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Synthesizing Digital Seismic Waveforms for Earthquake Early Warning System

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Abstract: The advancement of earthquake early warning systems (EEWS) plays a pivotal role in reducing the detrimental impacts of seismic events on human lives and infrastructure. This paper introduces a novel method for synthesizing seismic digital waveforms tailored specifically for EEWS applications. The method leverages Green's functions, which effectively characterize the Earth's response to a point source. By utilizing these functions, we simulated the propagation of seismic waves originating from diverse earthquake sources and tracked their movement to a designated receiver location. To evaluate the effectiveness of this approach, we conducted a thorough validation by comparing the synthetic seismic waveforms produced by the proposed method with real seismic waveforms recorded from historical earthquakes. The results demonstrate that the synthetic waveforms align closely with the real data in terms of amplitude, frequency content, and arrival times. This accuracy underscores the potential of the proposed method to significantly enhance the precision of seismic waveform simulation, thereby strengthening the foundation of EEWS.

Keywords: Earthquake Early Warning system, Synthetic seismic waveforms, Green's functions.

1. Introduction

1.1 Background

The concept of early warning involves a series of procedures and tools used to disseminate actionable information before a potential threat to decrease the associated risks [1]. Early warning systems are increasingly recognized as a valuable and effective method for mitigating the impacts of natural disasters [2]. Consequently, they are frequently employed to issue alerts related to a variety of natural hazards, such as floods [3], tornados [4], avalanches [5], glacier lake outbursts [6], landslides [7], debris flows [8], and tsunamis [9]. EEWS can provide critical seconds of warning before the arrival of strong ground motion, potentially saving lives and reducing damage. EEWS typically works by detecting the P-waves, which travel faster than the more destructive S-waves, and using this information to estimate the magnitude and location of the earthquake. One of the key challenges in developing EEWS is generating accurate synthetic seismic waveforms for different earthquake scenarios. Synthetic seismic waveforms can be used to test, tune EEWS algorithms, and develop new EEWS methods.

Even though EEWS is not new worldwide; it has never been used in ENSN. Nonetheless, we claim that the generation of synthetic seismic waveforms using Green's function has never been used before in ENSN and will be a great asset in deploying EEWS in ENSN and it will be a great tool serving both the scientific and public communities.

1.2 Egyptian National Seismic Network (ENSN)

The Egyptian National Seismic Network (ENSN) is a network of seismic stations operated by the National Research Institute of Astronomy and Geophysics (NRIAG) in Egypt. The network consists of 70 seismic stations distributed throughout the country. The ENSN is designed to monitor seismic activity in Egypt and the surrounding regions and to provide data for research on earthquakes and other seismic phenomena. Figure 1 shows the distribution of ENSN stations.

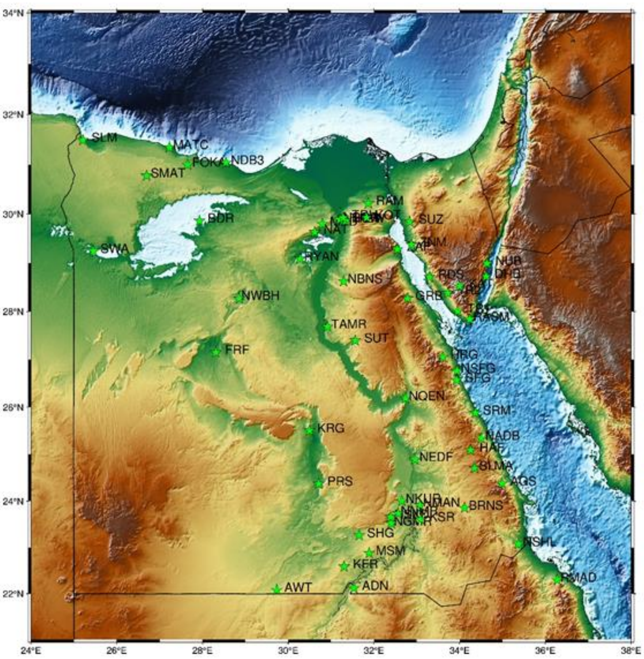

Figure 1 ENSN stations

From figures 2-a and 2-b; we can notice that many earthquakes have been detected in just (1998-2024) with the help of ENSN. Also, from Figure 1, it is clear that, although

ENSN consists of 70 stations (till now), some areas of Egypt (mainly in the western desert) have no stations to cover them.

