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Institute of Geophysics, Space Science and Astronomy

Seismic Investigation of Jan-Meda and Bole Area for Possible Implications of Site Classification

Submitted in Fulfillment of the Requirements for the Degree of Masters of Science in Earth System Physics (Seismology and Earthquake Geotechnical Engineering)

M.Sc. Thesis

By

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ADDIS ABABA UNIVERSITY

INSTITUTE OF GEOPHYSICS SPACE SCIENCE AND ASTRONOMY

Department of Seismology and Earthquake Geotechnical Engineering

ADVISOR AND EXAMINER'S THESIS APPROVAL SHEET

I, undersigned, approve that the thesis entitled "Seismic **Investigation of Jan-Meda and Bole for Possible Implications of Site Classification** "was presented by **Addisalem Tesfaye**. I also confirm that the thesis complies with the requirements of Addis Ababa University and with the standards regarding originality and quality.

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As members of the Board of Examiners of the M.Sc. Thesis open defense examination, we certify that we have read and evaluated the thesis prepared by Addisalem Tesfaye to examine the candidate. We recommended that the thesis be accepted as fulfilling the thesis requirements for the degree of Master of Science in Earth System Physics (Seismology and Earthquake Geotechnical Engineering).

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Acronyms/Abbreviation

EC8	Eurocode8
GMPE	Ground Motion Prediction Equations
MAM	Micrometer Analysis Measurement
MASW	Multichannel Analysis of Surface Waves
MSM	Micrometer Survey Method
NEHRP	National Earthquake Hazards Reduction Program
Vs	Shear wave velocity
NGA	Next Generation Attenuation
STP N	Standard penetration test number

Abstract:

Evaluating the seismic vulnerability of a building requires a significant understanding of subsurface conditions. This study employed the Multichannel Analysis of Surface Waves (MASW) technique to characterize and classify two distinct sites within Addis Ababa. By analyzing the dispersion of active and passive seismic records acquired by the 24-channel Geode seismograph, a significant contrast in the average shear wave velocity of the 30-meter-thick overburden (Vs30) was observed between the sites compared. This contrast directly translated into contrasting site classifications according to Eurocode 8 (EC8) and the National Seismic Hazard Program (NSHP). The findings highlight the importance of site-specific investigations for seismic resilience. Bole Homes area, characterized by a lower V_S30 of 354.8 m/s, necessitates stricter foundation design and seismic mitigation strategies compared to Jan-Meda, where we managed to obtain a V_S30 of 1304.7 m/s. The topmost layer of the Jan-Meda area seems to be dominated by volcanic rocks while velocity decreases at depth, and a clear discontinuity is visible at 50 meters depth, which needs further investigation. This research demonstrates the effectiveness of MASW in differentiating subsurface conditions and informing assisting site classification efforts. The resulting classification framework can guide construction practices, land-use planning, and targeted seismic risk mitigation efforts, ultimately fostering the development of earthquake-resistant building structure in Addis Ababa.

Keywords: MASW, Shear Wave Velocity, Site Classification, Addis Ababa

CHAPTER 1
INTRODUCTION

1.1 Background

The site effect is essential for accurately assessing seismic risks and ensuring the safety of buildings and infrastructure. It can significantly alter seismic motion in specific frequency ranges due to the resonance of soft deposits, leading to amplification or attenuation of ground motion (Gérard-Varet and Lacave 2013). Non-destructive geophysical techniques are among the best methods for evaluating subsurface conditions. Currently, various geophysical techniques are used to map the subsurface for engineering and seismic hazard projects. These techniques include seismic reflection, seismic refraction, self-potential, induced polarization, electrical resistivity tomography (ERT), multichannel analysis of surface waves (MASW), and ground-penetrating radar (GPR). The active MASW technique typically produces 1-D and 2-D shear-wave velocity profiles down to a depth of about 30 meters. It is essential to use optimal acquisition parameters to ensure the generation of the most accurate 1-D shear-wave velocity profiles. Shear-wave velocity (Vs) is commonly used to evaluate expected ground motion and predict earthquake damage (Douglas, 2021). Therefore, an in-situ assessment of Vs is one of the most critical steps for geotechnical engineering related to earthquakes. Shear-wave velocity is closely related to the elastic shear modulus (G), which measures material stiffness or rigidity. As a result, Vs is often used as a proxy for G in engineering, construction, and seismic response studies. Accurate calculations of shaking resistance thus depend on precise test results and appropriate interpretation.

Most engineering structure failures result from a lack of understanding of the characteristics and dynamic behavior of geological materials, as well as deficiencies in structural design (Bayewu, Oloruntola et al. 2018). In Ethiopia, adequate investigations and understanding of geological, engineering, geological, geotechnical, and hydrogeological factors related to infrastructure failures are not a primary focus for local authorities, planners, designers, and investors. As a result, roads, buildings, bridges, and other infrastructure constructed on problematic soils often do not perform as expected (Alemu T. et al., 2022).

Earthquake engineering relies on accurately predicting how structures will respond to ground shaking. Site classification, which involves categorizing locations based on their seismic response, is crucial in this process. In regions like Addis Ababa, particularly areas such as Jan-Meda and Bole Homes, understanding the subsurface conditions is essential for precise site classification. Conventional methods for site classification often rely on surface geology or basic soil properties (IBC 2018), which may not offer a comprehensive understanding. This research addresses this limitation by utilizing geophysical (seismic) investigations. Seismic methods provide a powerful tool for examining the subsurface, yielding data on critical parameters such as depth, layering, and shear wave velocity of the underlying materials (Boore, Joyner et al., 1993).

Earthquakes generate not only body waves that travel through the Earth's interior but also surface waves that ripple along the ground. These surface waves are similar to the ripples created when a pebble is dropped into a pond (Park, Miller, et al., 1999). There are two types of surface waves: Love waves and Rayleigh waves. Love waves cause the ground to vibrate side-to-side, like shaking a jump rope, while Rayleigh waves create a more complex rolling, elliptical motion, similar to a snake slithering forward with its head moving up and down. Rayleigh waves are particularly important for site-effect investigations due to their dispersive nature, where wave velocity depends on frequency. This dispersion property is crucial for the MASW method, as it allows for analyzing the arrival times of different frequency components of the Rayleigh wave to estimate the S-wave velocity profile of the subsurface.

A basic Multichannel Analysis of Surface Waves (MASW) field setup consists of several essential components for surface wave monitoring and analysis. This common configuration includes a linear geophone array: This array is made up of multiple geophones positioned on the ground in parallel. Geophones are devices that convert ground motion into electrical signals. They are spaced at regular intervals, usually ranging from a few to tens of meters apart, with the spacing determined by the desired resolution of the shear wave velocity profile. Impulsive Source: An impulsive source generates seismic waves in the ground. In MASW, the most common impulsive source is a sharp, rapid impact, typically produced by hammering or using a setup similar to striking a metal plate. This impact generates various types of seismic waves, including surface waves. Recording System: The signals from the geophones are captured using a recording system. This system typically consists of a computer or data acquisition unit for processing and storing the data and analog-todigital converters (ADCs) for digitizing the signals. Each geophone records its signal as a time-series waveform. Triggering Mechanism: A triggering mechanism is used to synchronize the activation of the impulsive source and the recording of the geophone signals. This ensures proper alignment and timing of the seismic waves from the source with the corresponding signals from the geophones (Xia, Yang, & others, 2003). This setup allows for effective monitoring and analysis of surface waves to derive accurate shear wave velocity profiles. By recording seismic wave arrivals at different geophones along a linear array, MASW data acquisition enables the characterization of surface wave propagation and the estimation of subsurface shear-wave velocities through subsequent analysis techniques.

Earthquakes generate various seismic waves, with shear waves (S-waves) being particularly influential on structures. The speed at which these waves travel (S-wave velocity) depends on the stiffness and density of the soil layers. Studies have established a strong correlation between S-wave velocity profiles and site effects. Soft, loose soils with low S-wave velocities tend to amplify ground motions. This amplification effect is particularly pronounced when a layer of soft soil sits on top of stiffer bedrock. The seismic waves get trapped and reverberate within the low-velocity layer, intensifying the shaking at the surface (Nakamura, Gojobori, et al., 2000). A sharp contrast in S-wave velocities between adjacent soil layers can significantly amplify ground motions. When a seismic wave encounters a sudden decrease in S-wave velocity, its energy concentrates and intensifies (Pedersen, Le Brun et al. 1994). MASW provides a cost-effective and non-invasive method to map S-wave velocity profiles. By analyzing the dispersion characteristics of surface waves, engineers can determine the stiffness variations and depths of soil layers. This information is crucial for: classifying areas based on their susceptibility to earthquake damage; accounting for site effects by incorporating the expected level of ground motion amplification; and evaluating the risk of soil liquefaction, a phenomenon where loose, saturated soils lose their strength during strong shaking.

MASW, by revealing S-wave velocity profiles, offers valuable insights into site effects. Understanding how soil layering and S-wave velocities influence earthquake ground motions is critical for mitigating seismic risks and ensuring the safety of structures and infrastructure.

Figure 2.1: Location map of Jan-Meda and Bole Homes (Bole community school). The red star in inset map shows the location of Addis Ababa.

By analyzing the seismic signatures obtained through our investigation, we can gain a more comprehensive understanding of the subsurface stratigraphy (multichannel analysis surface wave) MASW methods. This enhanced knowledge will be used to refine site classifications in Jan-Medea and Bole, ultimately contributing to safer and more resilient infrastructure development in the region.

1.1.1. Importance of Site Effect in Seismic Hazard Assessment

Site effects are frequency-dependent, meaning that local geology impacts different seismic wave frequencies in varying ways. It is crucial to assess the potential impact on structures to determine if this would result in the amplification or attenuation of specific frequency ranges. Site impacts can behave nonlinearly, with the response of rock or soil depending on the magnitude of the seismic waves. This must be considered in seismic hazard assessments to accurately predict ground motion. Employing site-specific response studies or ground motion prediction equations (GMPEs) allows for a more accurate depiction of local site effects, as highlighted by Anbazhagan and Bajaj (2022). This approach is more realistic than the generalized soil classes used in construction codes.

Site-specific seismic hazard studies often result in improved seismic design requirements because construction regulations are inherently conservative. This can lead to more cost-effective and efficient structural designs. Additionally, site-specific hazard evaluations help identify the dominant seismic source properties, which are essential for understanding the ground motion hazards associated with specific seismic source ruptures. By considering factors such as local soil conditions, source-to-site wave propagation characteristics, and earthquake source characteristics, seismic hazard assessments can provide more accurate ground motion estimates. This information is vital for assessing potential earthquake risks and developing strong, safe infrastructure.

Site Effect. Site effects refer to the modifications that seismic motion undergoes when traveling through the topmost layers of the Earth's subsurface before reaching the ground surface or a structure built on it. These modifications can significantly impact the ground motion, leading to amplification, modification, or even cancellation of the seismic waves. Site effects are influenced by the local geology, including the composition, thickness, and properties of the soil and rock layers, as well as the presence of underground structures or anomalies (Rezaeian, Powers et al., 2021).

Different Factors Influencing Site Effects. Include local geology, which is the composition, thickness, and properties of the soil and rock layers, including their velocity, density, and damping, which play a crucial role in determining site effects. The site effects are frequency-dependent, meaning that different frequencies of seismic waves are affected differently by the local geology. Site effects can cause seismic waves to be amplified, leading to increased ground motion and potential damage to structures (Lang 2004). Site effects can also cause seismic waves to be attenuated, reducing their intensity and impact. Site effects can exhibit nonlinear behavior, where the response of the soil or rock to seismic waves becomes dependent on the amplitude of the waves.

Surface soil classification plays a crucial role in designing earthquake-resistant buildings. Hard soil has a better damping ability compared to soft soil, which means it can more effectively attenuate seismic waves, converting high-frequency waves into low-frequency ones (Widodo, Syaifuddin et al., 2020).

Areas with hard soil types are safer from shock amplification (Aki K. et al., 1993). The amplification of seismic waves decreases with the increasing geological age of soils. The rate at which soil hardness decreases varies across different frequencies (Zeng, Aki et al., 1993).

1.1.2. Significance of Site Effects

The study of local site effects is crucial for assessing strong ground motion, seismic hazards, and engineering seismology. Understanding site effects is essential for assessing seismic risk and developing effective mitigation strategies (Chávez-García, Domínguez et al. 2007). Site effects must be considered in the design of structures to ensure they can withstand the modified ground motion (Chávez-García, Domínguez et al. 2007).Site effects are critical for accurately characterizing ground motion, which is necessary for evaluating the potential impact of seismic events on structures and infrastructure (Chávez-García, Domínguez et al. 2007).

Gound motion characterization. Ground motion characterization involves analyzing and predicting ground movement during seismic events. This process includes measuring ground displacement, velocity, and acceleration, as well as estimating spectral acceleration and other seismic parameters (Hallo, Imtiaz et al., 2023).

A Feature of ground motion characterization. The frequency composition of ground motion significantly impacts structural response, especially within the range from the structure's elastic frequency to a lower frequency that indicates a "softened" structure with some degree of inelastic deformation. While the duration of intense ground shaking is important, the frequency content has a more pronounced effect on how structures respond inelastically. "Wave passage effects" describe changes in horizontal ground motion linked to the apparent horizontal propagation speed of seismic waves. Slower seismic waves generally induce greater variability in response compared to faster, vertically propagating waves. This variability can affect the ground motion and response of structures differently, leading to varying levels of seismic risk and impact. Ground motion features, such as response spectra and peak accelerations, typically decrease sharply with depth within the normal embedment range of structures (Joyner and Boore, 1988). Deconvolution methods assuming vertically propagating shear waves offer reasonable approximations of these variations. Characterizing ground motion is crucial for evaluating potential seismic impacts on buildings and infrastructure and for developing effective mitigation strategies. It takes into account site-specific factors such as local soil conditions, characteristics of wave propagation from source to site, and earthquake source properties to produce accurate predictions of ground motion.

1.2. Statement of the Problem

Despite advancements in seismic research, there remains a need for comprehensive and detailed site-specific characterization of seismicity and ground motion. Current methodologies may not fully capture the complexities of local geological conditions, which can significantly influence the amplification and propagation of seismic waves.

The primary challenge is the lack of detailed site-specific information in current seismic hazard assessments. This deficiency leads to uncertainties in predicting ground motion at local scales, impacting the accuracy of seismic risk assessments and the design of resilient structures. The proposed research seeks to address this problem by utilizing geophysical methods to explore the geological and geotechnical factors influencing ground motion at specific sites.

Even with the advances in seismic research, a thorough and precise site-specific assessment of seismicity and ground motion is still required. The complexities of the local geology, which can greatly affect the amplification and propagation of seismic waves, may not be fully captured by current approaches. To solve this issue, the proposed study would investigate the geological and geotechnical elements affecting ground motion at particular locations using geophysical methods.

1.3 Objectives of the Study

1.3.1 General Objective

This study aims to identify relevant site effects during ground motion, such as vibrations from earthquakes. Since seismic activity varies depending on the region and the properties of the rock or sediment, it is important to assess vulnerabilities and ensure they can withstand seismic forces in civil structures.

1.3.2 Specific Objective

- To Define seismic responses across different sites in Addis Ababa
- To Assess ground motion site effects using Seismic Methods.

- To Provide insights into how geological variations impact seismic risk assessment and mitigation strategies, classify sites based on their subsurface geological conditions, and understand geological factors influencing ground motion.
- To determine seismic design practices and mitigate the impact of earthquakes.

1.4. Research Questions

- How do the local site conditions (e.g., rock type, soil layer thickness) influence ground motion amplification?
- What are the dominant resonance frequencies of different site zones, and how do they compare with predicted values?
- Are there spatial variations in amplification factors across the study area? If so, what factors explain these variations?
- Can geophysical methods accurately predict ground motion amplification compared to traditional geotechnical investigations?
- How can existing ground motion models be improved by incorporating data from geophysical investigations.

1.5. Significance of the research

This research will contribute significantly to the understanding of ground motion variability in Addis Ababa and provide valuable data for seismic hazard mitigation efforts. The developed ground motion amplification maps will serve as a critical tool for urban planning, earthquake-resistant design, and disaster preparedness in the city. Additionally, the research findings will promote the wider adoption of geophysical methods for cost-effective and efficient site investigations in earthquake-prone regions.

1.6. Scope/Limitation of The Study

Challenges can arise from complex urban environments with dense infrastructure and logistical constraints. To mitigate these, collaboration with local authorities and utility companies will be crucial to obtaining access permits and navigating logistical hurdles. Incomplete datasets, limited software capabilities, or a lack of advanced processing techniques can restrict the accuracy. Depending on site-specific complexities, uneven topography, buried utilities, or the presence of groundwater can introduce artifacts or uncertainties in data interpretation.

