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IMAGING DISPERSION CURVE OF DISPERSIVE WAVES USING SHORT-TIME FOURIER TRANSFORM: 2025 MYANMAR EARTHQUAKE M 7.7

PENCITRAAN KURVA DISPERSI GELOMBANG DISPERSIF MENGGUNAKAN TRANSFORMASI FOURIER WAKTU PENDEK: GEMPA BUMI MYANMAR 2025 M 7,7

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Abstract. Understanding of Earth's subsurface is crucial for mitigating geological hazards, particularly earthquakes. A key parameter for subsurface characterization is the surface wave dispersion curve, which strongly reflects shear wave velocity (Vs) at various depths. This study presents an extraction of dispersion curves from earthquake signals using the Short-Time Fourier Transform (STFT). The STFT method enables the analysis of non-stationary signals like earthquake signals by dividing them into small segment, assumed-stationary segments, then applying the Fourier Transform to each segment. This process generates a time-frequency spectrogram that represents the evolution of frequencies over time. Myanmar earthquake M 7.7 is one of the greatest earthquakes that have damaging impacts. We used three inline stations for evaluating the waveform at CHTO (Chiang Mai, Thailand), KAPI (Sulawesi, Indonesia), and WRAB (Tennant Creek, NT, Australia). Waveform for KAPI and WRAB stations categorized teleseismic event represented good penetration waves to image deeper subsurface layes. Surface waves clearly seen at KAPI and WRAB classified by very low frequency and high amplitude in wave group train. The spectrogram, energy peaks at each frequency can be identified, which directly correlate with the group velocity of the surface waves. STFT successfully extract dispersion curve of surface waves at KAPI and WRAB station. However, the dispersion curve could not be extracted at CHTO station because its too close to the epicentre resulted in significant interference of waves phase caused inseparable frequency spectrum on each wave phases. Remarks on the study is stations nearer to the epicenter exhibit a higher frequency and broader range of dominant frequency, while those farther away show a lower frequency and narrow frequency range. The advantage of the STFT method lies in its ability to enable the identification of dispersion modes with good time-frequency resolution.

Abstrak. *Pemahaman tentang bawah permukaan Bumi sangat penting untuk mitigasi bahaya geologis, khususnya gempa bumi. Parameter kunci untuk karakterisasi bawah permukaan adalah kurva dispersi gelombang permukaan, yang sangat mencerminkan kecepatan gelombang geser (Vs) pada berbagai kedalaman. Studi ini menyajikan ekstraksi kurva dispersi dari sinyal gempa bumi menggunakan Transformasi Fourier Waktu Pendek (STFT). Metode STFT memungkinkan analisis sinyal non-stasioner seperti sinyal gempa bumi dengan membaginya menjadi segmen-segmen kecil, yang diasumsikan stasioner, kemudian menerapkan Transformasi Fourier ke setiap segmen. Proses ini menghasilkan spektogram waktu-frekuensi yang mewakili evolusi frekuensi dari waktu ke waktu. Gempa bumi Myanmar M 7,7 adalah salah satu gempa bumi terbesar yang memiliki dampak merusak. Kami menggunakan tiga stasiun inline untuk mengevaluasi bentuk gelombang di CHTO (Chiang Mai, Thailand), KAPI (Sulawesi, Indonesia), dan WRAB (Tennant Creek, NT, Australia). Bentuk gelombang untuk stasiun KAPI dan WRAB yang dikategorikan sebagai peristiwa telesismik mewakili gelombang penetrasi yang baik untuk mencitrakan lapisan bawah permukaan yang lebih dalam. Gelombang permukaan terlihat jelas di KAPI dan WRAB diklasifikasikan berdasarkan frekuensi sangat rendah dan amplitudo tinggi dalam rangkaian grup gelombang. Spektogram, puncak energi pada setiap frekuensi dapat diidentifikasi, yang berkorelasi langsung dengan kecepatan grup gelombang permukaan. STFT berhasil mengekstraksi kurva dispersi gelombang permukaan di stasiun KAPI dan WRAB. Namun, kurva dispersi tidak dapat diekstraksi di stasiun CHTO karena terlalu dekat dengan episentrum mengakibatkan interferensi fase gelombang yang signifikan yang menyebabkan spektrum frekuensi yang tidak terpisahkan pada setiap fase gelombang. Keterangan pada penelitian ini adalah stasiun yang lebih dekat ke episentrum menunjukkan frekuensi yang lebih tinggi dan rentang frekuensi dominan yang lebih luas, sedangkan yang lebih jauh menunjukkan frekuensi yang lebih rendah dan rentang frekuensi yang sempit. Keuntungan dari metode STFT terletak pada kemampuannya untuk memungkinkan identifikasi mode dispersi dengan resolusi waktu-frekuensi yang baik.*

1. INTRODUCTION

Earthquake is a process of releasing energy from within the earth that suddenly occurs. The ground motion response caused by an earthquake is highly influenced by the geological conditions which the seismic waves travel. Inhomogeneity of the medium causes waves to undergo interference, diffraction, and attenuation mechanisms, resulting in a very complex subsurface information on seismograms. Shallow earthquakes will produce a larger of surface waves than deep earthquakes. Surface waves have low frequencies and high amplitudes, are responsible for infrastructure damage on the surface (Westermo, 1983). Surface waves have good sensitivity to the distribution of S-wave velocity in a medium. A characteristic of surface waves is that they are dispersive, meaning the wave velocity depends on the frequency / time.