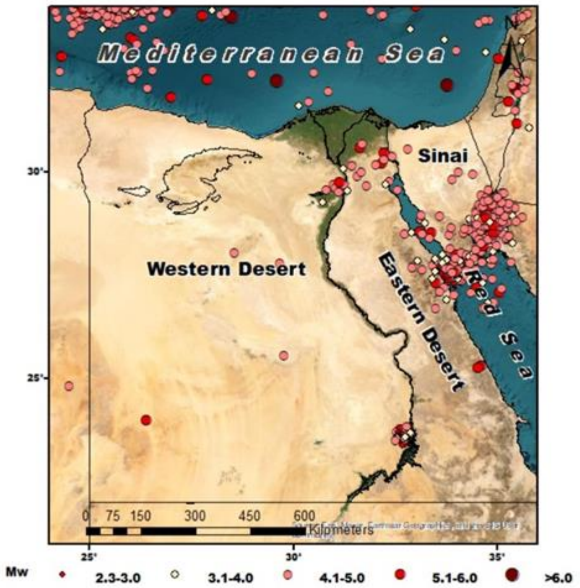

Figure 2-a Recorded events from 1900 to 1998

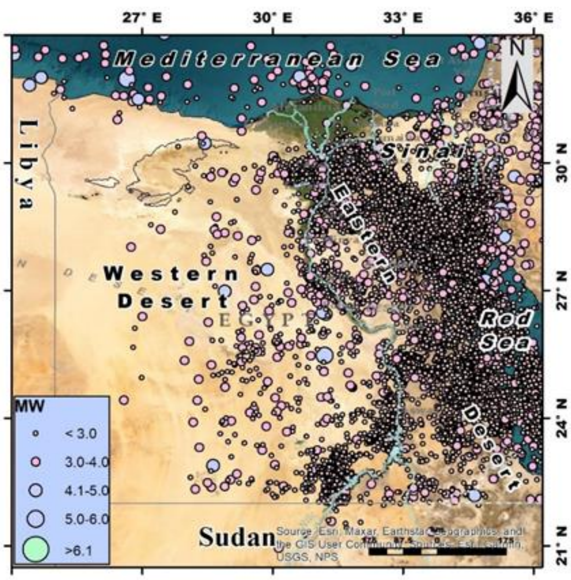

Figure 2-b Recorded events from 1998 to 2024

To overcome this problem, we have to install more stations in remote areas, this may sound like the obvious (and ideal) solution, but it is challenging to establish for some reasons including:

1. High cost.
2. Establishing and maintaining the stations in very harsh environments is difficult.

For those reasons and others, the only viable solution is to generate accurate (or at least similar) synthetic seismic waveforms for different earthquake scenarios that may happen in those empty regions, those synthetic waveforms will help seismologists get a better understanding of the areas of interest even though there are no real stations in those areas.

2. Synthetic Seismic Waveform Methods

Generating synthetic seismic waveforms involves simulating the complex vibrations produced by earthquakes traveling through the Earth's crust. There are several methods for generating synthetic earthquake waveforms, each with its strengths and limitations. The most appropriate method depends on the specific purpose and desired level of accuracy. Here are some of the common approaches:

1. Deterministic methods:

- Finite difference method (FDM): This method numerically solves the wave equation based on the earthquake source parameters (fault geometry, slip distribution, etc.), Earth's material properties, and propagation geometry. It offers high accuracy but can be computationally expensive for large or complex models [10] and [11].
- Spectral element method (SEM): Similar to FDM but uses Fourier transforms to efficiently solve the wave equation in specific frequency bands. This allows for faster calculations but may not be as accurate for high-frequency or near-field effects [12].
- Green's function approach: This method uses pre-computed solutions for point source earthquakes (Green's functions) to represent the earthquake source. Superposition of Green's functions with different source parameters can then be used to simulate more complex events. This method is efficient but requires a pre-computed Green's function database for the specific region of interest [13].