CHAPTER 2
LITERATURE REVIEW

2.1. Introduction

The use of geophysical tools is essential for examining subsurface conditions and their impact on ground motion. These non-invasive methods measure physical attributes of the subsurface, such as seismic velocities, electrical resistivity, and electromagnetic properties, to deduce details about the underlying geology and the characteristics of the soil and rock (Best, 2015).
By creating seismic waves and timing their arrival at several sites, seismic refraction is a frequently used technique to assess a site's geology, stratigraphy, and rock quality. The bedrock depth, subsurface layering, and geomechanical characteristics of the rock can all be precisely determined using this method. When analyzing the topography of shallow bedrock and spotting any tearing problems, seismic refraction is quite helpful.

Multichannel Analysis of Surface Waves (MASW) is a surface wave method used to assess the shear wave velocity (Vs) profile of near-surface soils and rock formations (Xia, 2014). This information is crucial for evaluating liquefaction risks and determining site classifications for seismic assessments. Surface wave techniques also help estimate dynamic soil properties, which are vital for understanding structural responses to ground motion. Integrating direct sample data with results from other geophysical methods offers a more detailed understanding of subsurface conditions. When planning and constructing infrastructure, it is essential to consider the risks of liquefaction, ground motion amplification, and other seismic hazards to ensure safety and resilience.

In-depth geotechnical and geophysical studies are needed to thoroughly assess seismicity and ground motion in Addis Ababa. Understanding these seismic risks is crucial for the region, which is influenced by tectonic activity in the East African Rift Valley, including the capital city of Ethiopia. This area is prone to seismic activity due to tectonic movements associated with the East African Rift, with earthquakes typically linked to the rift system rather than specific fault lines (Chorowicz, 2005). A comprehensive understanding of ground motion characteristics is necessary to ensure community safety and resilience during seismic events. This literature review aims to enhance human well-being, urban planning, and development preparedness for seismic occurrences by exploring the role of geophysical techniques in site-specific analyses. Effective seismic awareness strategies involve a combination of building codes, structural response analyses, and the integration of geophysical technologies into urban planning and monitoring.

2.2. Historical Earthquakes and Impact on Addis Ababa

According to Gouin (1961), the first earth tremors were felt in Addis Abeba, which is situated about 200 km south of Karakore, during breakfast on May 19, 1961, following the Majete-Karakore earthquake.A number of significant earthquakes occurred in the century that affected Addis Abeba, Nazret, Awassa, and other major cities. These included the earthquakes that struck Langano in 1906, Kara Kore in 1961, Wondo Genet in 1983, Langano in 1985, Dobi Graben in central Afar in 1989, and Nazret in 1993 (Fekadu, 1999). According to a similar study done in 1996 by Fekadu Kebede of the Ethiopian Geophysical Observatory at Addis Ababa University, there have only been 16 recorded earthquakes of magnitude 6.5 or greater in the century alone in some of Ethiopia's seismically active locations.

Addis Ababa has witnessed a number of earthquakes in 100 years of its existence, some are: the 1906 an earthquake of magnitude 6.8 at epicentral distance of about 100 km south of Addis Ababa, the 1961 an earthquake of magnitude 6.6 occurred at a distance of 200km (Karakore Earthquake), the July 1997 an earthquake with magnitude 4.0 at a distance of 22 km to the south west of the city. Some other earthquakes of smaller magnitude and at far distance (in 1977, 1984 and 1985) were felt at upper story of high-rise buildings (Asfaw L,1985).

Addis Ababa has a history of ***notable earthquakes***, each with varying magnitudes and impacts. Some of the recorded earthquakes in the region include a 6.2 magnitude earthquake in Sardo in 1969, resulting in the destruction of many houses, and a 5.1 magnitude earthquake in Jimma, Hossaena, and Wenjela in 2010, causing damage to numerous houses. These events serve as reminders of the ***seismic activity*** in Addis Ababa and the need for preparedness and adherence to building codes. The list of earthquakes in Addis Ababa spans several decades and showcases the occurrence of earthquakes in the region.

The seismic activity in the region underscores the importance of constructing buildings and infrastructure that adhere to seismic-resistant design standards. Older structures may be more vulnerable to damage during earthquakes. Given the seismic risk, efforts have likely been made to enhance the preparedness of critical infrastructure, including hospitals, schools, and emergency response systems. Earthquake preparedness and public awareness campaigns may have been implemented to educate the population on safety measures during seismic events. Felt moderately in Addis Ababa, causing minor panic but no significant damage. This event served as a reminder that even distant earthquakes can be felt in the city. While these are some notable historical earthquakes, smaller tremors and aftershocks also occur in Addis Ababa, contributing to the overall seismic risk. The impact of earthquakes on the city is influenced by various factors, including the earthquake magnitude, distance, focal depth, and local geology.

2.3. Ground Motion Characteristics and Site Effects

Understanding the characteristics of ground motion during seismic events is crucial for assessing potential effects on structures and infrastructure. This section looks at the ground motion parameters and how they relate to site-specific effects. Ground motion is influenced by site-specific factors such as topography, soil composition, and regional geology. The many site effects and how they impact seismic risk are shown by a thorough literature research.

Understanding the spatial and temporal distribution of ground motion and seismicity in Addis Ababa is crucial for assessing seismic hazard and implementing effective mitigation strategies. Seismicity at Addis Ababa sits within the East African Rift Valley, a seismically active region with potential for moderate to large earthquakes. Historical records document several earthquakes felt in the city, with varying intensities. While major earthquakes within the city limits are less frequent, smaller tremors and aftershocks do occur, contributing to the overall seismic risk. Understanding the distribution of past events in the vicinity can offer clues about potential future activity. The distribution of seismicity within Addis Ababa may not be uniform due to factors like underlying geological structures and fault lines. Identifying areas with higher seismic activity helps prioritize mitigation efforts.

Ground motion amplification occurs when seismic waves encounter specific soil or rock conditions, intensifying their shaking effect. This means different areas within Addis Ababa may experience varying levels of shaking during an earthquake, even if the epicenter is distant. The distribution of rock and sediment types across Addis Ababa plays a significant role in ground motion amplification. Understanding the city's geomorphology and subsurface properties is crucial for mapping amplification zones. Hills and valleys can further modify ground motion, leading to localized areas of stronger or weaker shaking. Analyzing the city's topography in conjunction with geotechnical data provides a more comprehensive understanding of amplification patterns.

2.3.1. Geophysical Methods for Site Characterization

Seismic refraction and reflection techniques are highly effective for exploring subsurface structures and distinguishing geological layers. This part examines research that uses these techniques to determine site-specific seismic characteristics. Methods involving surface waves, such as Love and Rayleigh waves, provide valuable information about near-surface soil properties. The literature discusses the use of surface-wave techniques for site characterization and their importance in ground motion research.

2.3.2. Integration with Building Codes and Structural Response Analysis

Harmonizing geophysical findings with building code requirements is crucial for designing earthquake-resistant structures. Literature in this area is examined to highlight the synergy between geophysical site characterization and building code implementation. Investigating how structures respond to site-specific ground motion is paramount. This section explores studies that bridge geophysical site characterization with structural response analysis, ensuring a holistic approach to seismic preparedness.

2.3.3. Urban Planning and Monitoring Integration

Integrating geophysical data into urban planning is a key aspect of seismic awareness. The literature review explores how site effects are considered in land-use planning and zoning regulations to enhance overall urban resilience. Incorporating real-time monitoring systems into urban planning strengthens early warning capabilities. This section delves into research showcasing the integration of geophysical methods into monitoring systems for improved seismic preparedness.

For example; Seismic site effects were first observed during the 1985 Mexico City earthquake. Although the earthquake's epicenter was situated along the Pacific Coast, several hundred kilometers from Mexico City, the seismic shaking in the city was exceptionally intense, causing extensive damage.

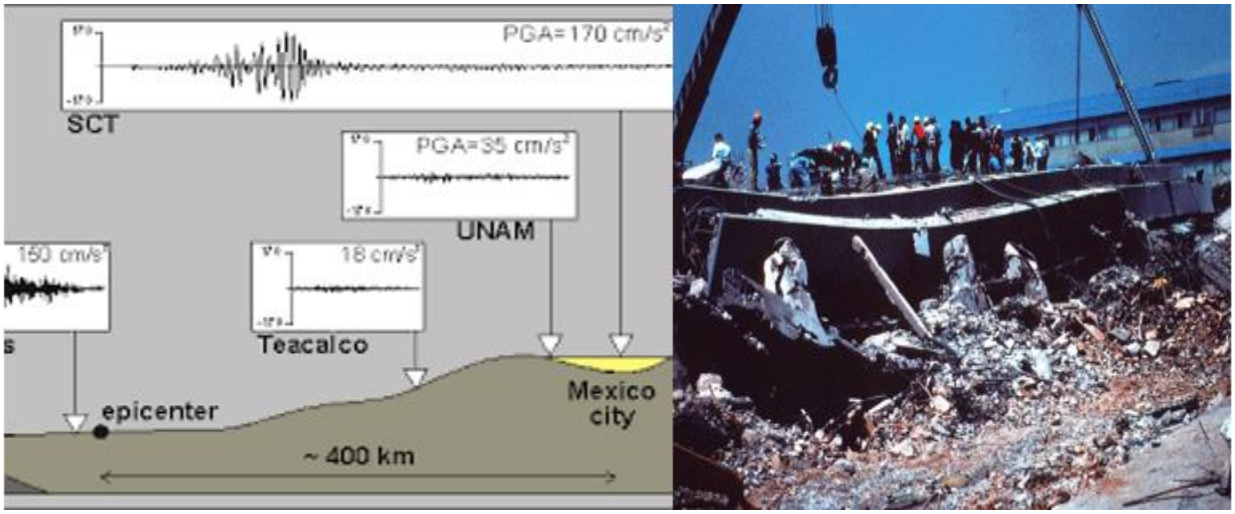

Figure 2.1. Site Effects in Mexico City: Recordings from the 1985 Earthquake (https://en.wikipedia.org/wiki/1985_Mexico_City_earthquake)

Figure 2. shows the recordings taken at various distances from the epicenter during the earthquake sequence. The measured acceleration amplitude varies significantly at these different distances:

The Campos station, situated very close to the epicenter, recorded a maximum acceleration of 150cm/s^2. The Teacalco station, situated over 200 km from the epicenter, recorded a significantly lower acceleration (18 cm/s^2). This reduction in amplitude is due to wave attenuation during propagation, which includes both geometrical attenuation from the expansion of the wavefront and material (or intrinsic) attenuation caused by energy dissipation within the medium. The UNAM station, positioned over 300 km from the epicenter, recorded a maximum acceleration that was 35m/s^2 greater than that of the Teacalco station. The SCT station, located in Mexico City approximately 400 km from the epicenter, recorded an exceptionally high maximum acceleration (about 170 m/s^2).

It is notable that the acceleration amplitude initially decreases significantly but then increases as the seismic waves reach the alluvial deposits on which Mexico City is built.

2.4. The Impact of Strong Seismic Activity Causes Occurrence Damage in Addis Ababa

Direct physical damage of Widespread in Addis Ababa, these structures are highly vulnerable to collapse during earthquakes, leading to casualties and displacement. If it is poor construction practices, buildings made with substandard materials or lacking seismic design are more prone to damage, even if they don't collapse entirely, and dense urban settlements Damage to critical infrastructure like power lines, water pipes, and communication networks disrupts essential services and hinders emergency response.

2.5. Strong Earth Quake Duration, Recurrence and Severity in Addis Ababa

The precise duration, frequency, or intensity of upcoming earthquakes in Addis Ababa cannot be predicted. Accurate predictions of earthquakes are difficult because they are complex natural occurrences impacted by a multitude of causes. However, based on historical data and seismic hazard assessments, Recurrence While earthquakes occur regularly in Ethiopia due to the Great Rift Valley system, strong tremors (above magnitude 5) are less frequent in the Addis Ababa region. The exact recurrence interval is uncertain. Studies indicate moderate to high seismic hazards in Addis Ababa, suggesting the possibility of future strong earthquakes. And if it makes a site-specific analysis to make more detailed assessments, we will consider local soil conditions and other factors, providing a more accurate picture of earthquake risk for specific locations. While predicting specific earthquake details is impossible.

By staying informed about earthquake updates and preparedness information, conducting site-specific evaluations of any structure's earthquake resilience, creating an emergency plan, and taking steps to mitigate risks, we can be better prepared for potential tremors in Addis Ababa.

In conclusion, the investigation of Site effects using geophysical methods is pivotal for advancing our understanding of ground motion characteristics. By integrating geophysical site characterization with building codes, structural response analysis, and urban planning, communities can take significant strides toward safe and resilient seismic event preparedness.\

2.6. Existing Literature and Recent Developments

Numerous studies have explored site characterization and estimation of shear wave velocity using diverse methodologies. Among the most commonly employed techniques are in-situ testing and laboratory testing. In-situ testing involves collecting soil or rock samples directly from the site and conducting tests under controlled conditions in a laboratory. Common laboratory methods for determining Vs include resonant column tests, torsional shear tests, and bender element tests.

Each approach has its own strengths and limitations. In-situ testing methods tend to be more costly and time-consuming compared to laboratory testing methods, but they yield more realistic measurements of soil and rock properties as they exist in their natural environment. Laboratory testing methods, on the other hand, offer more controlled conditions and potentially more precise measurements, although they may not fully replicate the in-situ behavior of soils and rocks. Geophysical methods are frequently non-invasive and can provide information across a wide area.

To date, numerous studies have investigated site investigations using various methods such as seismic refraction, Standard Penetration Test Number (STP N), and spectral analysis of surface waves. However, very few studies directly address the specific considerations for site investigations in contrasting rocky and sedimentary environments.

(Tesfaw, 2022) conducted a study at a construction site in Arba Minch Town, Southern Ethiopia, employing the seismic refraction method. The primary objective was to ascertain the depth and composition of the bedrock. Ultimately, the study found that layer thickness increased from west to east within the study area, correlating with the velocity of the third layer, which likely comprises the bedrock identified for engineering structures

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In March 2023, Alemayehu A. conducted a study in Hawassa town, focusing on seismic hazard assessment through site response analysis and amplitude parameters. The primary goals of the study were to forecast ground motion parameters using the DEEPSOIL V.7 software. Ultimately, the study emphasizes the critical importance of designing key structures at local, zonal, regional, and federal levels to obtain essential insights into the area's seismic risks, employing linear, equivalent linear, and nonlinear methodologies.

- (Woldesenbet, Arefaine et al., 2023) conducted a study to explore the factors contributing sSto landslides using geotechnical conditions and geophysical techniques. The landslides were triggered by a combination of factors, including soil type, heavy rainfall, deforestation, proximity to streams, and the naturally unstable geological features such as elevation and steepness of slopes in the area.
- In 2008, B. Yoseph and G. Raman conducted a study on earthquake ground-motion parameters at rigid sites in Addis Ababa, Ethiopia. Leveraging their understanding of regional geodynamics and seismic activity, they used numerical simulation techniques to estimate ground motion parameters crucial for earthquake-resistant design and disaster management. The study concluded by comparing the acceleration response spectra of ground motions with 5% damping obtained from simulations against the recently developed Campbell-Bozorgnia Next Generation Attenuation (NGA) empirical ground motion model and Brune's theoretical Random Vibration Theory (RVT) based on seismic sources.
- In 2018, Besrat E. Alemu conducted a study focusing on ground response analysis at representative sites in Hawassa City. The study aimed to analyze how soil deposits respond to bedrock motion, utilizing seismic refraction survey data as primary information and supplementing it with secondary data from existing geotechnical reports. The equivalent-linear approach was employed, which essentially applies the principle of superposition in a linear manner. Ultimately, the study's findings revealed considerable amplification effects that exceeded the spectral predictions outlined in current design codes.

No previous studies in Addis Ababa city have contrasted and compared multiple sites using MASW methods to analyze site effects. This study addresses this gap by examining various subsurface materials, providing essential data for hazard assessment, safe engineering design, and slope analysis based on shear wave velocity profiles.

2.7. Challenges And Future Directions

Instrumentation challenges may arise in both rocky and sediment sites, affecting the quality of shear wave velocity data. The interpretation of Vs profiles, especially at sediment sites, requires consideration of factors such as water content and soil compaction. Ongoing research focuses on improving instrumentation reliability and developing robust interpretation techniques.

There exists a notable research gap in the comprehensive understanding and comparison of techniques specifically tailored for rocky and sedimentary sites. Existing studies primarily focus on geological formation, often overlooking the distinct challenges posed by these contrasting terrains. In rocky sites, traditional methods such as seismic refraction and surface wave analysis have been extensively studied, providing valuable insights into subsurface conditions. However, the applicability and effectiveness of these methods at sediment sites characterized by unconsolidated materials remain inadequately addressed. The limited attention given to sediment sites is particularly concerning, given their prevalence in urban and coastal environments. Additionally, few studies explore integrated approaches that can seamlessly transition between these diverse terrains.