Dispersive wave analysis can be performed using frequency-time analysis (FTAN). FTAN can be carried out using several methods, including the Multiple Filter Technique (MFT)

(Dziewonski et al., 1969), Short-Time Fourier Transform (STFT) (Griffin & Lim, 1984), and wavelet transform (Abbate et al., 1995). MFT involves applying multiple frequency filters with varying ranges, thus the determination of the filter range significantly affects the results. This process yields a frequency-time relationship, from which the wave group velocity can be obtained as the maximum envelope value for each frequency (Dziewonski et al., 1969; Levshin et al., 1972). However, MFT has poor frequency-time resolution compared to the Short-Time Fourier Transform. The Short-Time Fourier Transform (STFT) is a popular method in signal analysis due to its ability to analyze non-stationary and noisy signals. STFT is frequently used in acoustic signal processing, radar technology, and even machine fault detection (Griffin & Lim, 1984; Zhivomirov, 2019; Kamiel & Fadilah, 2023). The Short-Time Fourier Transform (STFT) can be used to extract seismic wave dispersion curves more effectively and accurately compared to other conventional methods like the Fast Fourier Transform (FFT) and Multi-channel Filter (MFT). Technically, the Waveform Transform (WT) method is identical to STFT combined with a wavelet function. The choice of wavelet type significantly impacts the results of signal analysis. While the WT method is quite powerful for signal analysis, its computational implementation can be complex (He, 2006; Li et al., 2009).

In surface wave exploration, dispersive properties can be utilized to understand subsurface structures based on S-wave velocity profile. The dispersion curve shows relationship between wave velocity and frequency which used to study the physical parameters of rocks and geological structures, all derived from S-wave velocity characteristics (Meza-Fajardo, 2021; Yao et al., 2023). However, extracting the dispersion curves from seismogram often presents challenges due to inherent noise level, which increases the complexity of seismogram signals. Consequently, the accurate extraction of dispersion curves is a crucial stage before performing the inversion process for S-wave velocity structures (Hong et al., 2005; Su et al., 2021; Yao et al., 2023).

The objective of the study is to extract dispersion curves using the Short-Time Fourier Transform (STFT) method and evaluate its performance based on earthquake signals. The findings from this research are expected to contribute to the development of more accurate and effective methods for dispersion curve analysis. Ultimately, accurate curve extraction should enhance our understanding of subsurface of the earth.

2. LITERATURE REVIEW

The Fast Fourier Transform (FFT) is an optimized algorithm of the Discrete Fourier Transform (DFT). It works by decomposing the DFT into shorter segments, significantly increasing computational speed and reducing the DFT's complexity (Oberst, 2007). FFT analysis can accurately extract the frequency content from a certain periodic signal (Takatsuka, 1992). Bracewell (2000) applied the Fourier concept to analyze signals and understand wave propagation phenomena. While the resulting Fourier spectrum can reveal the energy of a wave, this analysis has limitations when dealing with non-stationary signals.

The magnitude – frequency response is characteristic of a bandpass filter, which is a quantification of how much the amplitude of the waveform at a specific frequency range is amplified or suppressed. The frequency response $H(\omega)$ is in general is complex, with real and imaginary components. In the frequency domain, the convolution of an input signal $X(\omega)$ with a frequency response $H(\omega)$ produces an output signal $Y(\omega)$ which is also a complex function (Krishnan, 2021).

$$Y(\omega) = X(\omega).H(\omega) \quad (1)$$

Earthquake signals are inherently non-stationary; the radiated signals exhibit varying spectral content and spectral changes throughout the earthquake's duration. The Short-Time Fourier Transform (STFT) is a mathematical equation designed to analysis such non-stationary signals (Goyal & Pabla, 2015). Simply put, STFT applies the basic concept of Fourier transform to each desired time segment (window length). STFT allows for the extraction of frequency content within each segment. The choice of window length in STFT is unique: a larger window segment increases frequency resolution but decreases time resolution. Conversely, a smaller window segment decreases frequency resolution but increases time resolution. In essence, STFT simultaneously applies the Fourier transform in both the time and frequency domains. The STFT method effectively solves the problem of non-stationary signals, where the signal's frequency content varies with time. Mathematically, the STFT equation can be written as follows:

$$STFT(f,t) = \int_{-\infty}^{\infty} s(\tau)\, h^*(\tau - t)\, e^{-i2\pi f\tau} d\tau \qquad (2)$$

where ω and t represent frequency and time, respectively. x(t) is the input signal, w(t) is the window function used, and the asterisk $*$ denotes a complex conjugate. The STFT method has been widely used for analysing time-frequency content due to its superiority in solving problems related to non-stationary signals. The simultaneous transformation of seismogram signals into the time-frequency domain is displayed in the form of a spectrogram (Tian, 2021; Manhertz & Bereczky, 2021; Kakhki et al., 2024).

The spectrogram provides a visualization of wave propagation variations in the time-frequency domain, showing the distribution of wave energy spectra (Rosyid & Yusoff, 2018). The highest energy spectrum correlates with the wave velocity at a specific frequency or period. By picking the highest energy values from the spectrogram, we can determine the group velocity dispersion curve (Zhang et al., 2023).