2. Stochastic methods:

- Random noise source models: These models represent the earthquake source as a random distribution of point sources within the fault area. This approach is computationally efficient but may not capture the specific features of real earthquake ruptures.
- Brune model: This widely used model represents the earthquake source as a simple pulse with exponential rise and decay time. It is easy to implement but may not be accurate for complex rupture processes.
- Empirical Green's function (EGF) method: This method utilizes real waveform recordings from small earthquakes as surrogates for individual point sources. Superposition of EGFS can then be used to simulate larger events. This approach can capture realistic source details but requires the availability of appropriate EGF data for the region [14].

3. Machine learning methods:

- Generative adversarial networks (GANs): These neural networks can learn from real earthquake waveform data and generate new, realistic-looking synthetic waveforms. This method is promising for data augmentation and improving earthquake detection algorithms but still under development [15].
- Physics-informed neural networks (PINNs): These networks incorporate physical laws into their architecture, allowing them to learn both data patterns and underlying physical processes. This approach has the potential to generate accurate and flexible synthetic

waveforms but requires careful training and validation [16].

- Denoising Diffusion Probabilistic Models (DDPMs): are generative models that work by iteratively adding noise to an input signal (like an image, text, or audio) and then learning to denoise from the noisy signal to generate new samples. This can be used to generate high-resolution seismic waveforms with a latent diffusion model [17].

In addition to the methods above, various software packages and online tools are available for generating synthetic earthquake waveforms. Some popular options include:

- SPECFEM2D [18]
- OpenSees [19]
- EQSIM [20]
- Pyrocko [21]

Choosing the best method for your specific needs depends on several factors, such as:

- Desired level of accuracy: If you need highly accurate waveforms for research or engineering applications, deterministic methods like FDM or SEM may be the best choice. However, if your goal is faster simulations or exploring broader parameter space, stochastic or machine learning methods may be sufficient.
- Computational resources: Deterministic methods can be computationally expensive, especially for complex models or large datasets. Stochastic and machine learning methods are generally faster but may require specialized software or hardware.
- Available data: Some methods, like the EGF approach, require specific types of data that may not be readily available for all regions.

3. Methodology

In the proposed work, we used Green’s function method. A Green's function represents the response of a system to a specific impulse or point source excitation. In seismology, Green's function for a particular Earth model describes the ground motion at a receiver location due to a point source force (delta function) acting at a source location within the model.

The process of generating synthetic waveform using Green's functions involves:

1. Pre-compute Green's functions: First, we must calculate Green's functions for a range of point source locations and source mechanisms (e.g., slip direction, rupture type) within the Earth model of interest. This can be done using numerical methods like finite difference or spectral element methods.
2. Represent the earthquake source: The earthquake source is discretized into smaller subfaults or point sources with specific slip distributions and source times.
3. Superposition of Green's functions: For each subfault, the corresponding Green's function is scaled by the slip amplitude and time-shifted according to the source time. The contributions from all subfaults are then summed up at each receiver location to obtain the synthetic seismogram.

Advantages of the Green's function approach:

- High accuracy: Can accurately capture the complex wave propagation effects and near-field ground motions due to realistic earthquake source mechanisms.
- Flexibility: Can be used to simulate earthquakes with various source complexities and scenarios by modifying the subfaulting, slip distributions, and source times.
- Computational efficiency: Once the Green's functions are pre-computed, the synthesis of waveforms for different sources is relatively fast.

Limitations of the Green's function approach:

- Computationally expensive: Pre-computing Green's functions for a wide range of scenarios can be computationally demanding, especially for 3D models.
- Requires accurate Earth model: The accuracy of the synthetic waveforms depends on the accuracy of the underlying Earth model used for calculating the Green's functions.
- May not capture all complexities: Real earthquake ruptures can be highly complex and involve non-linear processes that may not be fully captured by Green's function approach.

Overall, Green's function approach is a valuable tool for generating synthetic earthquake waveforms for various purposes, including:

- Earthquake hazard assessment and ground motion prediction
- Validation of earthquake source inversion techniques
- Development and testing of earthquake early warning systems
- Understanding the physics of earthquake rupture and wave propagate

3.1 Proposed framework

In the proposed work, we developed a Python code to build the green function using Fomosto, Green’s function database management tool by using QSEIS code to calculate synthetic seismograms based on a layered viscoelastic half-space model [22] and QSSP code to calculate complete synthetic seismograms of a layered, self-gravitating spherical Earth using the normal mode theo*ry* [23].

Figure 3 demonstrates the flowchart of the developed Python program.