As infrastructure projects increasingly encounter sites with mixed geological characteristics, the lack of a holistic and comparative investigation framework poses a significant hindrance to accurate and efficient site characterization. Addressing this research gap is crucial for advancing the field of geotechnical engineering and ensuring the applicability of site investigation methods across a broader spectrum of geological settings.

In overall, shear wave velocity estimation plays a pivotal role in site characterization, and the choice of methods depends on the geological characteristics of the site. While surface wave methods are effective in rocky environments, sediment sites require careful consideration of alternative techniques, such as seismic cone penetration testing. Ongoing research and technological advancements are essential to address the challenges associated with both types of sites, ensuring accurate and reliable shear wave velocity estimation for improved geotechnical engineering practices.

CHAPTER 3
MATERIALS AND METHODOLOGY

3.1 Site Selection

We chose this study area due to its vulnerability to earthquakes and its variety of geological features. Three distinct sites were selected to reflect various geological conditions: Site 1 is situated in a valley characterized by soft alluvial deposits; Site 2 is located on a bedrock outcrop with little soil cover; and Site 3 rests on hard soil, ensuring a comprehensive range of Site effects is captured. To better understand the regional geology of each site, geological maps and historical records were reviewed. Furthermore, borehole logs from prior construction projects near Site 1 were accessed to gather preliminary data on the subsurface soil layers. Site characterization involved the use of geological maps, seismic hazard evaluations, and site visits to guarantee representative sampling.

3.2 Seismic Techniques Employed

A multi-channel surface wave technique was employed in this study to examine the subsurface and characterize ground motion. One specific surface wave method utilized to assess subsurface conditions at each site was seismic refraction, which includes both active and passive surface wave approaches.

3.2.1. Theory of MASW

The Multichannel Analysis of Surface Waves (MASW) technique is grounded in the dispersive nature of Rayleigh waves in heterogeneous mediums. Rayleigh waves, which are elastic surface vibrations moving in circular patterns akin to ocean waves, travel along or near the surface at low velocities, high frequencies (above 2 Hz), and with significant energy or amplitude. These waves result from the interference of P-waves and vertically polarized S-waves.

MASW capitalizes on the principle that Rayleigh waves exhibit dispersion, meaning their propagation speed varies with frequency. Essentially, the velocity of Rayleigh waves is dependent on their wavelength or frequency. Lower frequencies (longer wavelengths) penetrate deeper into the ground compared to higher frequencies (shorter wavelengths) (Xia, Miller, et al., 1999). In the MASW method, an active source like a weight drops or sledgehammer generates surface waves, which are recorded by a multichannel array of geophones. The collected data is processed to produce a dispersion curve, which plots the phase velocity of Rayleigh waves against frequency. This curve is then inverted to obtain the shear wave velocity (Vs) profile of the subsurface.

MASW can determine material layer thickness, shear wave velocity (in both 1D depth and 2D depth/surface location), Poisson's ratio, and density. It is a non-destructive, cost-effective method for geotechnical characterization of near-surface materials, focusing on analyzing surface waves generated by a seismic source. By measuring the dispersion of these waves, MASW provides detailed shear-wave velocity profiles with depth.

3.2.2. Theory of Seismic Refraction

Seismic refraction theory examines how seismic waves behave as they move through the subsurface, with a primary focus on the propagation of P-waves (compressional waves). This technique is used to analyze subsurface velocity and the structure of layer interfaces by studying the first arrival times of P-waves at the Earth's surface. Seismic refraction is essential for various applications, including locating buried archaeological sites, assessing geological hazards, defining aquifer geometries, and exploring natural resources like oil.

In seismic refraction, critical refraction is a key concept, where a seismic wave travels along acoustic interfaces and generates detectable new waves. The critical angle is crucial, as it determines the angle at which the refracted wave propagates along the boundary interface. By examining the travel times of the first arrivals of seismic energy and plotting these against the distance between the source and geophones, the velocities of subsurface layers can be estimated. The thickness of layers and subsurface parameters can also be determined using calculations based on critical and crossover distances. This method measures the travel times of seismic waves generated by a hammer source to evaluate subsurface layering and calculate both compressional (P-wave) and shear wave (S-wave) velocities, with S-wave velocities being particularly important for understanding how the ground responds to earthquake shaking.

Overall, seismic refraction is a fundamental method in geophysics that utilizes the behavior of seismic waves to understand the subsurface structure, providing valuable insights for various fields such as environmental studies, engineering projects, and hydrogeological investigations.

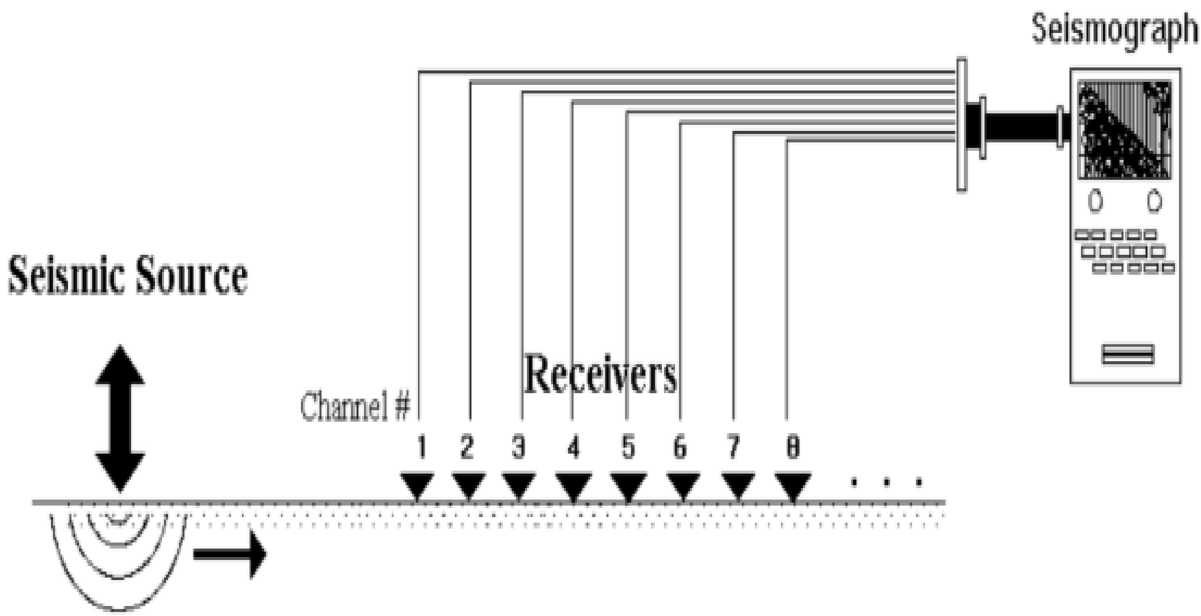


Figure 3.1: Basic configuration of multichannel analysis of surface wave (MASW) measurement

Shear wave velocities derived from surface wave energy can be accurately determined using the non-invasive MASW (Multichannel Analysis of Surface Waves) method (Sairam, Rastogi et al., 2011). This technique employs multiple receivers connected to multi-channel seismographs (Figure 3.1). A single geophone or an array of geophones spaced evenly can serve as the receiver (Xia, Miller et al., 1997). Utilizing the dispersion properties of surface waves, MASW is effective in obtaining shear wave velocity (Vs) profiles (Xia, Miller et al., 1997). This method is highly regarded in geology and geophysics for its cost-effectiveness, non-invasiveness, and non-destructive nature (Xia, 2014). By measuring the phase velocity of Rayleigh waves across different frequencies, it is possible to determine shear wave velocities at various depths (Satyam and Rao, 2010). Although this method is effective for constructing vertical shear wave velocity profiles, it heavily relies on the parameters set during the data collection and processing stages (Dal Moro, Pipan et al., 2003).

In the context of Jan-Meda and Bole Community High School, the MASW measurements are expected to produce 1D Vs profiles and categorize the soil types. These results can qualitatively describe the likelihood of seismic events and provide a strong foundation for improving seismic hazard mitigation through capacity building.

As illustrated in Figure 3.4, ground-surface waves are eventually overtaken by waves traveling longer, faster paths through deeper layers at a certain distance from the source. The distances from the source to the points where refracted waves are initially detected are influenced by the velocities and depths of the underlying strata.

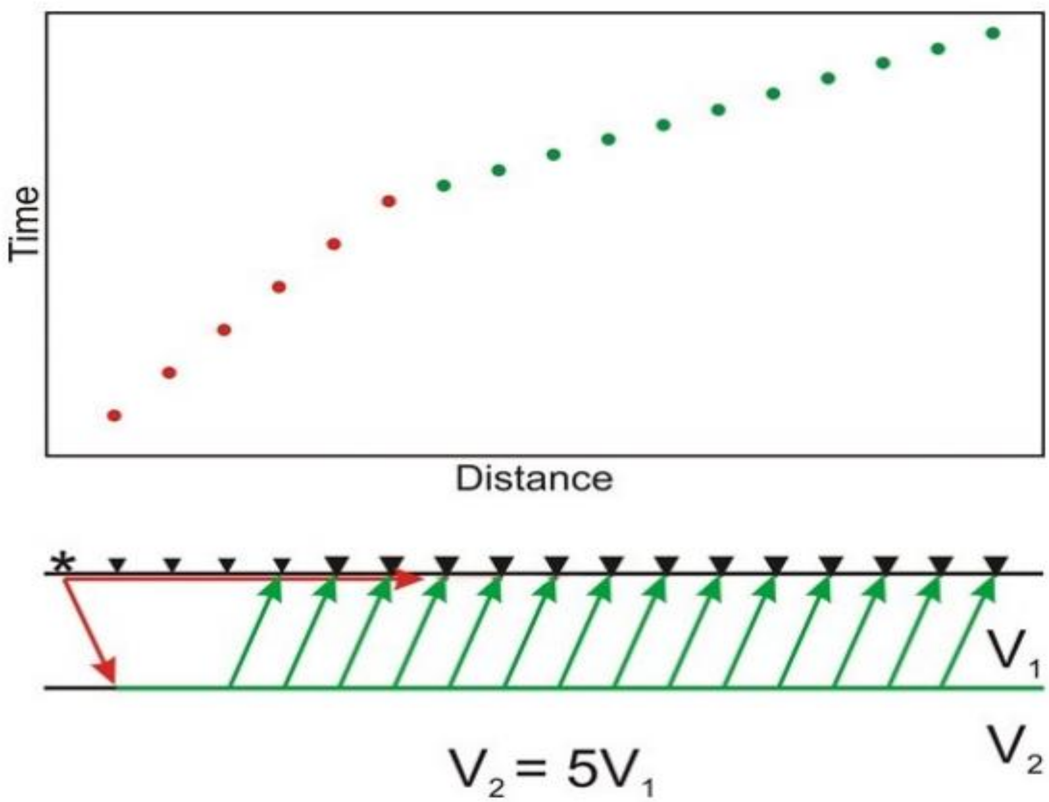


Figure 3.2: Schematic of seismic refraction survey

The depth and velocity of various layers can be determined either manually or through software. The accuracy of these estimates increases with the number of signal images captured. These images typically include front, middle, and rear shots, taken at the start, middle, and end of the survey line, respectively, along the spread length.

3.3. Geophysical Investigation

To investigate various subsurface targets, such as identifying shallow structures and features up to 30 meters deep, numerous fields have employed geophysical exploration techniques. Methods like the multichannel analysis of surface waves (MASW) are particularly useful in complex terrains for characterizing the subsurface (Alsulaimani 2017). This approach to limiting interpretation is commonly used due to its specific advantages and disadvantages.

3.3.1. Multichannel Analysis of Surface Waves (MASW)

3.3.1.1. Overview

Multichannel Analysis of Surface Waves (MASW) is a non-destructive seismic survey method that evaluates the elastic properties (stiffness) of the ground by measuring seismic surface waves generated either actively by a seismic source (active MASW) or passively from cultural activities (passive MASW). MASW has become widely adopted in geophysical studies due to its effectiveness in measuring shear-wave velocities and its ease of use (Park, 2013). It has emerged as a primary method for determining variations in shear-wave velocities for both geophysical and civil engineering applications, with an observed discrepancy of around 15% compared to borehole measurements (Xia et al., 2002; Xia, 2014). A typical MASW survey involves three main stages: data acquisition, data processing, and data interpretation. The resulting shear-wave profiles can be presented in 1D, 2D, and 3D formats (Park and Taylor, 2010)

3.3.1.2. Basic Concept

The MASW method utilizes the frequency-dependent characteristics of fundamental-mode Rayleigh waves, which travel horizontally along the Earth's surface from the source to the receiver array. This method delivers shear wave velocity data in various formats: 1-D (a single vertical shear wave velocity profile), 2-D (cross-sectional shear wave velocity profiles), or 3-D (interpolation between densely spaced 1-D profiles).

3.3.1.3. Seismic Waves

Seismic waves are essentially bundles of strain energy that radiate outward from a seismic source. These waves can be broadly categorized into two main types that travel through the ground and along its surface: body waves and surface waves (Aki & Richards, 2002; Evrett, 2013).

3.3.1.4. Waves in the Body

Two types of body waves exist: compressional waves (also known as longitudinal, primary, or dilatational waves) and S-waves (also referred to as transverse, secondary, or shear waves). These waves propagate through the internal energy of an elastic solid and manifest in specific ways. In compressional (P-) waves, particles within the medium move in the direction of wave travel, alternating between expansion and contraction. The particle motion in compressional waves runs parallel to the direction of wave propagation, resulting in the dilation and compression of elementary volume particles (Aki & Richards, 1980), illustrated in Figure 3. (a).

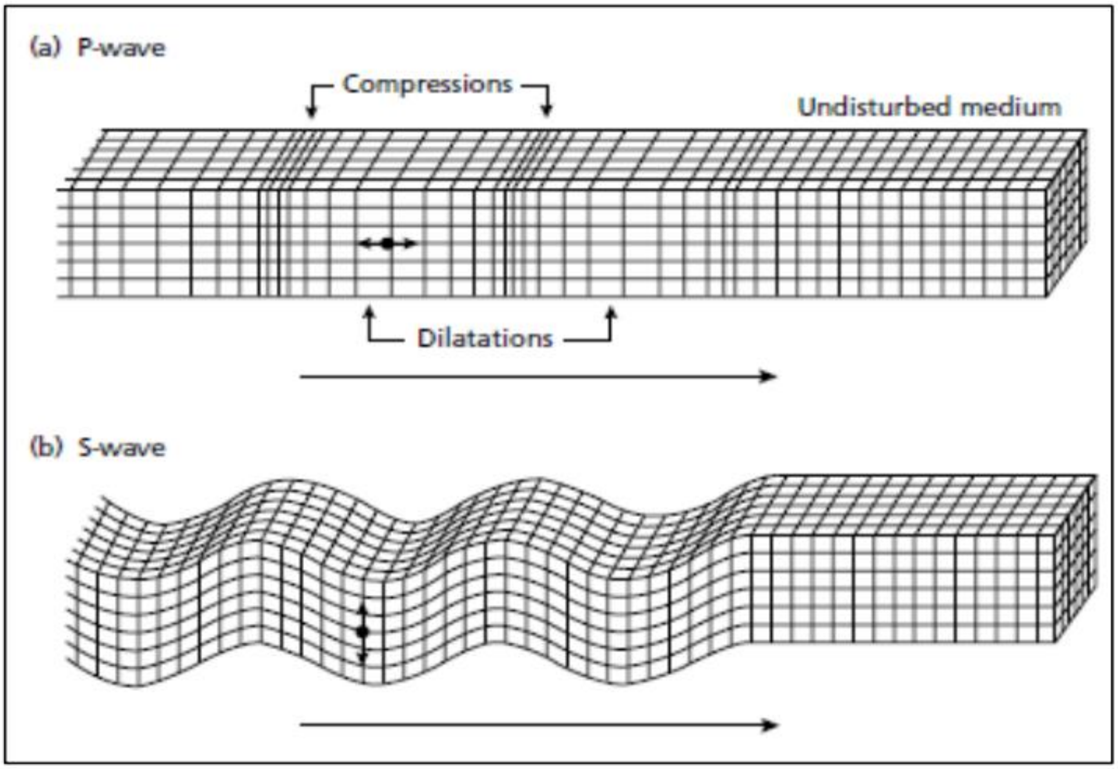


Figure 3.3: Elastic Deformation and ground particle motion associated with the passage of body waves. (a) p-wave. (b) s-wave. (Bolt,1980)

3.3.1.5. Surface Waves

Surface waves originate from the interaction of P-waves and/or S-waves, primarily traveling along free surfaces or at the interface of different materials (Kearey, Brooks, & Hill, 2002). These waves cause particle motion that is perpendicular to the wave's travel direction, with both vertical and horizontal components. There are two main types of surface waves relevant to engineering: Rayleigh waves and Love waves, distinguished by their propagation modes, dispersion velocities, and the depth range of particle motion. Rayleigh waves propagate along boundaries, with particle motion occurring vertically along the wave path, and they are always present on a free surface. Love waves, on the other hand, generate horizontal particle motion transverse to the wave direction and occur only when a softer layer lies atop a stiffer layer (Parasnis, 1997). Due to their horizontal particle motion, love waves are seldom detected in seismic surveys that utilize only vertical sources and receivers (Park et al., 1997), as depicted in Figure 3.2.