3. RESEARCH METHODS

On March 28, 2025, Myanmar was hit by a major "supershear" M 7.7 earthquake. The earthquake had a strike-slip mechanism and a shallow hypocentre at a depth of 10 km (USGS). A typical characteristic of "supershear" earthquakes is that they can cause significant damage at relatively greater distances from the epicentre. This was supported by the fact that Bangkok, Thailand, experienced considerable damage, in addition to the effects of wave amplification (Shahzada et al., 2025). In the study we used seismogram from IRIS. Data was collected from CHTO (Chiang Mai, Thailand), KAPI (Sulawesi, Indonesia), and WRAB (Tennant Creek, NT, Australia). The recordings length with of 60 minutes from the earthquake event with a sampling rate of 40 Hz. We choose KAPI and WRAB station because they have a great distance from the epicentre, so the recorded waveform contain a good wave penetration to represent deeper subsrface layers.

Fast Fourier Transform (FFT) analysis was performed to evaluate the dominant frequencies contained in the seismogram signals. The identified dominant frequency of the seismograms was used to define the frequency band for the bandpass filter process. A Bandpass filter empower the specific range of frequencies to pass through of the signals while attenuating frequencies outside of that range. The attenuation of the amplitude was affected by the magnitude response of a bandpass filter. The frequency range for each station was choosen based on its dominant frequency contain, establishing specific lower and upper frequencies. Therefore, the frequencies outside of this range were rejected, a process presented by the magnitude response of the bandpass filter. The bandpass's magnitude response shows in the **Figure 2c** for CHTO station, **Figure 3c** for KAPI station, and **Figure 4c** for WRAB station. The filtering process itself was conducted by convolving the signal with the magnitude – frequency response of bandpass filter. The Short-Time Fourier Transform (STFT) process used a Hamming window function (periodic). Hamming window function was chosen to reduce Gibbs effect and ensure a smooth transition between frequency bands when the signal devided into multiple windows.

4. RESULTS AND DISCUSSION

The selection of the three stations was based on their inline configuration relative to the earthquake's epicenter (**Figure 1**). This alignment ensures that the wave propagation, from the nearest to the farthest station, exhibits a clear wave relationship as a function of distance. In the study, we only use the vertical component of the seismogram, so the obtained group velocities are associated with Rayleigh surface wave velocity.

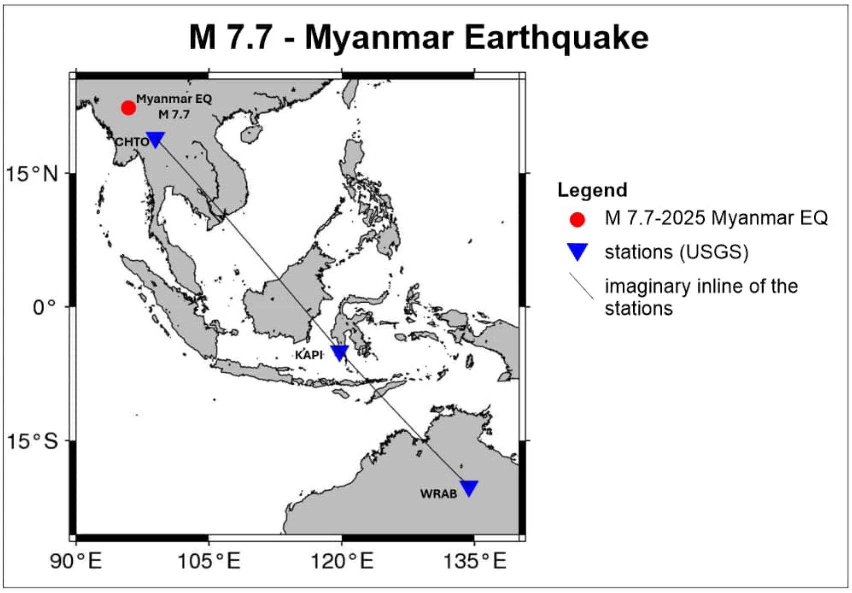

Figure 1. The location of the stations represented by blue triangle and mainshock of Myammar earthquake M 7.7 represented by red circle. Black line shows inline the stations configuration.

Figures 2 (**a** and **b**) present the Myanmar earthquake recordings at CHTO station in Thailand for 60 minutes after the Myanmar mainquake, being the closest to the epicenter, exhibits a higher amplitude and a shorter event duration. To analysis the frequency content, the waveform was transformed into frequency domain using Fast Fourier Transform (FFT), which revealed a broad spectrum as a multi peaks of dominant frequencies at CHTO. The frequency range was chosen by the clearly frequency dominant in ranges of 0.035 Hz to 0.098 Hz. **Figure 2c** presents the magnitude – frequency response of the bandpass filter. The magnitude – frequency demonstrates the filter's characteristic of passing signals within its specified frequency range (bandpass) and attenuating signals in the outer the its bandpass.

Figures 3 (**a** and **b**) present the Myanmar earthquake recordings at KAPI station in Indonesia for 60 minutes after the Myanmar mainquake. To analysis the frequency content, the waveform was transformed into frequency domain using Fast Fourier Transform (FFT), which revealed two peaks of frequency contain at KAPI. The frequency range was chosen by the clearly frequency dominant in ranges of 0.008 Hz to 0.040 Hz as a first peak. **Figure 3c** presents the magnitude – frequency response of the bandpass filter. The magnitude – frequency demonstrates the filter's characteristic of passing signals within its specified frequency range (bandpass) and attenuating signals in the outer the its bandpass.