The first step in the proposed code is the installation of both QSEIS and QSSP. We used them to start the process of building an empty Greens function. To start building the Greens function; the earth’s model must be provided of the area of interest. Then the Greens function will be ready regarding the provided earth model. To start the generation of the synthetic seismic waveforms; a series of steps has to be done; starting with loading earthquakes’ raw data from which we will extract both the actual seismic data and source parameters which will be fed into the Green function to generate the synthetic waveforms. By comparing the actual seismic waveforms with the generated synthetic data we calculate the mean difference between them. If the error is high, the earth model we have to updated and the process starts again, otherwise in case of low error the program will terminate.

3.2 Data set

To validate the proposed method of generating the synthetic seismic waveforms; we used a group of recorded earthquakes continuous data by ENSN to test the proposed code. We will list here only two earthquakes:

- (2010-07-15_11-25, 28.955°N, 34.8508°E, 4.2 MW)
- (2023-02-06_01-17, 37.166°N, 37.032°E, 7.8 MW)

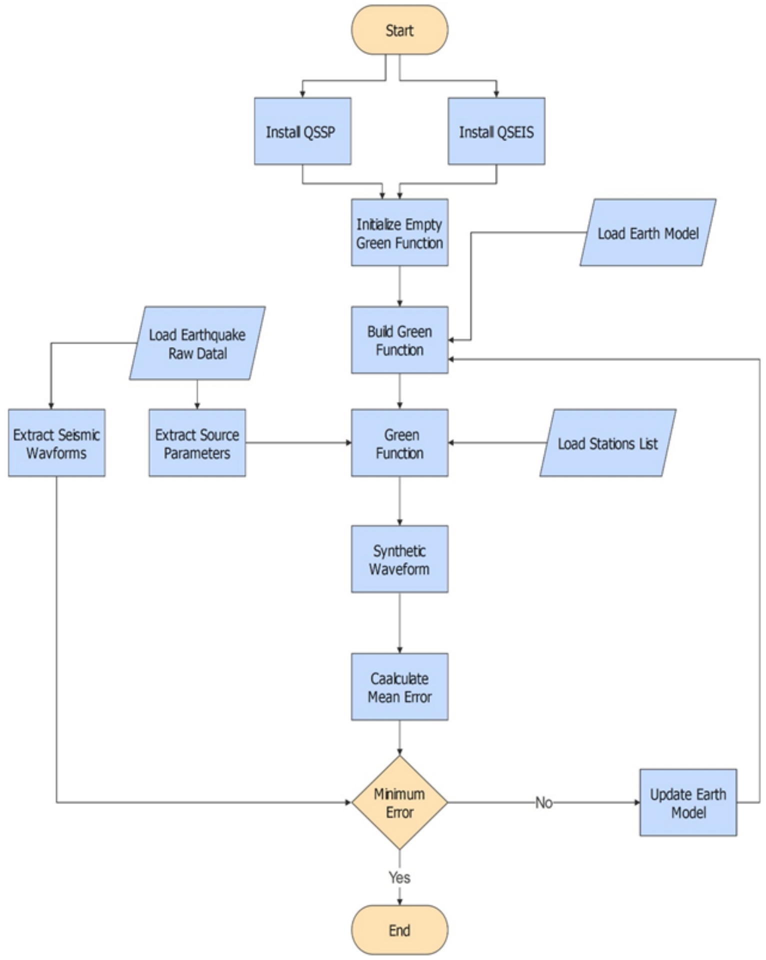

Figure 3 Procedure Flowchart

4. Results

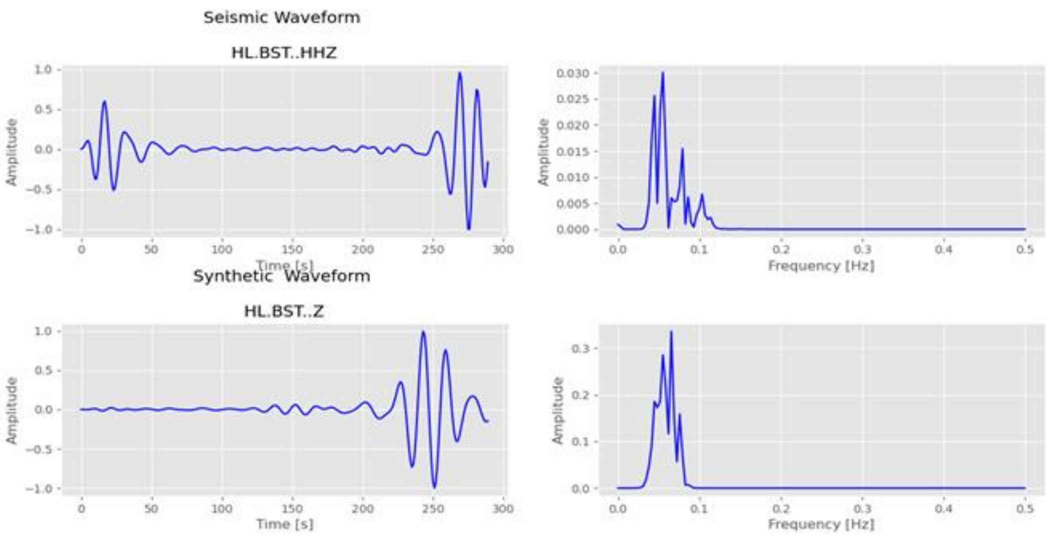

Figure 4 Earthquake 2010-07-15

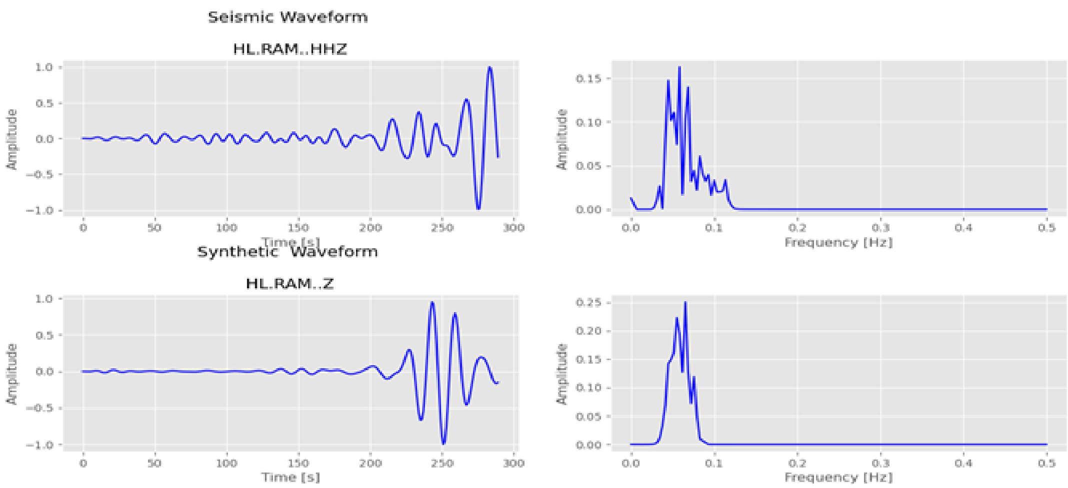

Figure 5 Earthquake 2023-02-06

