.3 (Zeng et al., 2001) and 1999 Izmit Mw 7.6 (Barka et al., 2022)) with constant velocity, as well as uniform and realistic slips on a segmented velocity rupture. By oscillating between two EGFs in the rupture propagation, we mimicked a realistic earthquake with a set input velocity. We fitted velocity slopes to the leading radiators of the back projection plots and analyzed the effects of different rupture scenarios on velocity estimation assessing how different variables influenced rupture dynamics.

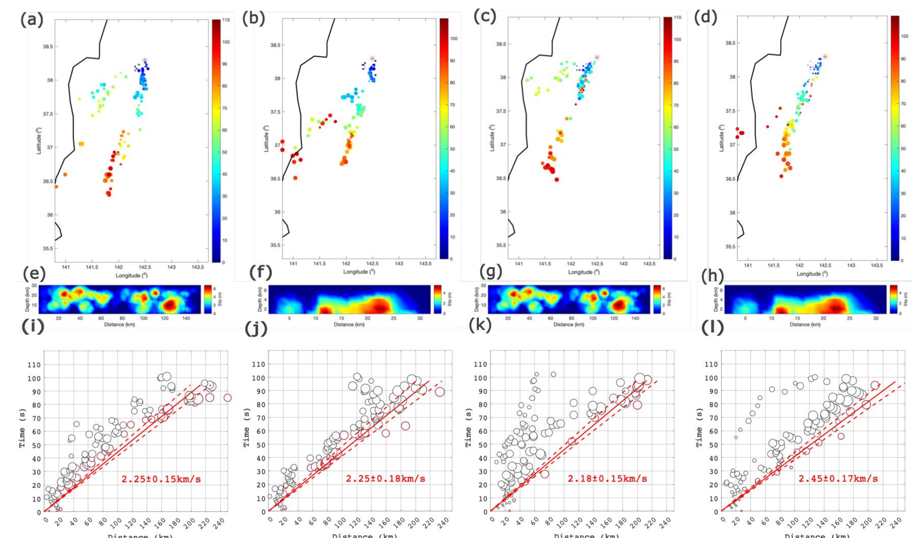

Figure 2: (a-d) BP summary, (e-h) Slip Models, (i-l) velocity fit plots. (a,e,i) - US EGF12, Model 1 (Landers), Velocity 3, (b,f,j) - US EGF12, Model 2 (Izmit), Velocity 3 (c,g,k) - US EGF14, Model 1, Velocity 3, (d,h,l) - US EGF14, Model 2, Velocity 3. Leading radiators in red