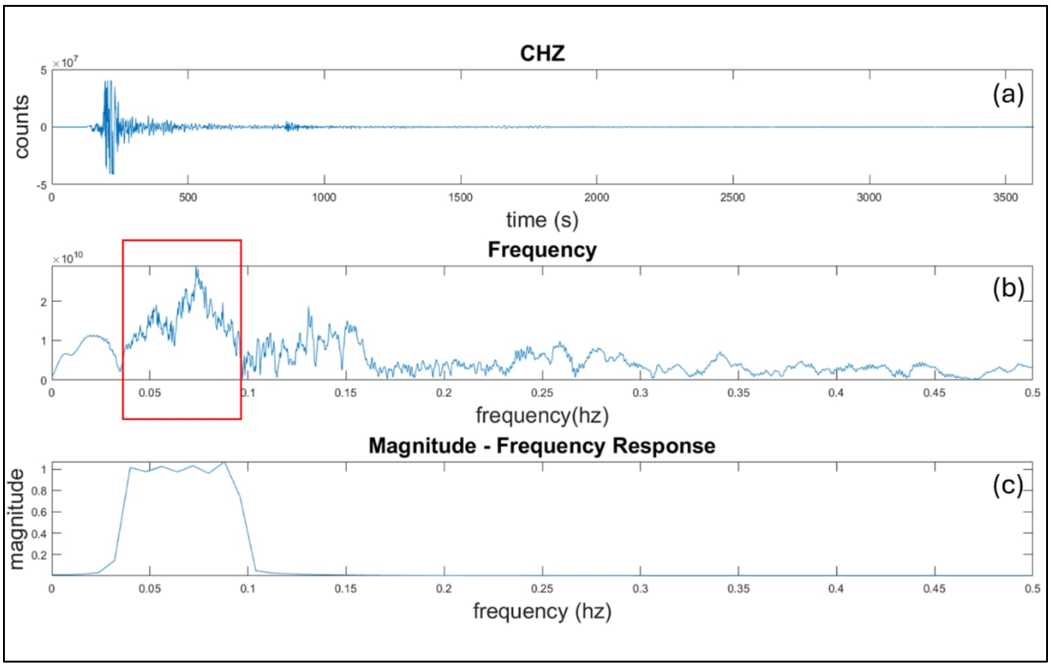

Figure 2. (a) Waveform at CHTO station (Chiang Mai, Thailand) that recorded for 60 minutes after the Myanmar mainquake, (b) The Fast Fourier Transform (FFT) process reveals the frequency content of the waveform at CHTO station and the red box shows the dominant frequency range, with lower and upper frequencies of 0.035 Hz and 0.098 Hz, respectively, and (c) magnitude - frequency response of bandpass filter presents the amplitude attenuation based on the magnitude response.

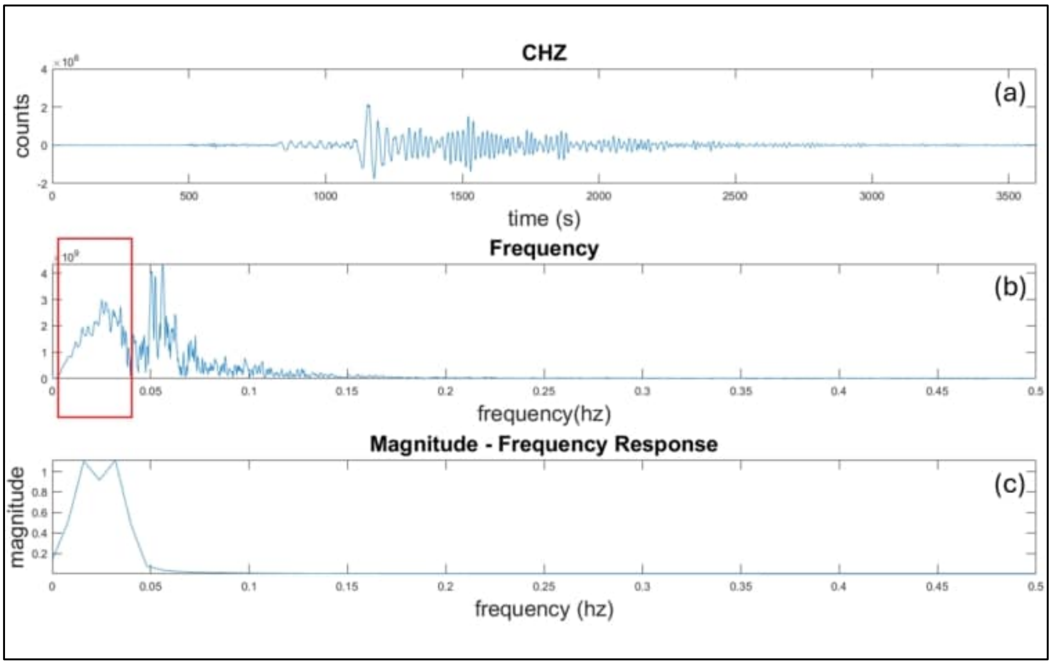

Figure 3. (a) Waveform at KAPI station (Sulawesi, Indonesia) that recorded for 60 minutes after the Myanmar mainquake, (b) The Fast Fourier Transform (FFT) process reveals the frequency content of the waveform at KAPI station and the red box shows the dominant frequency range, with lower and upper frequencies of 0.008 Hz and 0.040 Hz, respectively, and (c) magnitude -

frequency response of bandpass filter presents the amplitude attenuation based on the magnitude response.

Figures 4 (**a** and **b**) present the Myanmar earthquake recordings at WRAB station in Indonesia for 60 minutes after the Myanmar mainquake. To analysis the frequency content, the waveform was transformed into frequency domain using Fast Fourier Transform (FFT), which revealed dominantly in single peaks of frequency contain at WRAB. The frequency range was chosen by the clearly frequency dominant in ranges of 0.008 Hz to 0.040 Hz as a single peak. **Figure 3c** presents the magnitude – frequency response of the bandpass filter. The magnitude – frequency demonstrates the filter's characteristic of passing signals within its specified frequency range (bandpass) and attenuating signals in the outer the its bandpass.