Surface waves constitute the most intense part of the signal detected during a seismic survey. For initial assessments, an average Vp/Vs ratio of 1.73 is typically used for the Earth's crust. However, the Vp/Vs ratio can be precisely calculated using the Wadati-plot method (Wadati, 1933).

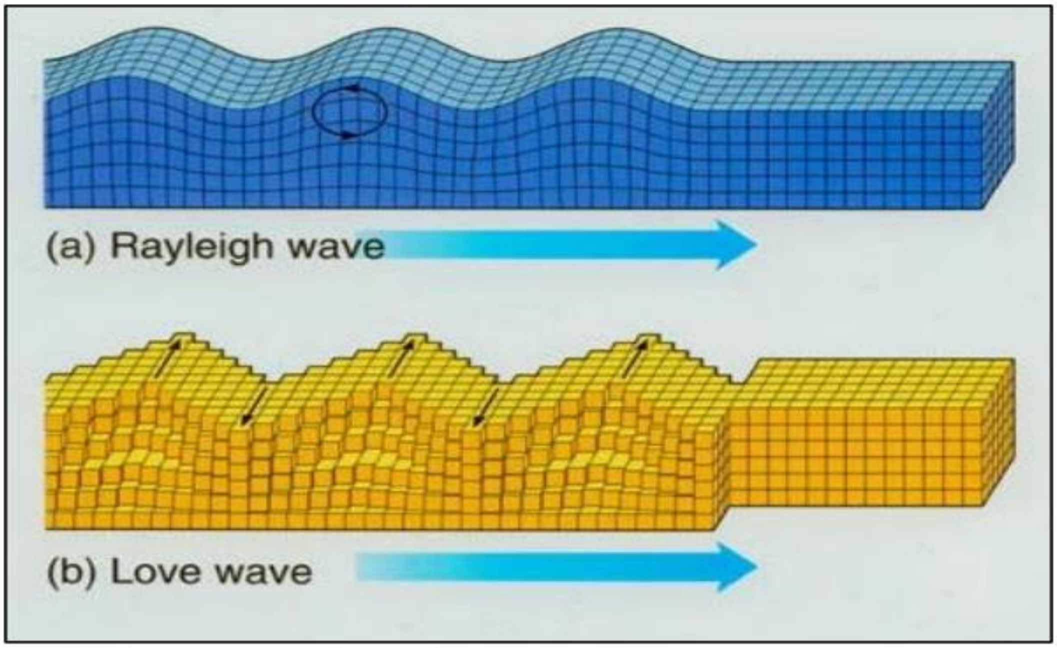


Figure 3.4: (a) Rayleigh wave motion. (b) love motion (http://thinkgeogeek.blogspot.com).

In this specific method, phase velocities are computed for each frequency component of the field-recorded Rayleigh waves. The resulting dispersion curve, which plots phase velocity against frequency, is inverted using a least squares technique to produce a vertical shear-wave velocity profile (Miller et al., 2000; Nazarian et al., 1983; Stokoe et al., 1994; Park et al., 1999a, 1999b, 2000; Xia et al., 1999).

Love waves exhibit particle motion that is parallel to the free surface and perpendicular to their propagation direction, while Rayleigh waves cause particle motion perpendicular to the surface and travel along the wave path (Kearey, Brooks, & Hill, 2002). Love waves, a type of polarized shear wave, occur in multilayered media when the shear wave velocity of the upper layer is less than that of the lower layer (Parasnis, 1997). These waves are the fastest among surface waves, moving side-to-side along the ground and confined to the Earth's crust. Due to their consistently horizontal particle motion, love waves are rarely detected in seismic surveys that use only vertical sources and receivers (Park et al., 1997).

An impact on the surface of an isotropic, homogeneous, elastic half-space can generate three distinct types of waves: Rayleigh waves, shear waves, and compressional waves (P-waves). During seismic surveys using impact sources, approximately 26% of the seismic energy is converted into Rayleigh waves, while only about 7% becomes compressional waves (Richart Jr., 1975). Figure 3.5 illustrates how seismic wave velocities vary with Poisson's ratio.

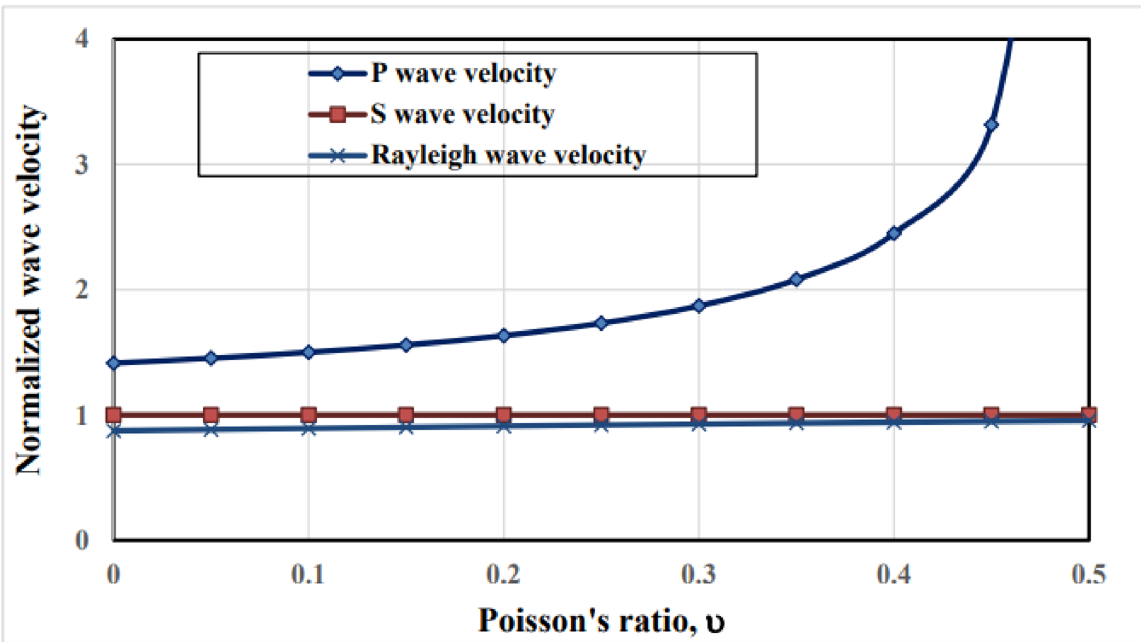


Figure 3.5: Variation of compressional, shear and Rayleigh wave propagation velocities in a homogeneous medium with Poisson's ratio (Richart etal.,1970).

3.3.1.6. Active Surface Waves and Passive Surface Waves

To understand near-surface geology and seismic risks, two primary methods are used to generate and analyze surface waves: active and passive techniques. The theory that surfaces wave travel at velocities dictated by the properties of the underlying soil is utilized in both methods.

Active Surface Waves: An artificial seismic source is established at the surface and then monitored to measure the propagation of waves. This allows for focused analysis of specific areas. A controlled source, like a vibrator, weight drop, or hammer impact, initiates surface waves. The waves' velocity as they move through the near-surface strata is influenced by variations in density and stiffness. Geophones are positioned at various distances from the source to record wave arrivals.

In active surface wave methods, a controlled seismic source, such as a vibrator, weight drop, or hammer impact, is used at the surface to generate waves. These waves are then monitored to focus the analysis on specific areas. The velocity of the waves as they travel through near-surface layers is affected by changes in density and stiffness. Geophones placed at different distances from the source record the wave arrivals.

Passive Surface Waves: Conversely, passive surface wave methods use the ambient seismic noise that already exists as the source. There are numerous potential causes of this noise, such as distant earthquakes, wind, and cars. Constantly occurring ambient vibrations that move through the layers near the surface give rise to surface waves. By means of the analysis of the characteristics of these waves, namely their frequency composition, passive methods extract information on the subsurface shear-wave velocity profile.

In contrast, passive surface wave methods rely on ambient seismic noise, which can originate from sources such as distant earthquakes, wind, and vehicles. These constantly occurring vibrations propagate through near-surface layers, generating surface waves. By analyzing the characteristics of these waves, particularly their frequency composition, passive methods can determine the subsurface shear-wave velocity profile.

The surface wave technique is increasingly recognized as an effective method for determining the shear-wave velocity (Vs) of near-surface materials, with various applications in geotechnical projects. Using an artificial seismic source, such as a sledgehammer, the active method can typically measure Vs down to depths of a few tens of meters (e.g., 30 m). However, this depth may be insufficient when the elastic properties of near-surface materials are challenging or when deeper investigations are required. While more powerful active sources, such as heavy-weight drops, can sometimes extend the depth range, the additional depth is usually minimal.

Significantly increasing investigation depth may require impact power several orders of magnitude greater than most active sources can provide. Developing such a powerful source would be prohibitively expensive and impractical for widespread use in engineering projects. Consequently, researchers are focusing on passive surface waves generated by cultural activities (such as traffic), which produce wavelengths long enough to extend below the maximum depth reached by active surveys. Passive surveys complement active surveys by filling in the dispersion trend at lower frequencies (e.g., 5–20 Hz), whereas active surveys cover a higher frequency range (e.g., 20–50 Hz). By combining these two sets of dispersion curves, researchers can construct a dispersion curve for a known mode (such as the fundamental mode) and back-calculate a Vs profile over a broad depth range (Park et al., 2005).

Accurately identifying modes is essential when calculating shear-wave velocity (Vs) using dispersion curves in a surface wave approach. Therefore, the dispersion imaging method is vital, as it can directly modify the wavefield to display the multimodal characteristics of surface waves. It is necessary to assess the modal nature of both passive and active curves, even though the fundamental mode is traditionally considered. Sometimes, combining studies of both passive and active surface waves can produce a composite dispersion curve over a broader frequency range, enhancing the depth of Vs estimation.

An active MASW survey may struggle to penetrate down to thirty meters due to the density of near-surface materials. While weight drop sources were developed to tackle this issue, their high cost and inconvenience prevent seismic surveyors from using them. Currently, passive surface waves generated by ambient noise fill this gap; their longer wavelengths ensure they reach deeper than any active survey can achieve (Park et al., 2005).

3.3.1.7. Micrometer Analysis Measurements (MAM)

Passive surface waves, originating from both natural sources like tidal and atmospheric activities and cultural sources such as traffic and industry, typically operate at frequencies (wavelengths) lower (longer) than a few hertz (a few hundred meters) (Park, Miller et al., 2005). In contrast, modern engineering research often focuses on surface waves generated by traffic at frequencies higher than approximately 5 Hz (with wavelengths in the tens of meters) (Park, 2005).

For passive surface waves where the fundamental mode Microtremor Survey Method (MSM) is dominant, the active curve is typically assumed to represent the fundamental mode in engineering applications, if feasible (Park et al., 2005). There is a common perception that higher modes with significant energy are more prevalent at high frequencies (> 20 Hz), while the fundamental mode exhibits strong dispersive characteristics at low frequencies (< 20 Hz). This perception may contribute to biases in mode selection.

The active survey recorded frequencies ranging from 15 to 40 Hz, whereas the passive survey captured frequencies between 2 and 15 Hz. Combining these two sets of dispersion curves through data inversion allows for the creation of a shear wave profile across a wide depth range.

Micrometer Analysis Measurements (MAM) were employed in the passive investigation (Park, Miller et al., 2005), suggesting the integration of both active and passive modes for verification, even though MAM primarily identifies the fundamental mode. During micrometer analysis measurements (MAM), two techniques commonly used are cross-correlation and SPAC (spatial autocorrelation).

Cross-correlation: Cross-correlation is a technique used to compare two seismic signals or waveforms to measure their similarity or correlation in terms of time delay and amplitude. It helps identify common features or events in different seismic recordings, and its application is commonly used in seismology for tasks such as detecting seismic events, locating earthquakes, or correlating seismic data from different stations to determine the characteristics of seismic waves.

SPAC (Spatial Autocorrelation): SPAC is a method used to analyze the spatial distribution of seismic signals recorded by multiple stations. It examines how similar seismic signals are in terms of their spatial arrangement and correlation between different seismic sensors, and their application is useful for studying the spatial coherence of seismic waves, identifying wave propagation characteristics, and understanding the structural properties of the Earth's subsurface based on seismic data. These techniques are essential in seismic investigations for interpreting seismic data, understanding earthquake sources, and studying Earth's subsurface properties.

Cross-correlation Coefficient:

$$\rho_{ij} = \frac{C_{ij}(t)}{\sqrt{C_{ii}(0)\cdot C_{jj}(0)}}$$

where $C_{ii}(0)$ and $C_{jj}(0)$ are the auto-correlation functions of signals recorded at sensors i and j, respectively.

Spatial Autocorrelation (SPAC):

$$\rho(r) = \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1, j \neq i}^{N} C_{ij}(r)$$

where N is the total number of sensors, and $C_{ij}(r)$ is the cross-correlation function at lag distance r between sensors i and j.

Both cross-correlation and spatial autocorrelation (SPAC) methods are essential in extracting dispersion information from seismic data during Multichannel Analysis of Surface Waves (MASW) site investigations. Cross-correlation measures time delays between signals, while SPAC extracts dispersion information directly from the data using spatial autocorrelation. Integrating both methods offers a comprehensive approach to characterizing subsurface properties and deriving accurate dispersion curves.

3.3.1.8. Micrometer Analysis Measurements (Mam) Data Acquisition

In microtremor analysis, it's crucial for the signal to be both directional and flat. The SeisImager/SW software utilizes its built-in spatial autocorrelation capability to address challenges related to source orientation and positioning. Among various setup orientations (linear, circular, L-shaped, and triangular), the L-shape is chosen for its practicality in field setup and its ability to capture signals from both North-South (NS) and East-West (EW) directions efficiently. After processing, a unified dispersion curve covering a broad frequency range is generated by combining dispersion curves obtained from both Micrometer Analysis Measurements (MAM) and Multichannel Analysis of Surface Waves (MASW).

3.3.2. Multichannel Analysis of Surface Waves Data Acquisition

In general, Rayleigh wave velocities tend to increase with depth, particularly for waves with longer wavelengths and lower frequencies, which propagate faster than those with shorter wavelengths. The relationship between frequency (f) and Rayleigh wavelength is termed phase velocity (c(f)). These distinct characteristics are depicted by the Rayleigh wavelength (λ(f)), as illustrated in Figure 3.6 (Kramer, 1996).

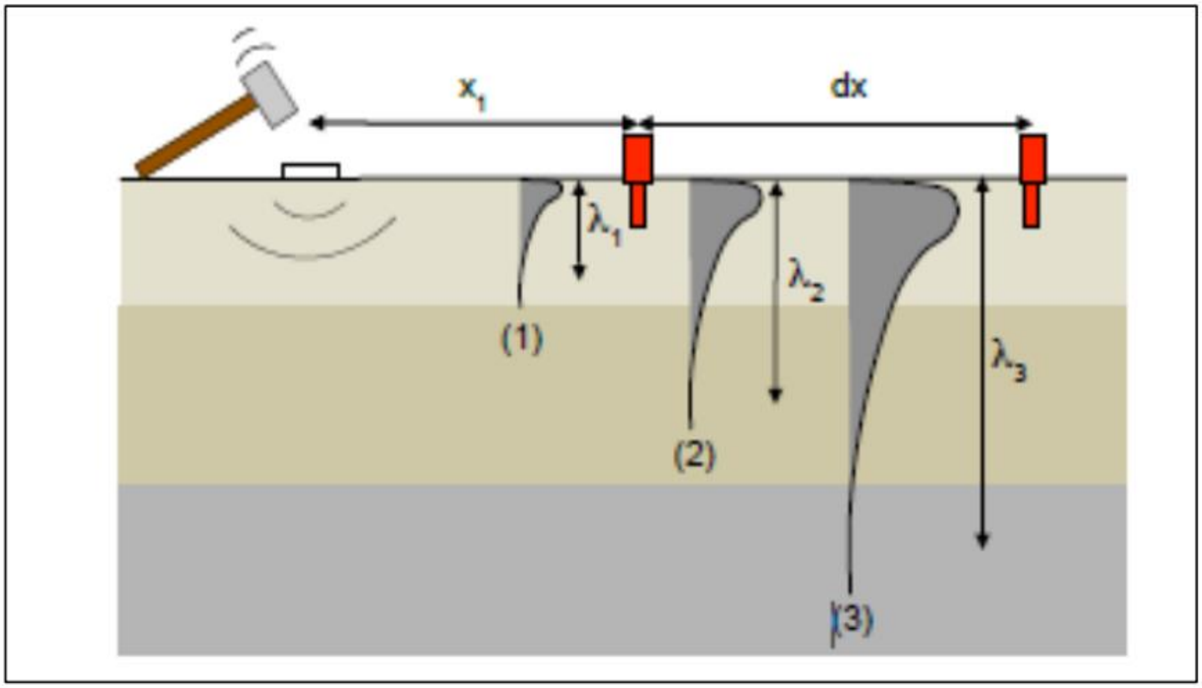


Figure 3.6: Rayleigh wave components with different Rayleigh wavelengths propagating through a layered medium. Wave components with different frequencies reflect soil properties at diverse depths.