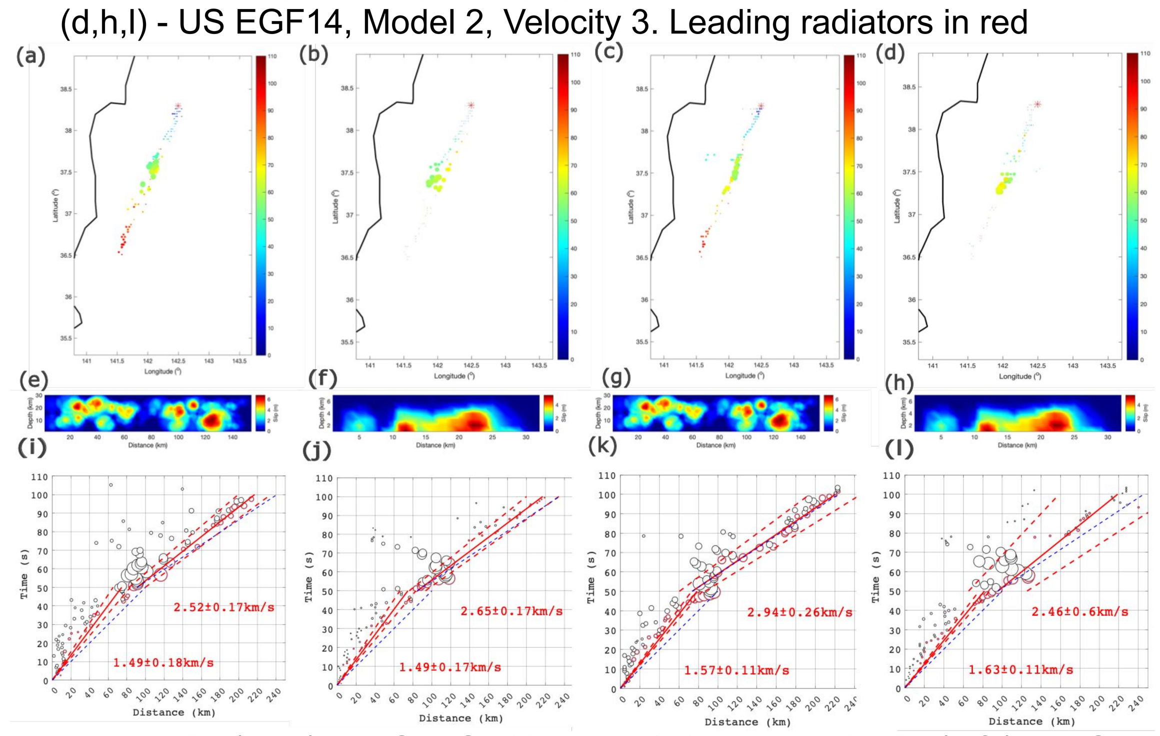

Figure 3: (a,e,i) - US EGF12, Model 1, Vjump 2->3, (b,f,j) - US EGF12, Model 2, Vjump 2->3 (c,g,k) - Euro EGF12, Model 1, Vjump 2->3, (d,h,l) - Euro EGF12, Model 2, Vjump 2-> 3

Results

An increasing underestimation on the rupture velocity for all combinations of variables was expected ($V_{EU} = 0.786Vr - 0.01$, $V_{US} = 0.832Vr - 0.04$) (figure 4 a & b). We also predicted a high dependence on the receiver array, with US/EU having large differences in best-fit lines for the input 2,3,4 km/s velocity until the 5km/s input.

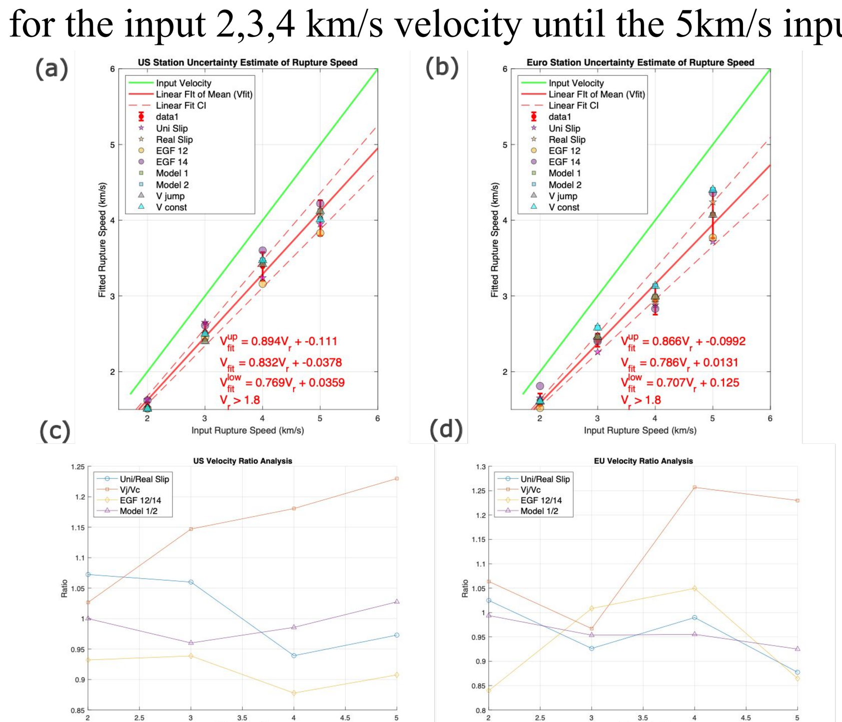

Figure 4: a & b) US and EU Station statistical velocity summary rupture vs input velocity c & d) US and EU variable ratio plotted over velocity