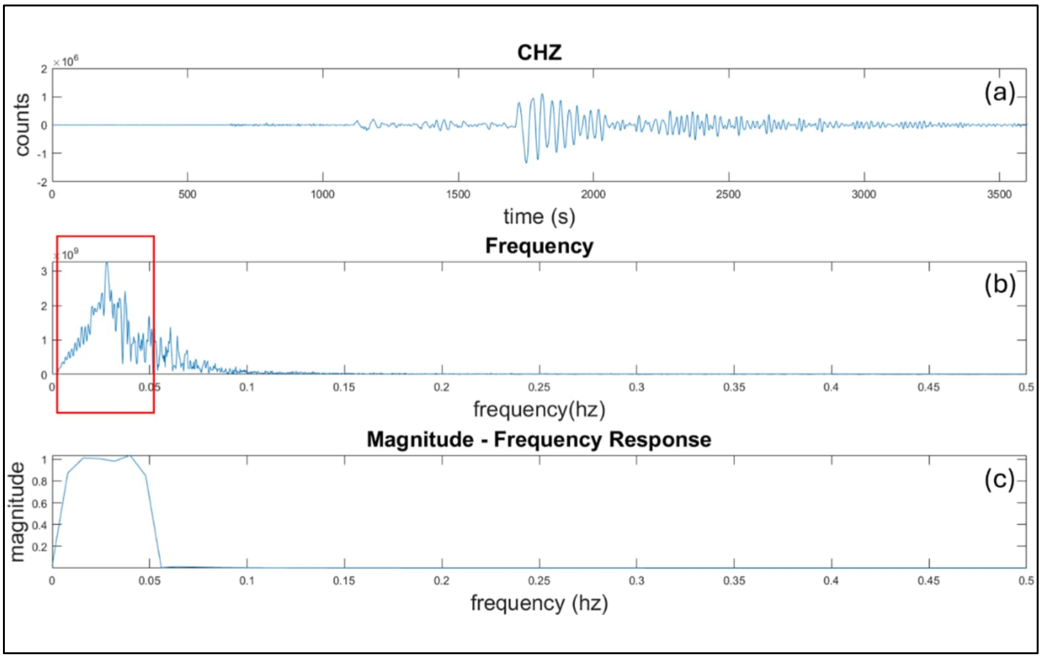

Figure 4. (a) Waveform at WRAB station (Tennant Creek, NT, Australia) that recorded for 60 minutes after the Myanmar mainquake, (b) The Fast Fourier Transform (FFT) process reveals the frequency content of the waveform at WRAB station and the red box shows the dominant frequency range, with lower and upper frequencies of 0.005 Hz and 0.051 Hz, respectively, and (c) magnitude - frequency response of bandpass filter presents the amplitude attenuation based on the magnitude response.

Figures 5 shows the filtered waveform by convoluting the waveform data and the magnitude – frequency of bandpass filter each stations. We can see at KAPI and WRAB stations have more clearer surface wave patterns than CHTO station. The characteristics of surface waves determined by the high amplitude and low frequency. The difference obtained from the Myanmar earthquake's close to the CHTO station. Because of short distance epicentre to CHTO, the arrival times of different wave phases (body waves and surface waves) had very small discrepancies. Based on these results, we can conclude that the filtering technique using the FFT is not effective for such conditions. The frequencies of P-waves, S-waves, and surface waves overlap significantly, making it challenging for FFT to separate the frequencies for each wave phase. Furthermore, the maximum amplitude on a seismogram recording represents the energy of a travelled wave. The wave energy recorded at CHTO station was considerably larger compared to the energy observed at KAPI and WRAB stations.