We can see from Figures 4 and 5 similarities between the actual seismic and synthetic waveform, even though they are not completely identical. We can say that the reason for this is the simple claustral model we used in the generation of Green's function in which we have assumed a constant velocity of the wave propagation in each layer. In reality, this is not the actual case. For this reason, in future work, we will integrate the proposed model with a genetic algorithm to generate a more realistic claustral model for each area.

5. Conclusions

In conclusion, the proposed work demonstrates a promising method for generating accurate synthetic seismic waveforms for Earthquake Early Warning Systems (EEWS) using Green's functions. This method offers several key benefits:

- Improved EEWS testing and tuning: By simulating various earthquake scenarios, the proposed method allows for more thorough testing and fine-tuning of EEWS algorithms, potentially leading to faster and more accurate warnings.
- Development of new EEWS methods: The ability to generate realistic seismic waveforms opens doors for developing and testing new approaches to EEWS, potentially enhancing their effectiveness in different geographical contexts.
- Validation through real-world data: The successful comparison of synthetic waveforms with real ones validates the accuracy and reliability of the proposed method, further strengthening its potential for practical applications.

Overall, the proposed work contributes significantly to the advancement of EEWS technology, with the potential to save lives and mitigate earthquake damage. Continued research and refinement of the proposed method hold promise for even greater accuracy and effectiveness in future EEWS implementation.

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