The phase velocity of wave component (1) is influenced by the material properties of the topmost layer, whereas the phase velocities of wave components (2) and (3) depend on the properties of the deeper layers.

$$\lambda (f) = C(f)/f \tag{1}$$

The variable C is a constant that varies slightly depending on the Poisson's ratio of the material through which seismic waves propagate. Even with significant changes in Poisson's ratio, C typically ranges from 0.874 to 0.955 (Anderson, 2010). It is proposed that assuming a value for C and recording frequencies along with their corresponding surface wave velocities allows for the development of a shear-wave velocity profile through analysis, enabling the generation of a subsurface velocity image (Anderson, 2010). These distinct characteristics contribute to variations in the Rayleigh wavelength λ.

Depending on the type of seismic source used, the Multichannel Analysis of Surface Waves (MASW) method can be classified as active or passive. Active MASW employs traditional seismic refraction survey techniques with an active source such as a sledgehammer, accelerated weight drop, or vibroseis, moving along a linear array of receivers (Park et al., 1999). In contrast, passive MASW utilizes surface waves generated naturally or by cultural activities such as highway traffic and construction equipment (Park et al., 2007).

Passive MASW surveys can be conducted in two ways depending on receiver configuration: passive remote MASW (Park et al., 2004; Park et al., 2005) with a two-dimensional receiver array, and passive roadside MASW (Park and Miller, 2008) using a linear one-dimensional receiver array. Data acquisition in MASW is more flexible in parameter selection compared to other seismic methods due to the typically high signal-to-noise ratio achievable in seismic field records.

For active MASW data acquisition, vertically polarized geophones with a low frequency sensitivity (e.g., 4.5 Hz) are deployed on the surface of the test site at regular intervals. Typically, a minimum of 24 geophones are used, each with an optimized spacing determined by site-specific geological conditions (Donohue, Forristal, & Donohue, 2013; Lin, Chang, & Chang, 2004). Each geophone is connected to an individual recording channel (Park et al., 1997), and the entire array is linked to an engineering seismograph and a field laptop equipped with the necessary software for data recording.

A surface wave is induced by an impact load at one end of the geophone lineup, and the geophones record the resulting wave motion over time. The seismic source can vary depending on the depth of investigation and site conditions, ranging from a 20-lb sledgehammer to mechanical impact devices, shotguns, or explosives. The arrival of surface waves is detected across the geophone array and recorded on the seismograph, with each geophone's output displayed as a single trace.

Proper setup of data acquisition parameters, including the total length of the receiver spread, source offset (distance between the source and nearest geophone), and geophone spacing, is crucial for the success of the surface wave survey. Geophones, which record vertical motion only, must be accurately positioned vertically in the subsurface. Each geophone is connected via a separate recording channel to a data acquisition card and a computer equipped with the necessary software (see Figure 3.7).

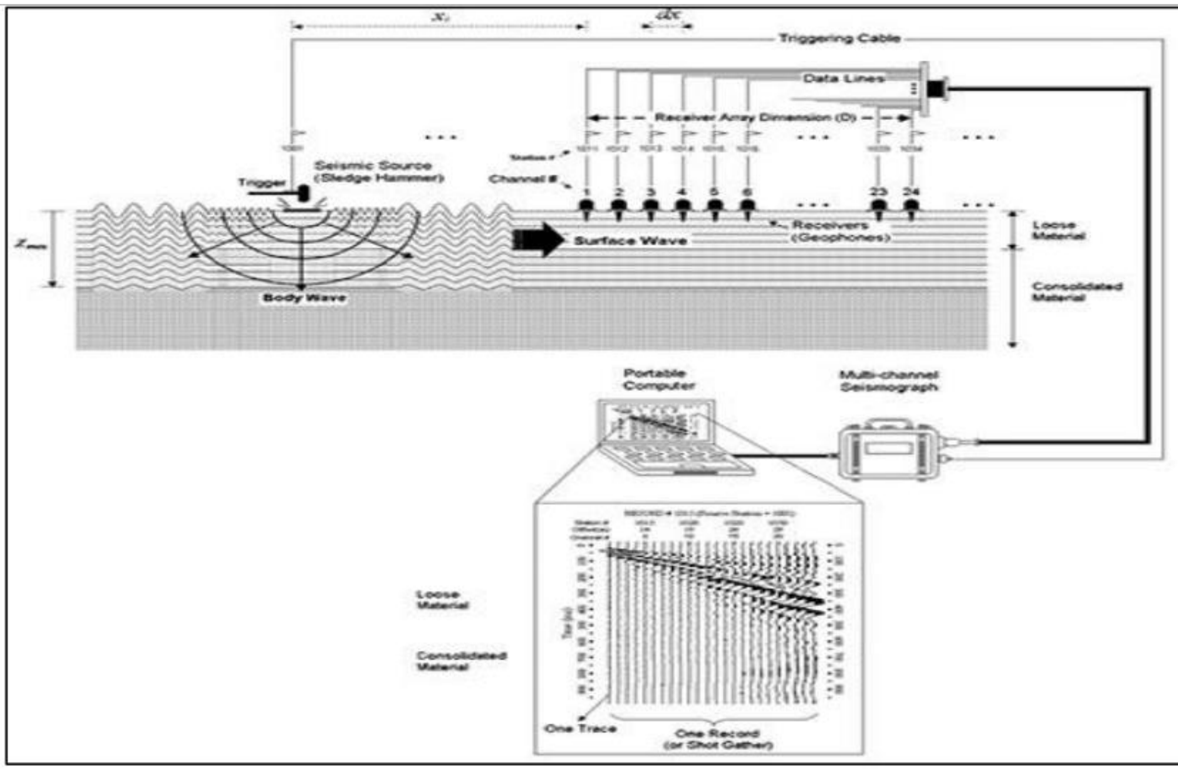


Figure 3.7: 1The instrumentation used in the MASW tomography survey (Park et al.,2002)

Geophones are positioned on the surface of the test site. A wave is generated, and its propagation is recorded during the survey. The maximum depth of investigation (Zmax) varies depending on factors such as the site characteristics, the natural frequency (fe) of the geophones, and the type of seismic source used. The determination of the maximum investigation depth relies on capturing the longest Rayleigh wavelength observed during data acquisition (λmax). According to a widely adopted empirical guideline (Park & Carnevale, 2010):

$$Z_{max} \approx 0.5\lambda_{max} \qquad (2)$$

3.3.2.1. Geophone Spread Length.

The total length of the geophone spread (D) determines the maximum wavelength of Rayleigh waves that can be analyzed. This length is also directly linked to the maximum investigation depth (Zmax), as the receiver array's span affects the longest Rayleigh wavelength recorded during data collection. According to a common criterion, the longest Rayleigh wavelength (λmax) that can be effectively analyzed is typically equal to the length of the receiver array (Park & Carnevale, 2010).

$$\lambda max \approx D. \tag{3}$$

Attempting to analyze Rayleigh wavelengths longer than those defined by Equation 3.9 can result in reduced accuracy. Recent studies indicate that despite some variability, inaccuracies typically remain within 5% for the range $D \leq \lambda max \leq 2D$ (Park & Carnevale, 2010), due to inherent uncertainties (noise) in measurements. It is advisable to avoid using excessively long receiver spreads, as surface waves generated by common seismic sources (e.g., moderately heavy sledgehammers) may experience increased noise levels at the far end of such arrays, rendering data from the outermost receivers too noisy for reliable use (Park et al., 1999; Xia et al., 2009). Typically, the maximum wavelength accurately analyzed is approximately half the length of the overall geophone spread.

3.3.2.2. Source Offset

Choosing an appropriate source offset is crucial to avoid the near-field effect, where geophones might detect incompletely developed surface waves. A longer source offset can generate energy conducive to longer-wavelength surface waves but may attenuate short-wavelength components. For long offsets, where the path traveled along the refractor exceeds several Rayleigh wavelengths, the amplitude of head waves decreases significantly, approximately by the inverse square of the offset. In cases involving low-velocity layers (LVLs) or weathering surveys, smaller offsets are typically preferred, leading to a slightly lesser amplitude decrease. Additionally, if the refractor is thin, significant attenuation occurs, a phenomenon known as shingling, which manifests as energy shifting to progressively later cycles with increasing offset, creating an echelon pattern (Press et al., 1954). This effect is illustrated in Figure 3.8.

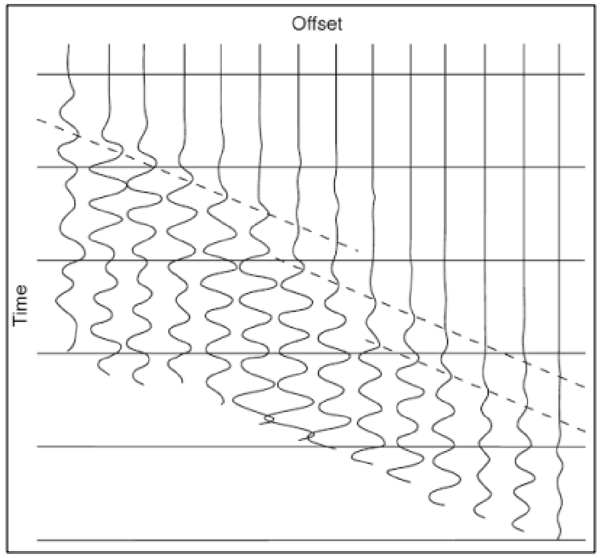


Figure 3.8: Refraction arrivals showing the shingling degree pattern often associated with layers

3.3.2.3. Receiver Spacing

The receiver spacing (dx) determines the shortest wavelength that can be analyzed and the shallowest depth resolved in a MASW survey. The minimum investigation depth, shortest Rayleigh wavelength (λmin), is linked to the minimum distance between geophones (O'Neill, 2003), assuming that the maximum penetration depth is approximately half of the longest recorded Rayleigh wavelength (Park et al., 2009). Receiver spacing directly influences the shortest Rayleigh wavelength (λmin) included in a dispersion curve. Generally, to prevent spatial aliasing, the receiver spacing should not exceed half of the shortest Rayleigh wavelength (Xia et al., 2009).

$$dx \approx \lambda min \approx Zmin$$

$$dx \leq 0.5\ \lambda min. \qquad (4)$$

Additionally, Park et al. (1999) and Xia et al. (2009) suggest that the receiver spacing provides guidance for determining the minimum thickness (Hmin) of the shallowest layer in the layered earth model used for inversion analysis.

3.3.2.4. Orientation

The alignment of profiles should accurately reflect subsurface structures, which is crucial for effective interpretation. Seismic data interpretation often incorporates well-logged log data and findings from prior geological surveys (Sheriff & Geldart, 1995). It's essential to maintain small spacing in all orientations to prevent surface irregularities. Uniform subsurface coverage is necessary, ensuring consistency across various source offsets and azimuths (Bacon et al., 2003).

Generally, there was a reasonable correlation between surveys conducted in opposite orientations. If one orientation yielded poor-quality data and a challenging dispersion curve extraction, the opposite orientation typically showed a similar quality curve, often due to subsurface lateral heterogeneities. Analyzing data from both orientations helped mitigate these influences.

In essence, both receiver spacing and source array methods can introduce additional orientation effects. Therefore, a comprehensive consideration of source array parameters, receiver spacing, and acquisition system geometry forms the basis for conducting a high-quality and efficient seismic survey project.

3.3.2.5. Topographical Conditions.

Topographical conditions significantly influence the quality of recorded surface wave data and consequently affect the resulting dispersion curves. They also impact the acquisition quality of surface wave data, influencing the quality of generated dispersion images (Zeng, Xia, Miller, Tsoflias, & Wang, 2012). To achieve optimal results, receivers should be positioned on relatively flat terrain, as illustrated in Figures 3.9 (1) and 3.8 (2), which are suitable for active MASW surveys.

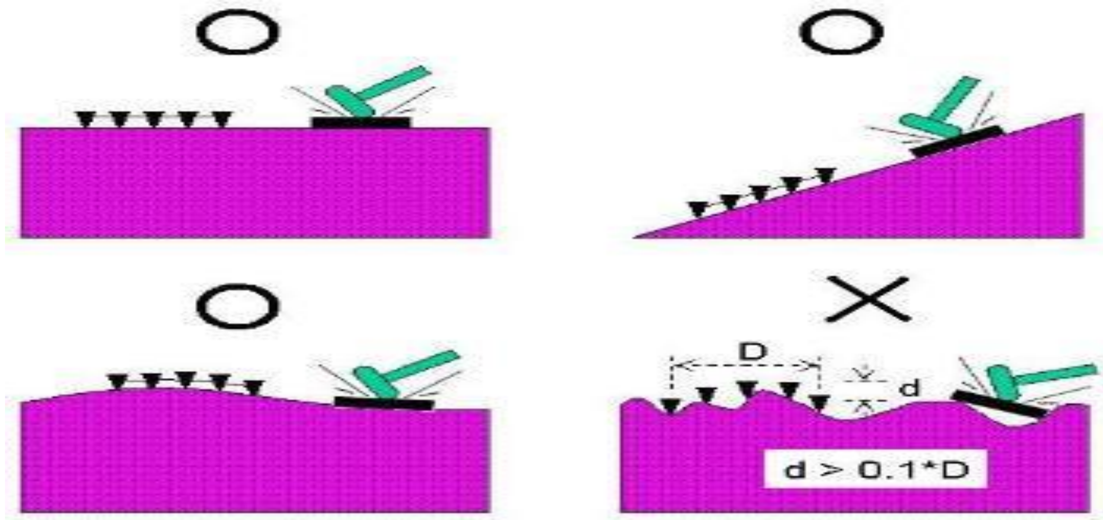


Figure 3.9: Typical terrain conditions favorable and unfavorable for the MASW survey

Surface variations within the receiver spread exceeding 0.1 times the receiver spacing (2) can notably impact the generation of surface waves (Park, 2015), as depicted in Figure 3.8 (3), and should be minimized. Additionally, the slope of the surface along the receiver spread can influence the quality of surface wave recordings, as illustrated in Figure 3.8 (4).

3.3.3. Multichannel Analysis of Surface Waves Data Processing

Different frequencies of Rayleigh waves correspond to particle motion at different depths, with lower frequencies indicating deeper particle motion. As a result, Rayleigh waves at various frequencies exhibit distinct phase velocities. The MASW technique relies on understanding this relationship between Rayleigh wave phase velocities and the depth range of particle motion.

The quality of the acquired surface wave data can be assessed based on the resolution of the phase velocity spectrum. This includes the sharpness of amplitude peaks at each frequency, the range of frequencies that can be reliably extracted, and the continuity of the high-amplitude band of the fundamental mode.

Furthermore, natural geological conditions can adversely affect MASW data quality by preventing the computation of reliable shear-wave velocity models or the production of well-defined dispersion curves.

After field recordings are collected, they are analyzed using software like SeisImager by Geometrics, Inc. to estimate shear wave velocity. The process involves several critical steps: first, extracting the fundamental-mode dispersion curve from a dispersion image, which represents phase velocity against frequency intensity. The software computes phase velocities for each frequency component based on MASW data. Then, a least-squares method is applied to invert the dispersion curve and generate a vertical shear-wave velocity profile.

In essence, the software translates the wavefield from the offset-to-time domain into a dispersion image in the frequency-phase velocity domain using multichannel records. This data is then processed to produce a 1-D (depth) shear wave velocity profile derived from the raw seismic record and the dispersion curve extracted from the dispersion image. As shown in figure 3.11

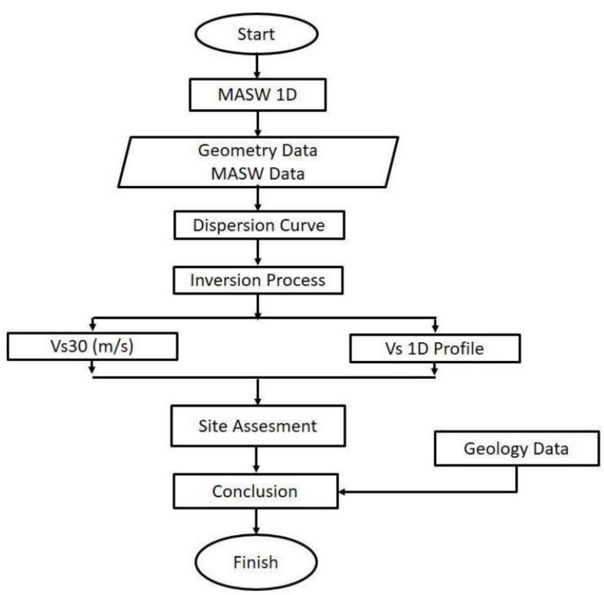


Figure 3.10: The flowchart of this research using a multichannel analysis of surface wave (MASW) method.