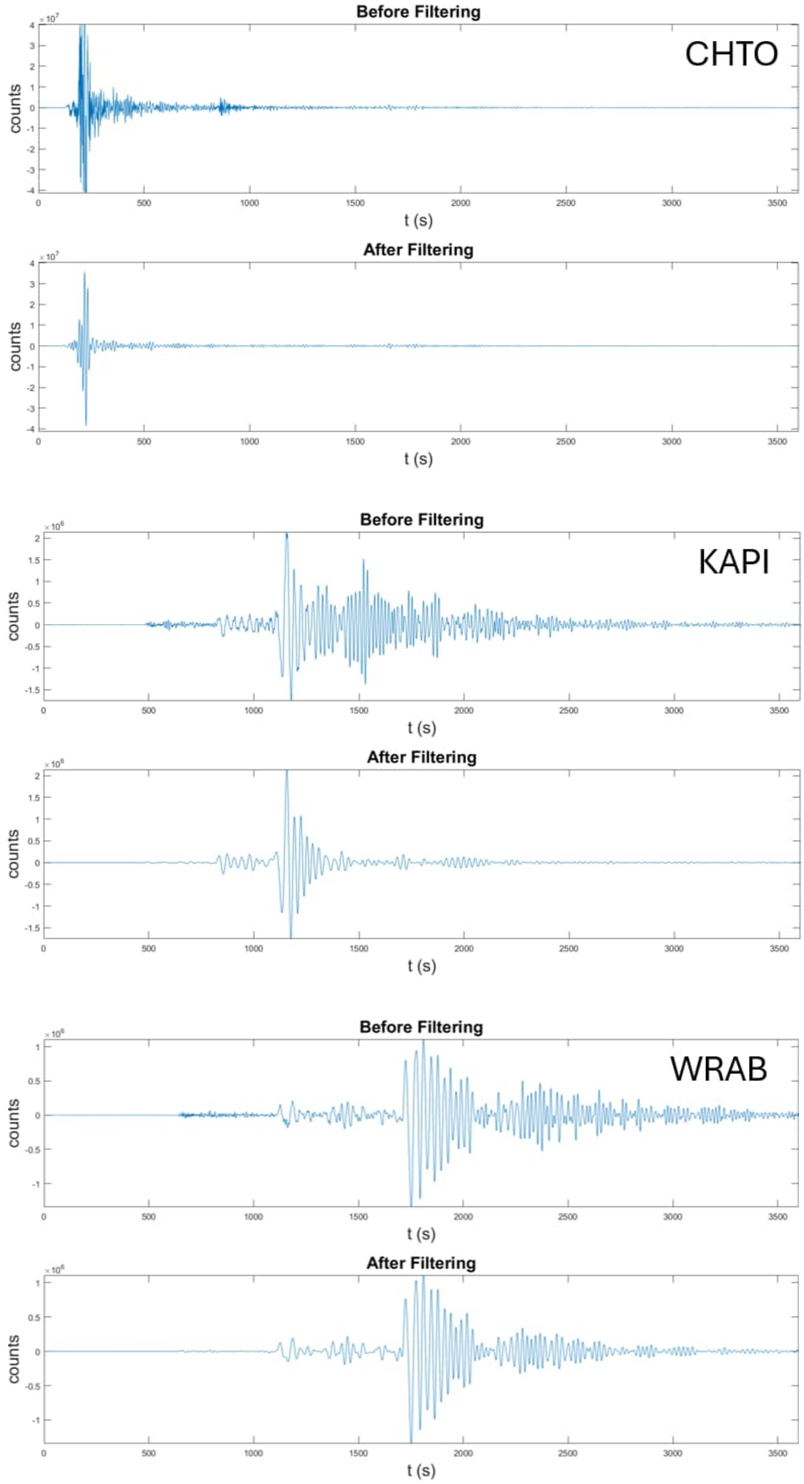

Figure 5. Seismogram for CHTO, KAPI, and WRAB stations before and after the filtering process using FFT method showing the characteristics of surface waves that have high amplitude and low frequency.

Figure 6 illustrates the seismograms recorded at the KAPI and WRAB stations both before and after the filtering process. The filtering clearly reveals distinct surface wave patterns characterized by low frequency and high amplitude. The travel time of surface waves from the epicentre to the KAPI station was 1056.5 seconds, and to the WRAB station, it was 1652.3 seconds. The different travel time is around 595.8 seconds between the two stations. It's evident that the maximum amplitude of the surface waves at the WRAB station is lower than at KAPI which is associated with the attenuation of wave energy as a function of distance. The length of epicentre to WRAB has larger than KAPI, so the fact of the geological condition implicated with the medium between epicentre to WRAB has become more dispersive than KAPI.

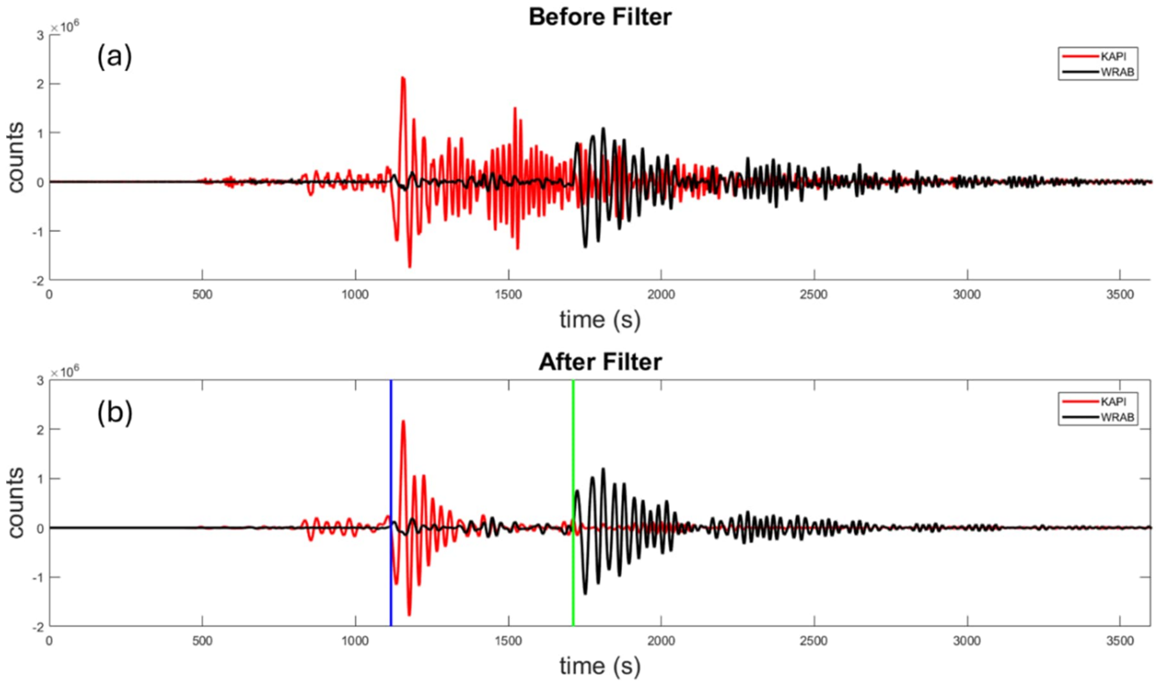

Figure 6. (a) The unfiltered waveform data at KAPI station (red line) and WRAB station (black line). (b) The filtered waveform data, which was processed with a bandpass filter set at its dominant frequency between KAPI (red line) and WRAB (black line). The vertical blue and green lines mark the arrival times of the surface waves at KAPI and WRAB, respectively.