More Results

Moderately high dependence on EGF source combinations was not expected to be as significant as it was, overshadowing even the effects of the slip model (figure 4 a&b). We also see an increase in accuracy when applying the velocity jump and realistic slip models in comparison to the constant velocity and uniform slip models (figure 4). The fault jump scenario revealed a high underestimation and a closer/overestimation for the second portion revealing effects of high energy jumps regarding velocity estimation (figure 5 c & e).

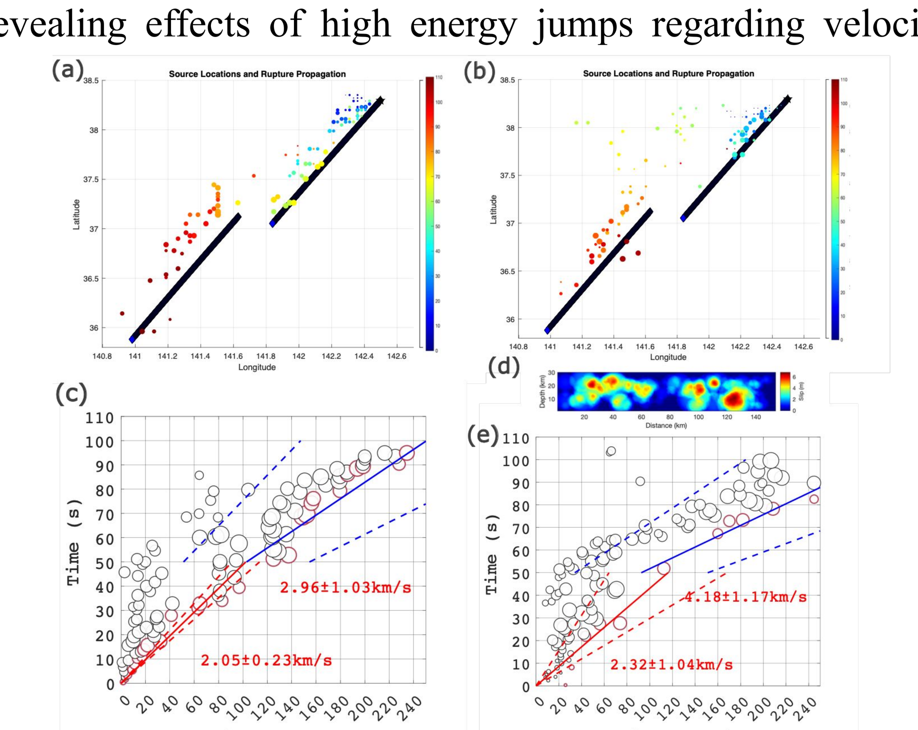

Figure 5: a & b) Summary Fault jumps 20km velocity 3, a) EGF14 unislip, b) EGF14 Model1. c & e) velocity fit models, c) - EGF14 unislip, e) EGF14 Model1, d) Slip Model 1 Landers

Conclusion/Future work

The study fills a critical gap by providing additional data on variables affecting velocity estimation of rupture fronts when applying BP, enhancing the accuracy of rupture simulations. Future research should focus on producing Incoherent Green's Functions to replicate the effects observed in EGF's where watching coherence values will be essential to prevent the overshadowing of unattenuated waves, ensuring more accurate simulations and expanding our ability to model earthquakes under a variety of conditions especially, in scenarios with limited direct data or fault geometry information.