3.3.3.1. Dispersion Analysis.

Dispersion analysis seeks to estimate one or more dispersion curves, which are crucial inputs for the inversion process. The primary factors influencing dispersion analysis include:

1. The frequency range covered by the analysis.
2. The approximate range of phase velocities.
3. Identification and mitigation of noise events.
4. Characterization of simple higher modes.

These factors play a critical role in analysis, depending on the signal-to-noise ratio (S/N) of the data. Surface waves, with their highest S/N, are the primary seismic event in high-quality data collections, while noise typically affects lower-quality datasets. In dispersion curve analysis, the fundamental mode of surface waves is considered the signal, with all other components regarded as noise.

3.3.3.2. Inversion analysis.

Inversion analysis is employed to construct a shear wave profile by reverse-calculating shear wave velocity and associated depths from experimental dispersion curves through an iterative process. This relies on modeling Rayleigh wave propagation in a flat-strata earth model. The iterative nature of solving the inversion problem is crucial for accurately deriving a realistic layered earth model from nonlinear Rayleigh wave dispersion data. Theoretical fundamental mode dispersion curves are extracted using a mathematical model with specific input parameters. Throughout the inversion process, multiple sets of layer parameters are adjusted until observed experimental dispersion curves align closely with anticipated curves (Park, Miller et al., 2002).

The goal of multi-parameter optimization is to achieve an accurate shear wave profile by minimizing discrepancies between observed and projected dispersion curves. This inversion analysis program is structured around three main components. The first algorithm estimates initial model parameters, while the second employs a mathematical model developed by Kausel and Roësset in 1981, utilizing assumed soil properties to generate theoretical dispersion curves based on stiffness matrices. The third component focuses on minimizing mismatches between experimental and theoretical basic mode dispersion curves through algorithmic evaluation.

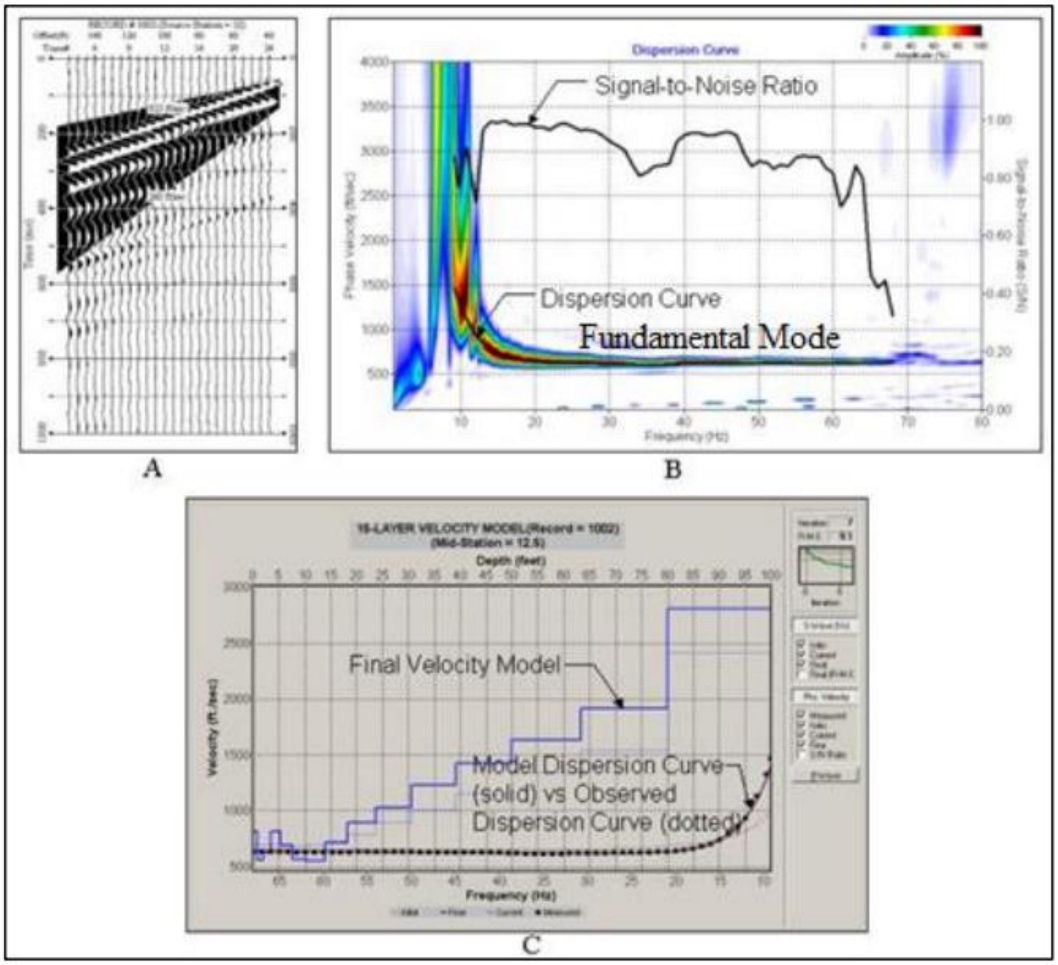


Figure 3.11: (A) Acquisition of seismic time series data; (B) Dispersion curves extraction frequency and phase velocity; and (C) 1-D shear-wave velocity profiles Vs.1-D depth curve (http://www.kgs.ku.edu/software/surfseis/gifs/masw).

Software evaluates the phase velocity range for surface waves, typically spanning from 200 m/sec to 760 m/sec, depending on the material. This range guides the software in identifying the phase velocity corresponding to a specific surface wave frequency that exhibits the highest coherence across various offsets and the highest signal-to-noise ratio (S/N), indicating robust data confidence (Figure 3.11). The SeisImager software calculates phase velocities within this specified frequency range and iteratively refines parameters to identify an optimal solution. Generally, the curve with the highest S/N ratio is considered the most reliable.

The quality of dispersion curves is assessed based on two main criteria: the S/N ratio and the overall direction of the dispersion curve. The next step involves extracting a fundamental-mode dispersion curve from the dispersion image, termed the "measured" dispersion curve, which serves as input for subsequent inversion analysis. Evaluation of surface wave records focuses on the resolution of the phase velocity spectrum, the clarity of amplitude peaks at each frequency, the frequency range that can be accurately extracted, and the continuity of the fundamental mode's high-amplitude band.

The quality of the dispersion curve match is quantitatively evaluated using the root-mean-square error between the observed and theoretical curves (Xia et al., 1999). The inversion process facilitated by SeisImager Software is fully automated, minimizing potential human errors during calculations and ensuring a straightforward analysis.

3.3.4. Multichannel Analysis of Surface Waves Data Interpretation

Interpreting MASW data involves analyzing variations in shear wave velocities with depth to create a geological model of the subsurface. In karst terrains, interpreting subsidence features can be challenging due to the complex nature of the subsurface and the resolution limitations of MASW techniques. Shear wave velocity models can reveal low-velocity zones, potentially indicating sinkholes, voids, fractured bedrock, or collapsed features that are naturally filled. Stiff earth materials generally exhibit higher shear wave velocities compared to fractured or weak earth materials (Table 3.1).

The reliability of shear wave velocity data decreases with increased lateral and vertical heterogeneity in soil or rock properties. Factors such as steep dips in subsurface layers (>10%), challenging topography, or known variability in soil or rock properties can render field data unsuitable for straightforward interpretation in terms of simple vertical subsurface variations.

Table 3.1. Shear wave velocity (Vs) of some earth materials (National earthquake hazards reduction program).

Earth materials	**Shear wave velocity (vs) m/sec**
Rock Hard (A)	>1500
Hard (B)	760-1500
Very Dense Soil & Soft Rock(C)	360-760
Stiff Soil (D)	180-360
Soft clay (E)	<180
Soil requiring additional response (F)	<180 & meeting some additional condition

3.4. Data Acquisition of The Study Area

The study sites are located in the southeast and northwest directions of Bole and Jan Meda, respectively, which are areas within Addis Ababa, Ethiopia. Bole, with Bole being a prominent district known for Bole International Airport and commercial activities, while Jan Meda is recognized for its open fields and recreational spaces. Bole could be an area that moves towards residential neighborhoods or emerging commercial zones**.** Jan-Meda could lead into more residential areas or regions that are less commercially dense compared to Bole. This is an area a primarily known for recreational activities, sports fields, and being a cultural landmark, construction, and a major transportation hub.

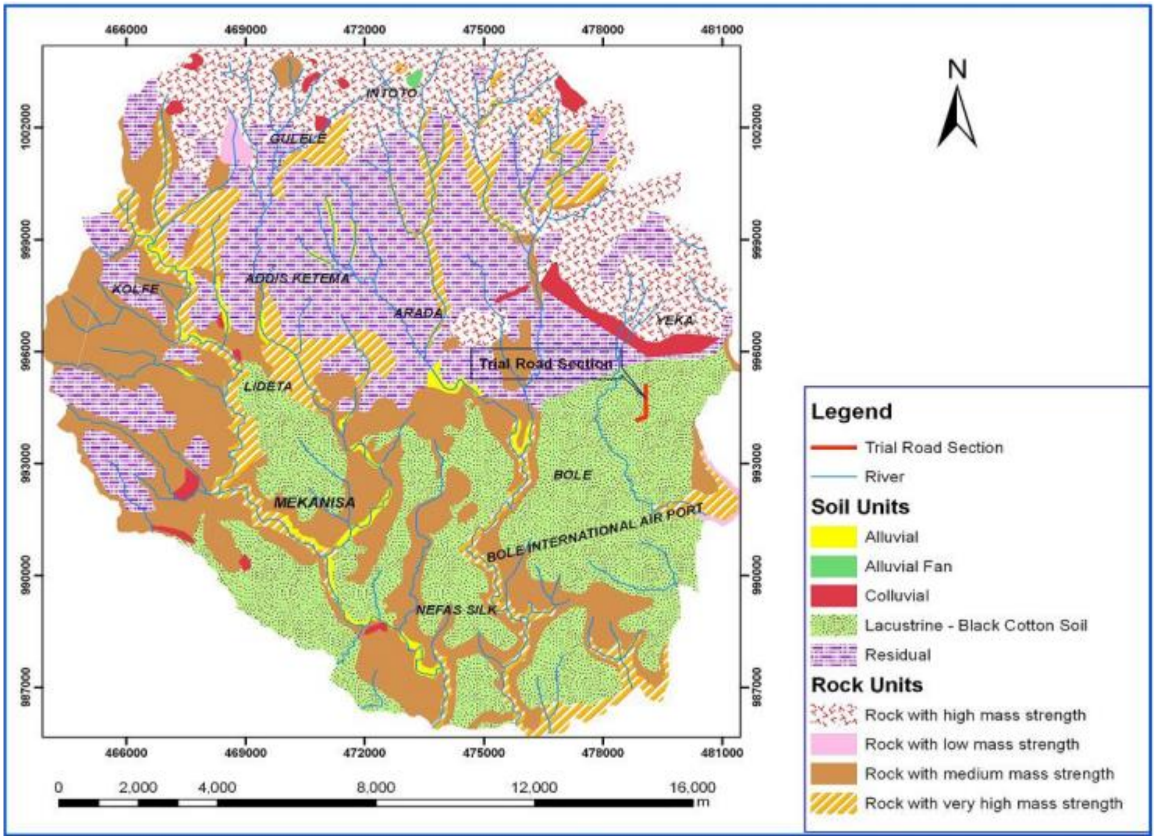


Figure 3.12: Engineering Geological Map of Addis Ababa (Kebede Tsehayu et al., 1990 and Dejenie Abere et al.)

Bole Homes' largely level terrain makes it an attractive site for urban expansion. The bulk of the soil in this area is made up of alluvial deposits, which are typically stable but can pose issues with settlement if not managed appropriately. The underlying volcanic rocks, which are primarily basalts and tuffs, were formed by earlier volcanic activity in the Ethiopian Rift. Effective soil management strategies are essential to lowering possible risks in this area. Jan Meda is near the Entoto Mountains and features more elevated and rugged terrain. This region's rocks are a blend of volcanic and metamorphic types. Construction is made more challenging by the clayey soil that is often built of weathered volcanic rubble due to the danger of landslides and erosion. To ensure safety and longevity, building in Jan Meda necessitates careful consideration of slope stability and erosion control methods

3.4.1. The Equipment and Field Procedure

To conduct seismic refraction and MASW surveys, specific equipment is essential, including a seismograph, geophones, spread cable, strike plate, battery, hammer, and trigger cable.

The seismograph is crucial as it precisely records the arrival times of waves at each geophone. In this study, a 24-channel Geode seismograph from Geometrics Inc. (Figure 3.13) was used for recording refraction and MASW data. The Geode is controlled via Seismodule Controller Software (SCS), which runs on a personal computer.

Figure 3.13: Geode Seismograph.

Geophones and spread cables play a crucial role in seismic surveys. Geophones are devices that detect seismic waves generated by impacts. They consist of a coil wrapped around a bar magnet, allowing the coil to oscillate freely along vertical or horizontal axes depending on the wave type (P-wave or S-wave). The magnet is housed within the geophone's case.

When seismic waves hit, geophones convert mechanical energy into a small electric current. This current travels through cables to a recording apparatus, where it is amplified and recorded directly. For optimal performance, geophones should be securely planted in the ground, sometimes requiring the removal of loose topsoil and placement in small holes to minimize wind interference.

The cables that connect geophones to the seismograph are known as spread cables, as illustrated in Figure 3.14. These cables have multiple takeouts, allowing up to 24 geophones to be connected simultaneously. They transmit the ground motion signals (geophone current) to the seismograph.

Both horizontal and vertical geophones are used to capture a broad range of wave patterns and motions, enhancing sensitivity during data collection (see Figure 3.14).

Figure 3.14: Geophones.

Hammer and strike plate. The selection of seismic sources is influenced by the type of seismic investigation, geological conditions, and the depth of the survey. Various energy sources are employed in seismic refraction and MASW surveys, including explosives, sledgehammers and mechanical weight drops. In the present survey, seismic P-waves and MASW were generated using a 10-kg sledgehammer. A switch taped along the handle, near the hammer head, initiates the zero-time for seismic recordings. To enhance energy transmission to the ground, strikes were directed onto a 20×20 cm^2 plastic plate.

Trigger cable. A MASW trigger cable is a cable that connects a trigger sensor to a seismograph in a Multi-channel Analysis of Surface Waves (MASW) survey. The trigger sensor is typically a simple contact-closure switch that is activated by the impact of a sledgehammer or weight drop on a strike plate. This triggers the seismograph to start recording the seismic waves generated by the impact. It is typically short, rugged cables with two or three conductors. They may have a connector on one or both ends, depending on the specific seismograph and trigger sensor being used.

3.4.2. Data Acquisition.

MASW surveys can be tailored to investigate different subsurface conditions by adjusting data acquisition parameters. MASW data were collected at two sites that were both active surface waves and passive surface waves with different orientations; a total of 60 MASW profiles were acquired.

At the Bole Homes site, where we want to understand the top 30 meters, we would use spaced geophones at 10 meters for better resolution in shallow depths. A linear array of 24 geophones with a 230-meter array size would provide a good spread for capturing relevant wavelengths. The hammer's impact point would be 12 meters from the first geophone. To capture the extended wave propagation characteristic of soft soils, a sampling frequency of 4.5 Hz and a recording duration of 32 seconds might be employed.

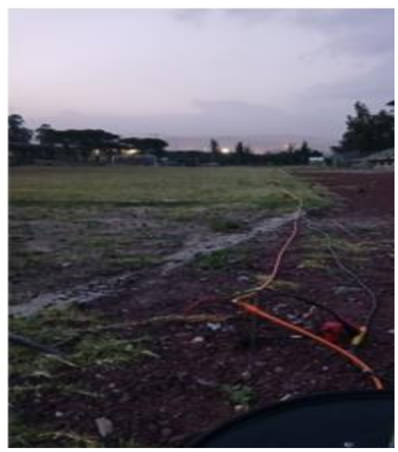


Figure 3.15: MASW data acquisition at bole community school

In contrast, a Jan-Meda site requiring S-wave velocity assessment down to 50 meters would necessitate a wider geophone spacing of 10 m at 230 m array size and 5 m at 115 m array size on the liner array for active and passive surface waves, and a geophone spacing of 10 m at 50 m array size on the L-shape array for passive surface waves. The source offset was 7 m due to the expected higher velocities. A 24-geophone and 11-geophone array would offer a larger spread for capturing deeper wavelengths. The hammer impact might be positioned 15 meters from the first geophone. Anticipating potentially higher wave frequencies in sand, we might use a higher sampling frequency of 4.5 Hz. Recording time could be reduced to 1 second due to the faster wave propagation in stiffer material.