Figure 7 presents the spectrograms of the CHTO, KAPI, and WRAB stations. These spectrograms illustrate the changes amplitude (wave energy represented with yellow colour scale) over time and frequency. **Figure 7a** the amplitude respect to frequency and time is not significantly changes that indicates that in the CHTO waveform, the different frequency spectra of the various wave phases overlap making them inseparable using this method. The spectrogram in **Figure 7a** further supports the argument made in the explanation of **Figure 2a**. In the other results, **Figures 7b** and **7c** show clear changes in amplitude as frequency and time. The physical characteristic confirms that the surface waves recorded at KAPI and WRAB stations underwent dispersion and the STFT could be effectively separated from other wave phases.

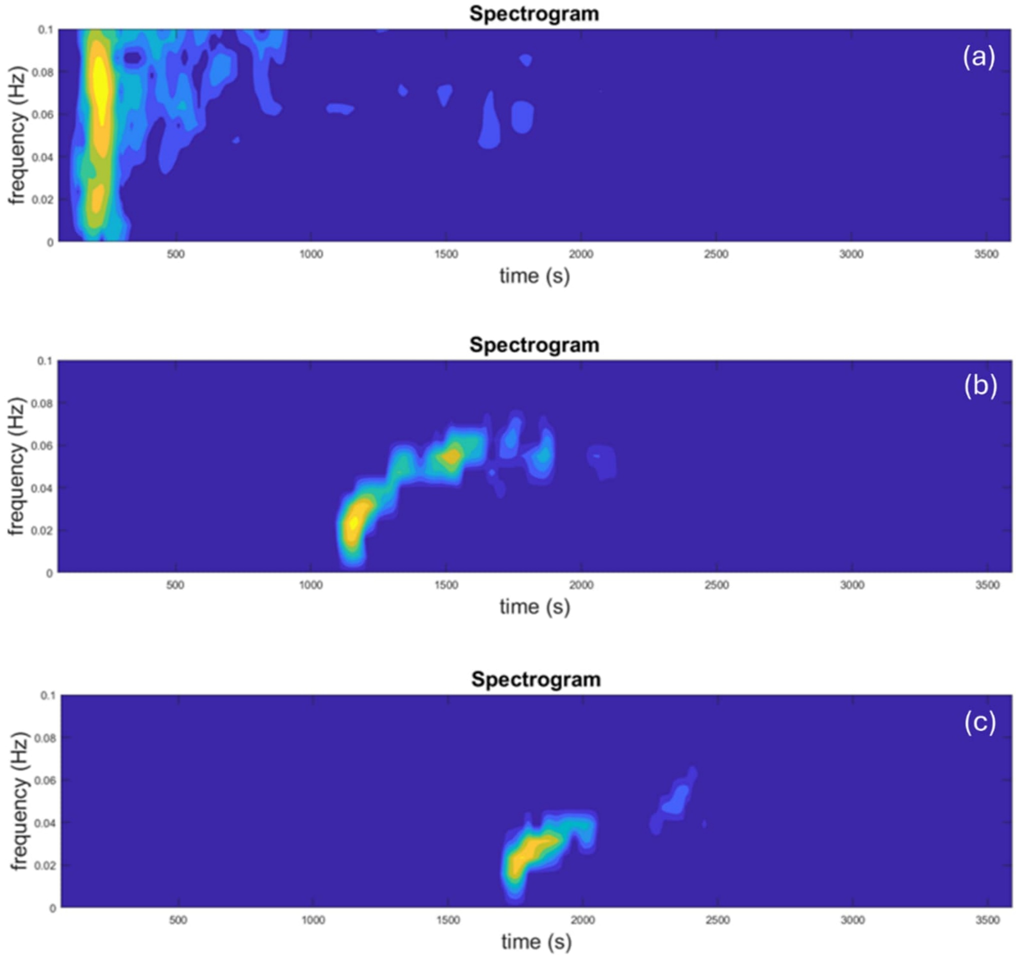

Figure 7. Spectrogram of the waveform for (a) CHTO, (b) KAPI, dan (c) WRAB stations.

Figure 8 a and **b** show the spectrogram like as **Figure 7** within certain period for focusing the observation. **Figure 8 a** and **b** represents spectrogram KAPI and WRAB within 0.01 – 0.03 Hz of frequencies. The frequencies show that the characteristic of earthquake signals in KAPI and WRAB which have very low frequency characterized as teleseismic event. Essentially, picking spectrogram involves selecting the maximum amplitude wave for each specific frequency and time. Extraction of dispersion curve involves the certain time and distant of the station to epicentre to present the wave group velocity. **Figure 8c** presents the extraction of dispersion curves from the seismograms of the KAPI and WRAB stations using the STFT. The dispersion curves give focused energy from 30 to 80 seconds per period, and the group velocity is around ~3 to ~3.5 km/s. The longer period of focused wave energy can obtain the deeper structure of the earth by doing the inversion process to get Vs profiling.