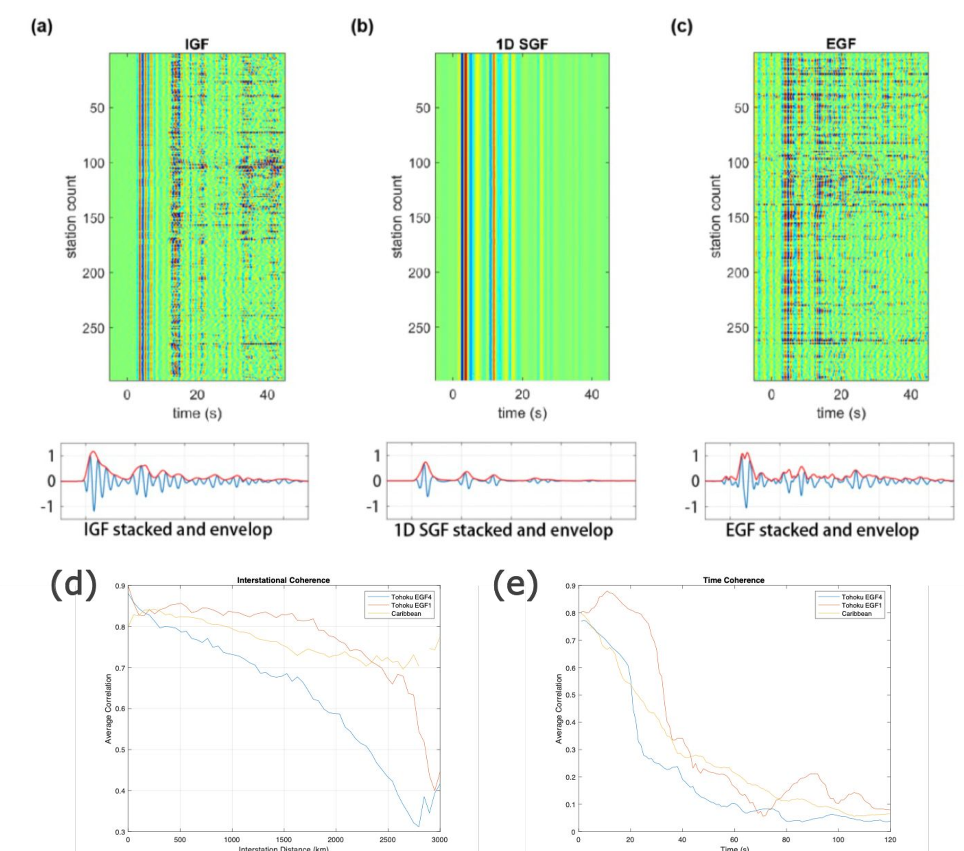

Figure 6: a) Waveform Coherence for IGF b) Waveform coherence for 1D Synthetic Green's Function c) Waveform coherence for EGF d) Interstational coherence for Tohoku EGF 1 & 4 as well as caribbean e) Time coherence for Tohoku EGF 1 & 4 and caribbean

References

[1]Meng, L., Zhou, T., Bao, H., Xu, L., & Ampuero, J. P. (2024). A Test Platform of Back-Projection Imaging with Stochastic Waveform Generation, Part I: The Role of Incoherent Green Functions.

[2]Meng, L., Bao, H., Xu, L., & Zhou, T. (2024 BSSA Review Unpublished). A Test Platform of Back-Projection Imaging with Stochastic Waveform Generation, Part II: Accuracy of Rupture Speed Estimations.

[3]Kiser, E., & Ishii, M. (2017a). Back-projection imaging of earthquakes. *Annual Review of Earth and Planetary Sciences*, *45*(1), 271–299. https://doi.org/10.1146/annurev-earth-063016-015801

[4] Zeng, Y. (2001). Viscoelastic stress-triggering of the 1999 Hector Mine earthquake by the 1992 Landers earthquake. *Geophysical research letters*, *28*(15), 3007-3010.

[5] Barka, A., Akyuz, H. S., Altunel, E. R. H. A. N., Sunal, G., Cakir, Z., Dikbas, A. Y. N. U. R., ... & Page, W. (2002). The surface rupture and slip distribution of the 17 August 1999 Izmit earthquake (M 7.4), North Anatolian fault. *Bulletin of the Seismological Society of America*, *92*(1), 43-60.

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