Data acquisition is started by turning on the trigger microphone and starting the recording software. When the MASW array has started, at passive, the operator releases the seismic source (10-kilogram sledgehammer), signaling the seismograph to start collecting data. Five stacks of seismic data were collected at each traversal in an effort to minimize background noise and to passively deploy the seismometers for a longer duration to capture naturally occurring vibrations from sources like wind, traffic, or distant earthquakes. The primary objective of the study was to optimize acquisition parameters and compare the characteristics of rocky and hard soil and sediment sites through MASW surveys conducted in the topography of Addis Ababa. This aimed to refine design parameters and assess site-specific influences. Figure 4.3 illustrates the MASW equipment utilized, including a Geode seismograph and 24 vertically polarized 4.5 Hz geophones. Data collection employed source offsets of 12 m, with active receiver spacings of 3 m, 5 m, and 10 m, and a passive receiver spacing of 10 m. These configurations were chosen to minimize lateral blurring and enhance vertical resolution in MASW data collection, focusing on research depths up to 45 m.

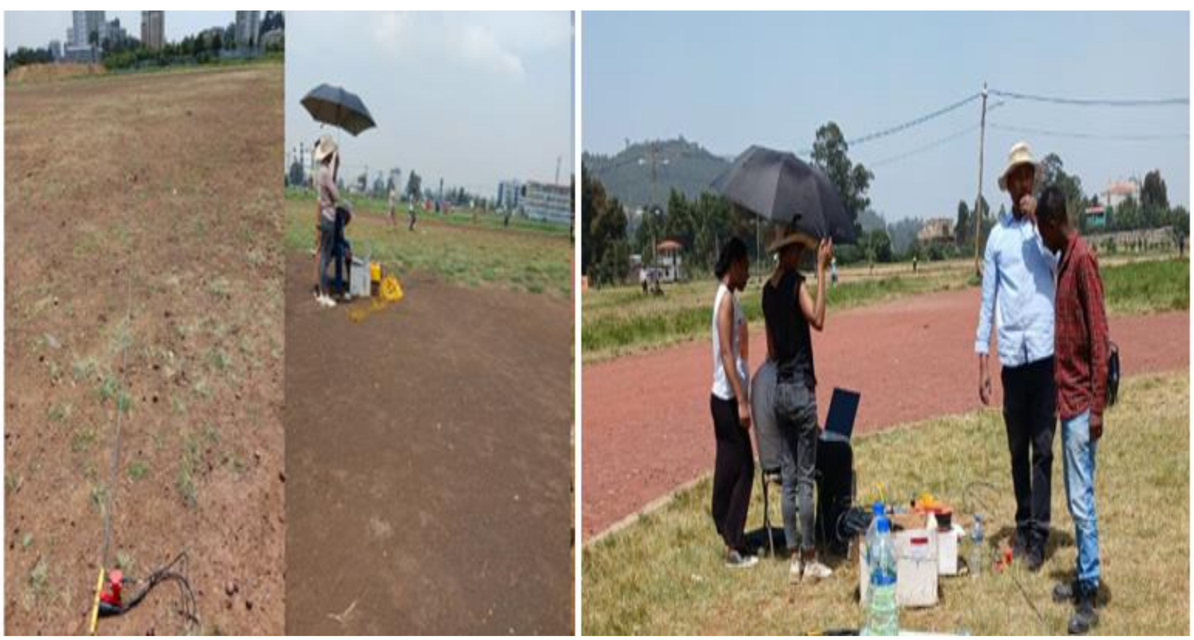


Figure 3.16: Active and passive MASW data acquisition field campaign at Jan-Meda

Table 3.2. Acquisition parameters for MASW active surveys in this study.

Source type	10kg hammer
stacks	5times
Geophone frequency	4.5Hz vertical geophone
Sample interval	0.5
Geophone interval	3m
offset	7m
Record length	1sec
Spread length	69m

Table 3.3. Acquisition parameters for MASAW passive surface wave

Parameters	Linear (24 Geophones)	L-shape (L11 Configuration)
Spread Configuration	115 meters	50 meters
Geophone Interval	3 meters	10 meters
Total Number of Geophones	24 geophones	11 geophones
Geophone Type	4.5 Hz	4.5 Hz
Sample Interval	2 milliseconds	2 milliseconds
Record Length	32 seconds for each record	32 seconds for each record

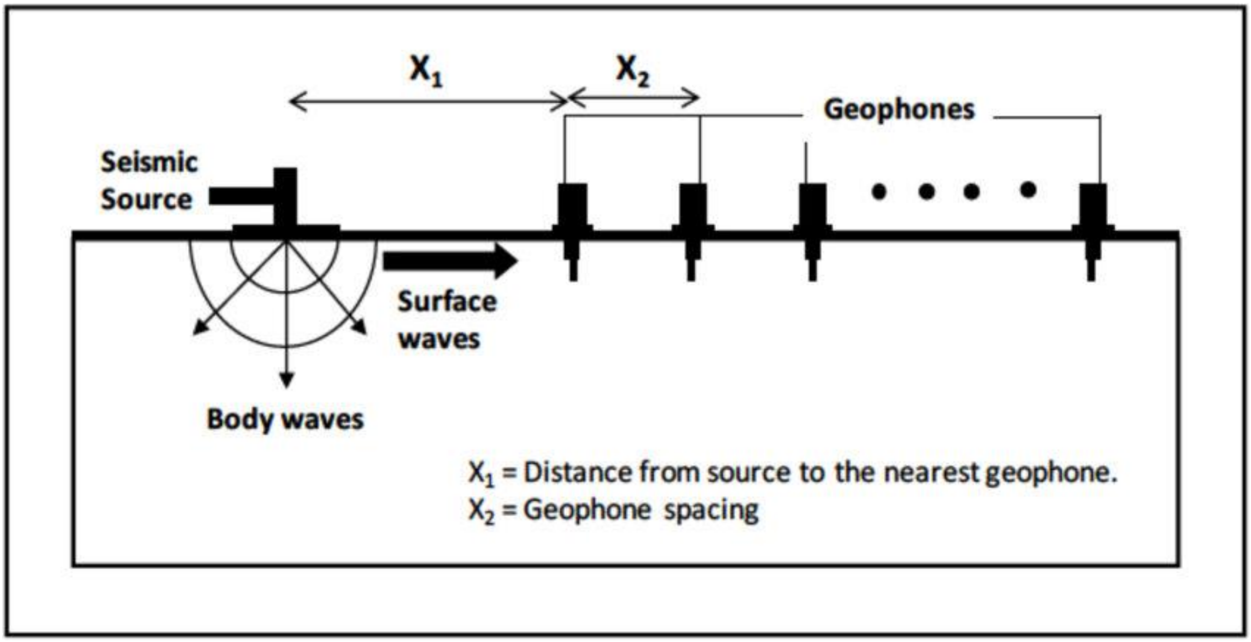


Figure 3.17: Schematic diagram of MASW data acquisition setup

3.2.2. Data Processing and Interpretation.

All seismic data collected in this study underwent processing using the SeisImager software. It is a software package used for seismic data processing and interpretation. It was developed by Geometrics, Inc., a company that specializes in the design and manufacture of geophysical instruments and software. SeisImager is widely used for analyzing both active and passive seismic data to create subsurface models, particularly in applications such as engineering, environmental studies, and geotechnical investigations. The software provides tools for refraction and surface wave analysis, making it a versatile tool for seismic imaging.

The initial assessment of data quality involves overlaying multichannel seismic recordings with processing algorithms. This stage ensures a fundamental grasp of dominant frequencies, surface wave velocity ranges, overall data quality, and the likelihood of higher-mode interference. Data categorized as "excellent" or "good" indicates the clear prominence of surface waves with high signal-to-noise ratios. In contrast, "fair" and "poor" quality datasets may suffer from noise contamination due to factors like void spaces, malfunctioning receivers, proximity to construction sites, uneven bedrock surfaces, and other sources. Such recordings may not display detectable surface wave signals suitable for processing, as depicted in Figure 3.3.

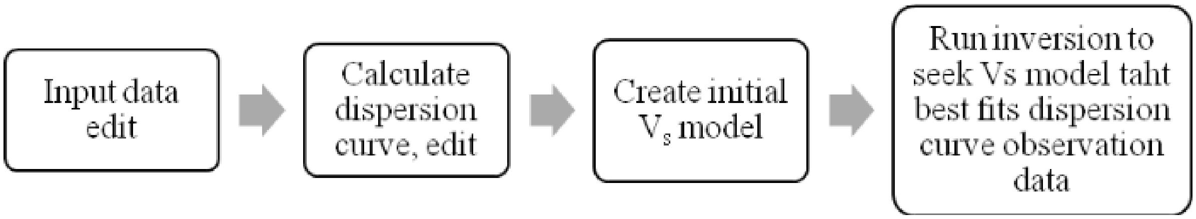


Figure 3.18: General Data Processing Flow of MASW Method. (Geometrics, 2009)

After conducting a visual review, muting was implemented during the active survey, and numerous photos were stacked as part of the initial processing steps. Muting is applied to selectively eliminate seismic energy that appears within a defined time window due to varying propagation velocities (Miller, Ivano, et al., 2001).

The primary or fundamental mode, also known as the intended mode, shows notable enhancement in quality and observational range after appropriate muting. However, muting introduces a drawback by creating a noticeable velocity gradient characteristic, particularly at the lower frequencies of the dispersion curve compared to its pre-muted state. This issue can be effectively addressed by utilizing the dispersion curve derived from non-muted data covering the same frequency spectrum. According to Miller, Ivanov, et al. (2001), this approach indicates that excessively high velocity readings are benign and can be disregarded.

The seismic data was collected using a source offset of 7 meter and a receiver spacing of 3 meters specifically to demonstrate the impact of muting. Both pre- and post-muting dispersion curves of the recorded data were compared. Surface waves contribute predominantly to the seismic energy observed in the recordings.

CHPTER 4
DATA ANALYSIS AND RESULTS

4.1 Data Analysis

4.1.1. Data analysis of the Bole Homes site:

A. Data Acquisition

Active surface wave method: We deployed 24 geophones in a linear array along a 230-meter survey line with 10-meter spacing between geophones. Using a sledgehammer, we struck the ground as the seismic source, positioned 12 meters away from the first geophone. Each profile was recorded five times using a multichannel seismograph to capture the seismic waves.

Passive surface wave method: Similarly, we arranged 24 geophones in a linear array over the same 230-meter survey line with 10-meter spacing between geophones. Here, we relied on natural seismic sources such as traffic and wind, akin to earthquake tremors. The subsequent analysis followed identical procedures for both active and passive surface wave methods, yielding differing results.

B. Data Preprocessing

We imported the raw seismic data files into SeisImager's surface wave analysis wizard module. A band-pass filter with a frequency range of 15 Hz was applied to eliminate noise from the data. Improvements in overall data quality were achieved by reviewing and muting noisy or corrupted traces. Figure 4.1 illustrates plots depicting seismic wave energy recorded over time for each geophone in the spread.

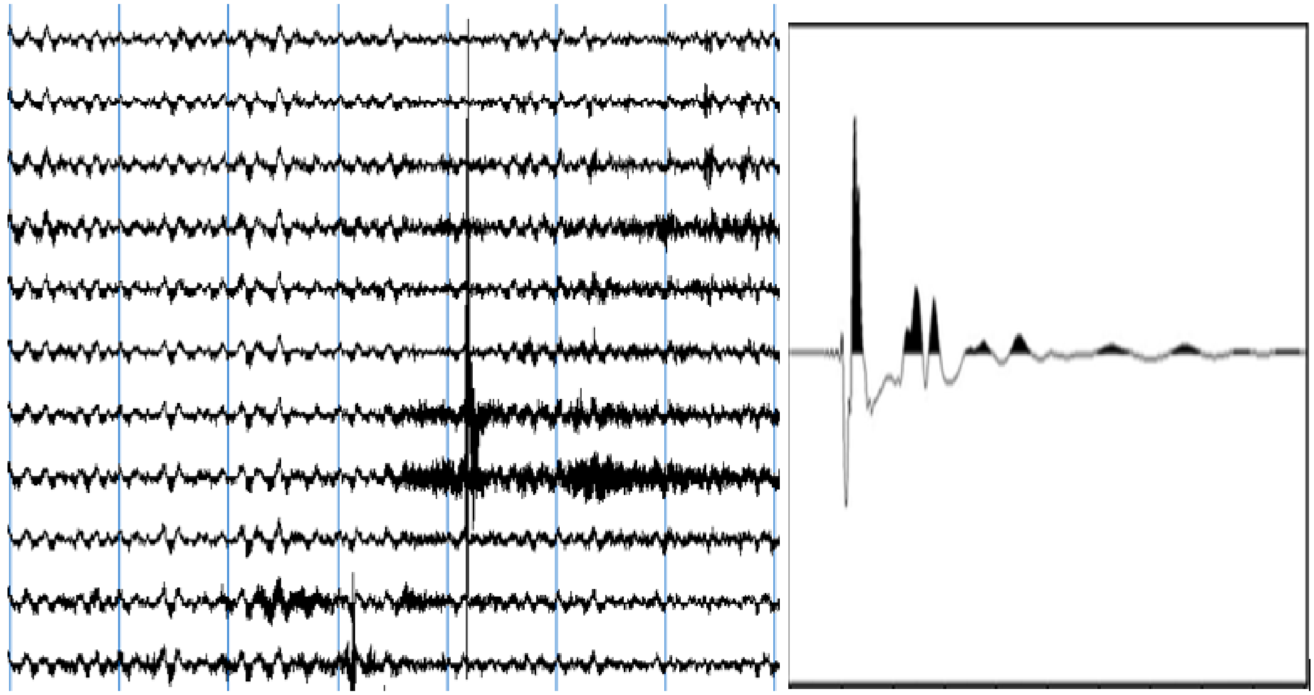
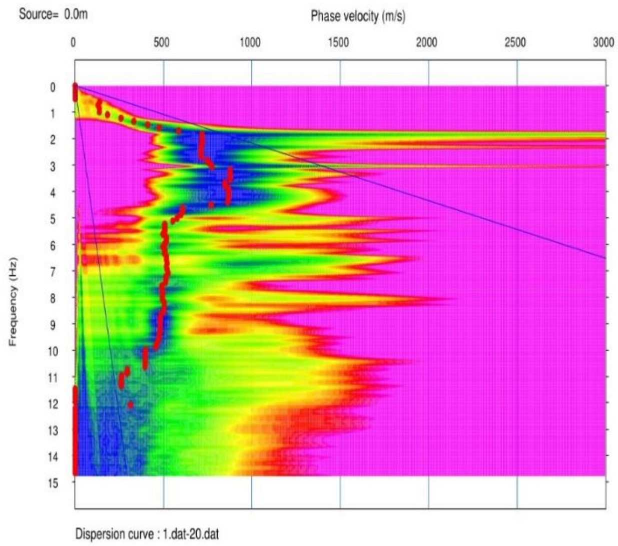
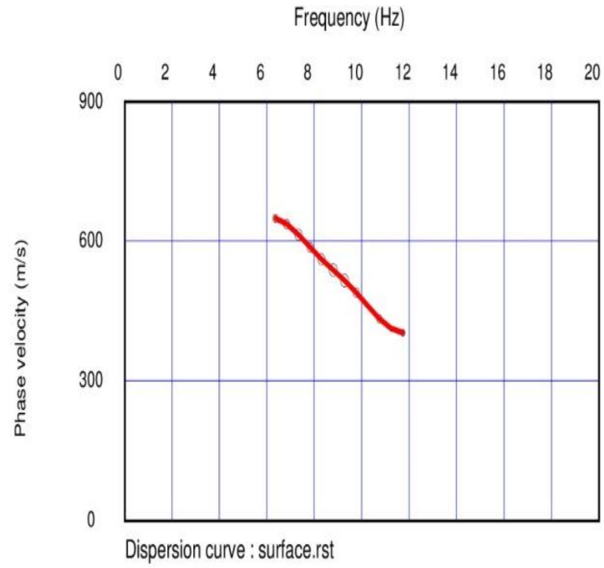


Figure 4.1: Raw seismic data recorded traces of distance versus time

C.Dispersion Curve Analysis

The study focused on shear wave velocities derived from active, passive, and combined surface wave methods. At the Bole site, one active and one linear passive surface wave measurement (MAM) were conducted. Time-domain data was transformed into the frequency-wavenumber domain using the SeisImager/SW module for frequency-wavenumber (f-k) analysis. The fundamental mode of the Rayleigh wave in the f-k spectrum was identified, and we manually selected the dispersion curve representing this mode for use in the inversion process.