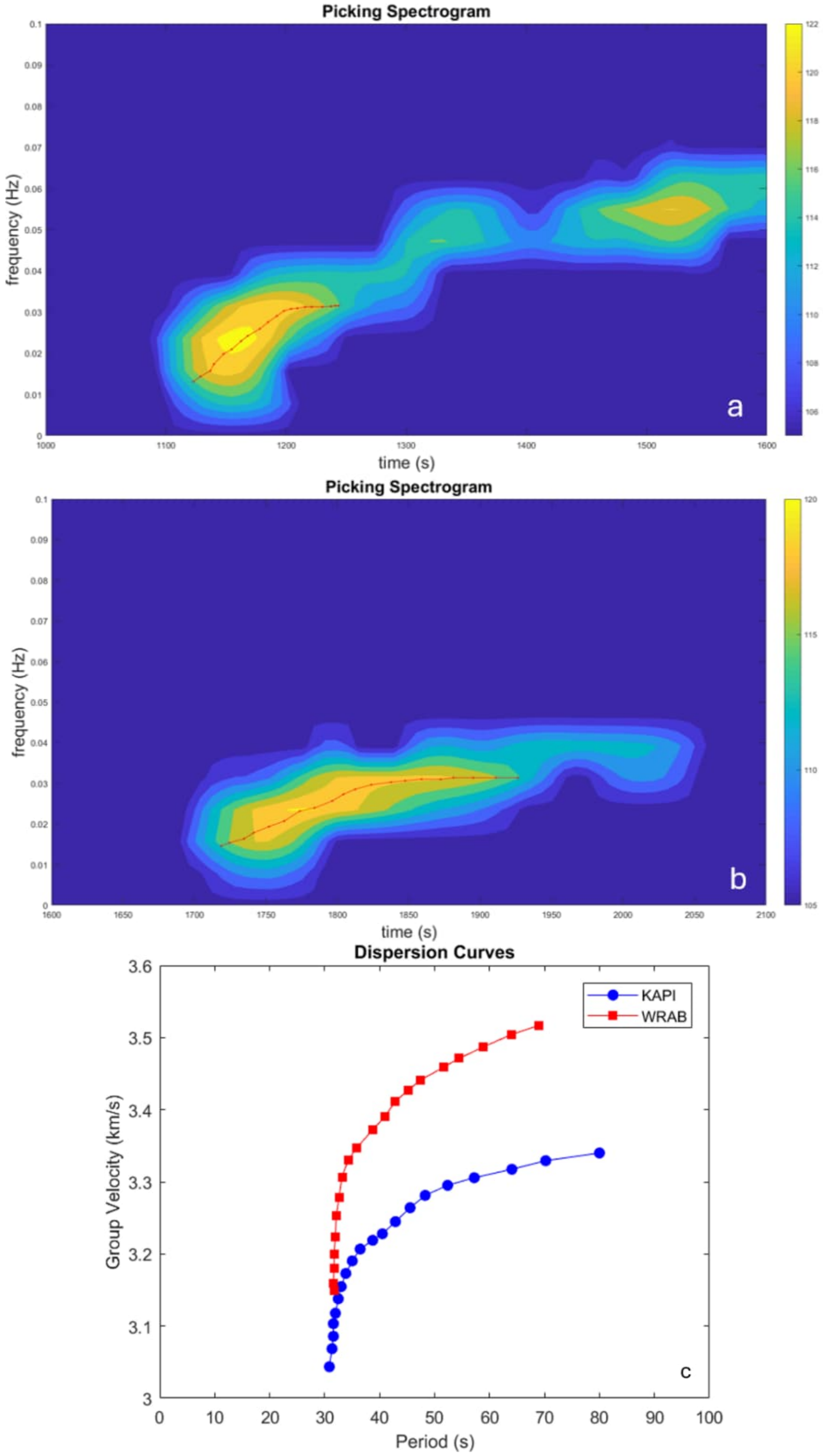

Figure 8. Manually picking on the spectrograms that have highest energy in time – frequency (presented by red dot – line) (a) KAPI and (b) WRAB, and (c) extraction of dispersion curves both KAPI and WRAB stations.

5. CONCLUSION

Time – frequency analysis is an effective method for distinguishing different waves within a non-stationary waveform based on their frequency spectrum. While Fourier transform algorithms can be used for filtering in the teleseismic waves, this approach becomes less effective for the station located very close to the epicentre. Determining the frequency range plays an important role in signal analysis and frequency contain must clearly have dominan spectrum from the waveform.

The remarks of this study is a relationship between distance and frequency content: stations nearer to the epicenter exhibit a higher frequency and broader range of dominant frequency, while those farther away show a lower frequency and narrow frequency range.

The Short-Time Fourier Transform (STFT) method proves to be a good tool for extracting dispersion curves from seismogram, especially when their frequency content does not significantly overlap. STFT method has been successfully used to extract the dispersion curve of a Myanmar earthquake performed on data from the KAPI and WRAB stations.

This event is categorized as a teleseismic event due to its great epicentre distance (>1,000 km), and the analysis focused on the very low-frequency range (0.01–0.03 Hz). The extraction of dispersion curves in this study gives focused energy from 30 to 80 seconds per period and the waves group velocity is around ~3 to ~3.5 km/s. On the data from CHTO station, STFT can not extract the dispersion curve due to inseparable frequency spectrum on each wave phases. The accurate imaging of these dispersion curves is crucial for the subsequent S-wave inversion process. A method employing a wavelet basis is required to overcome the limitations of STFT for extracting the dispersion curve of surface waves. This approach enables the customization of the mother wavelet according to the specific characteristics of the waveform data.

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