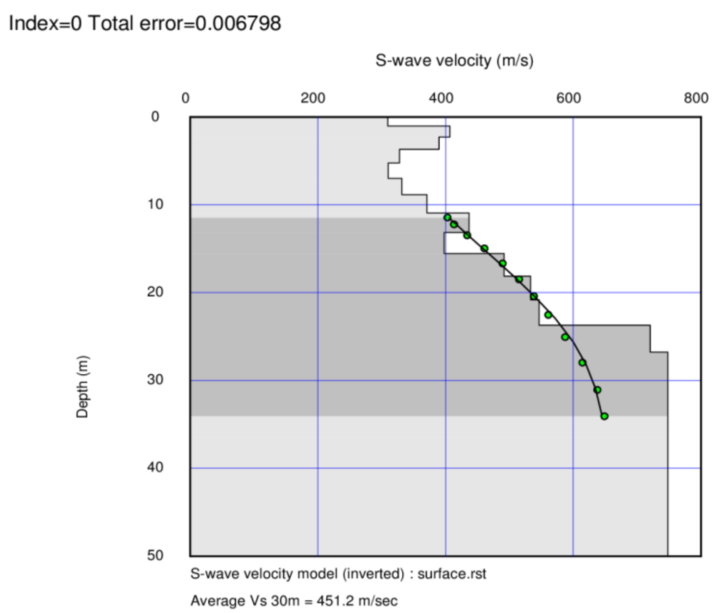


Figure 4.2: (a) The dispersion image of bole site for active surface wave and (b) the corresponding dispersion curve of bole site.

The dispersion curve was derived from two separate surface wave measurements and merged to form a comprehensive curve covering a broad frequency range. Utilizing the surface wave module, a dispersion image was generated and the dispersion curve was computed, as illustrated in figure 4.2b.

D. Inversion Analysis

The selected dispersion curve was imported into the inversion tool within SeisImager/SW, using an initial model composed of 15 layers. The layer thickness in the model ranged gradually from 1 to 5 meters. The inversion process is iterated ten times, adjusting the model parameters to minimize the mismatch between the observed and calculated dispersion curves. Following inversion, a 1D shear-wave velocity profile was generated, depicted in figure 4.3.

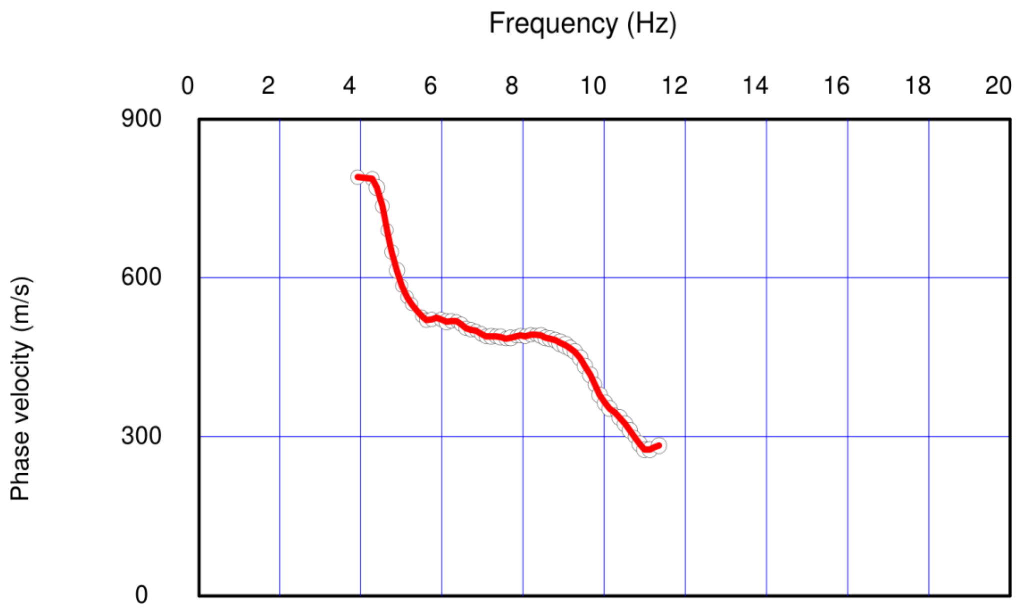


Figure 4.3: Dispersion curve of passive surface wave at bole site

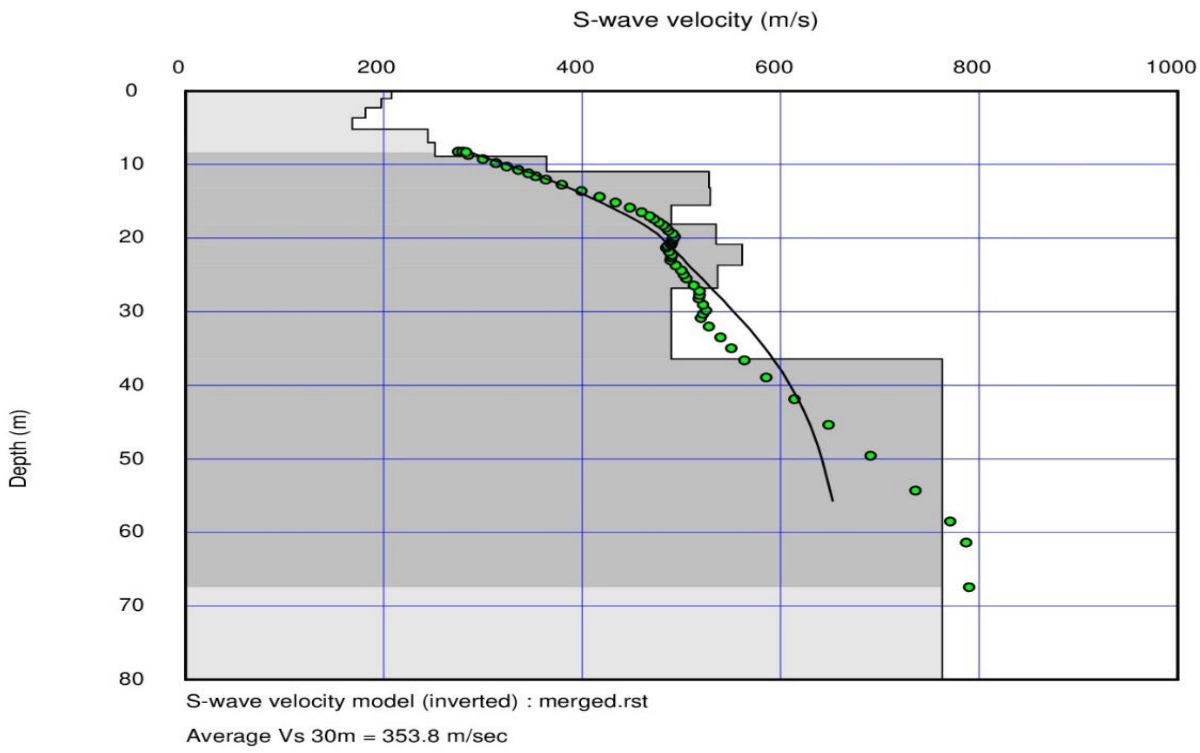


Figure 4.4: 1-D Shear velocity model (Vs30) profiles obtained from the merged dispersion curves Bole site

4.1.2. Data analysis of the Jan-Meda site: profile 1.

***A. Data Acquisition*:**

Both profile 1 and profile 2 MASW surveys were executed under these specified parameters:

Active Surface Wave Survey: Twenty-four geophones were arranged in a linear array for both Profile 1 and Profile 2 surveys. The survey lines measured 69 meters in length, with geophones spaced at 3-meter intervals. A sledgehammer was used as the seismic source, positioned 7 meters away from the first geophone. Data were recorded for each profile with five strikes of the sledgehammer, and seismic waves were recorded using a multichannel seismograph.

Passive Surface Wave Survey (Linear Array): Twenty-four geophones were set up in a linear array for both Profile 1 and Profile 2 surveys. The survey lines measured 69 meters and 115 meters in length, with geophones spaced at 3-meter and 5-meter intervals, respectively. Natural seismic sources, such as traffic and wind, were used. The subsequent analysis was identical for both active and passive surface wave surveys, although the outcomes differed.

B. Data Preprocessing:

We imported the raw seismic data files into the surface wave analysis wizard module of SeisImager. To enhance data quality, we applied a 15 Hz band-pass filter to eliminate noise. We conducted a thorough review and muted any traces that were excessively noisy or corrupted, resulting in overall improved data quality. These plots depict the recorded seismic wave energy over time for each geophone in the array.

C. Dispersion Curve Analysis:

Our analysis focused on shear wave velocities derived from active, passive, and combined surface wave methods. We conducted one active surface wave and one linear passive surface wave (MAM) measurement at the Jan-Meda Site. For frequency-wavenumber (f-k) analysis, we utilized the SeisImager/SW module to convert time-domain data into the frequency-wavenumber domain. We identified the fundamental mode of the Rayleigh wave in the f-k spectrum and manually selected the dispersion curve representing this mode. This selected dispersion curve was saved for use in the inversion process.

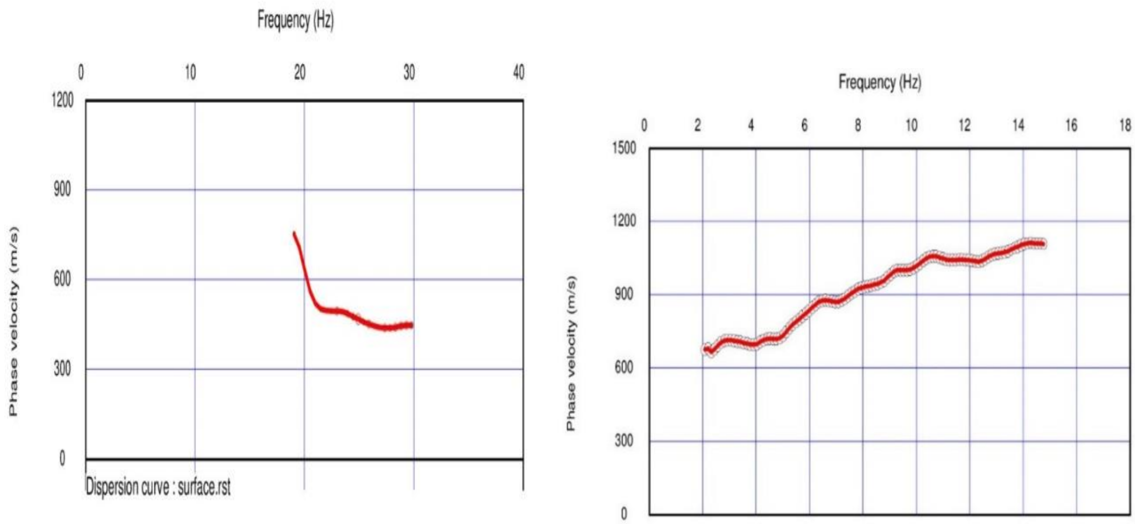


Figure 4.5: Dispersion image and dispersion curve of active and passive surface wave of profile 1 at Jan-Meda.

Dispersion Image Description: This dispersion image portrays the distribution of surface wave energy based on phase velocity and frequency for the Jan-Meda site. The dispersion curve for profile 1 reveals consistently higher phase velocities across various frequencies, indicative of denser and more consolidated subsurface materials.

D. Inversion Analysis:

The manually selected dispersion curve was imported into the inversion tool within SeisImager/SW. Utilizing an initial model consisting of 15 layers with gradually increasing thickness, the inversion process was iterated ten times. This iterative adjustment aimed to minimize discrepancies between the observed and calculated dispersion curves. The inversion successfully generated a 1D shear-wave velocity profile.

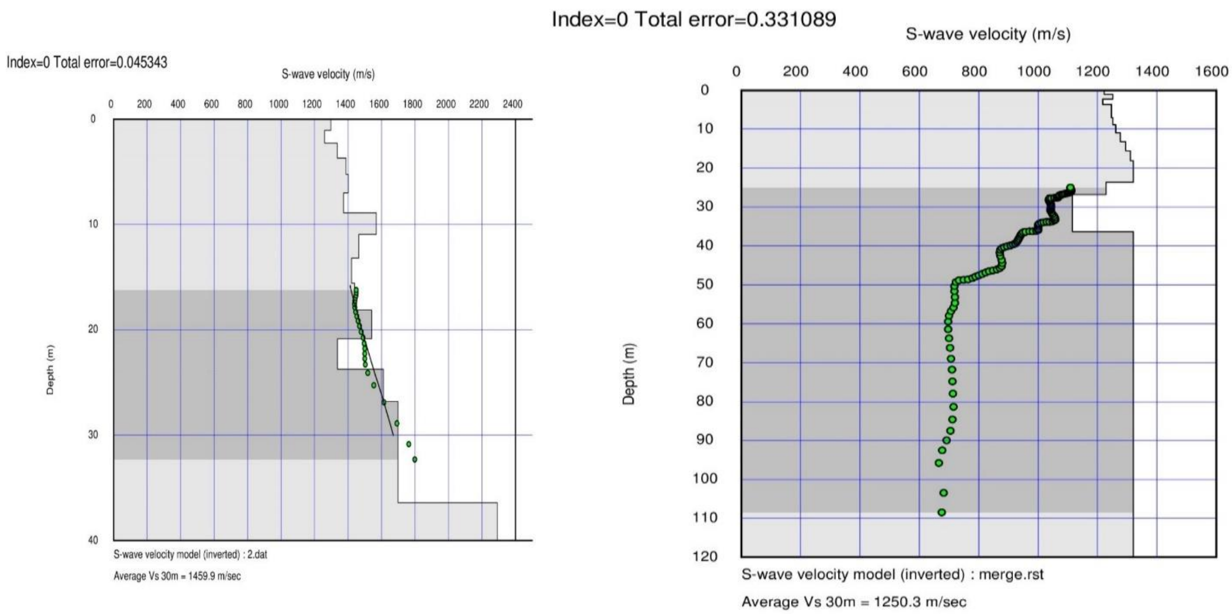


Figure 4.6: The 1-D shear velocity model (Vs30) using active surface waves of profile 1 at Jan-Meda.

The shear wave velocity profile for Jan Meda reveals significantly higher velocities at all depths, suggesting a stiffer and more homogeneous subsurface.

4.1.3. Data analysis of the Jan-Meda site: profile 2:

a. Data Acquisition:

The MASW survey was conducted under the following parameters and procedures:

Active Surface Wave: A linear array of 24 geophones was deployed along a survey line of 115 meters, with each geophone spaced 5 meters apart. Seismic waves were generated using a sledgehammer positioned 7 meters from the first geophone. Data were recorded five times per profile using a multichannel seismograph.

Passive Surface Wave (L-shape): An L-shaped array consisting of 11 geophones was used, covering a survey line length of 50 meters. Geophones were spaced 10 meters apart. Natural seismic sources such as traffic, wind, or earthquakes were utilized. The data collected underwent processing using SeisImager/SW software, which facilitated the extraction of dispersion curves and subsequent inversion to derive shear wave velocity profiles.

B. Dispersion Curve Analysis:

The analysis focused on extracting shear wave velocities from active and passive surface wave methods.

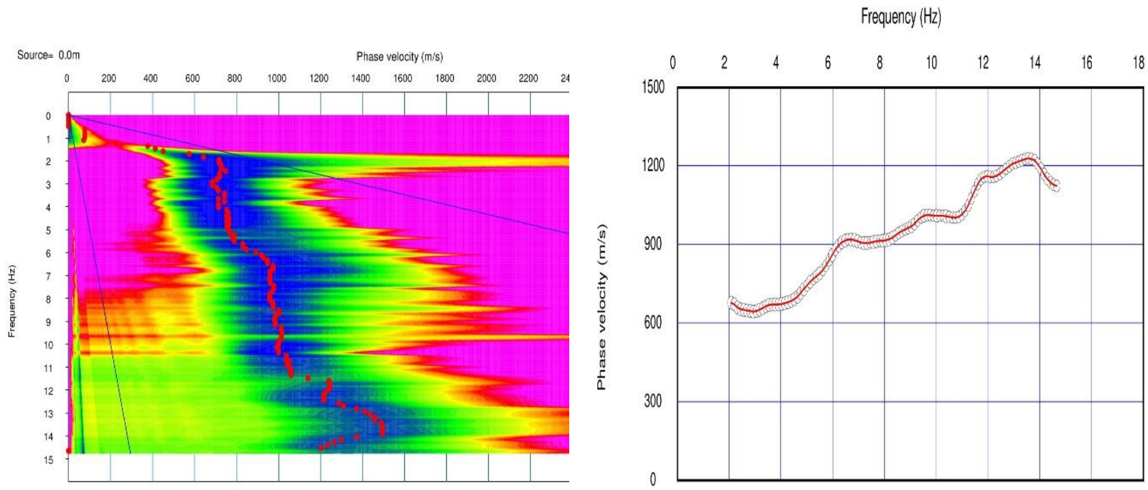


Figure 4.7: The dispersion image and dispersion curve.

C. ***Inversion Analysis:***

The picked dispersion curve extracted from SeisImager/SW was inputted into the inversion tool. Initially, a model comprising 15 layers was used. The inversion process iteratively adjusted these layers ten times to minimize the mismatch between the observed and calculated dispersion curves. Ultimately, it generated a 1D shear-wave velocity profile, representing the merged Vs (shear-wave velocity).

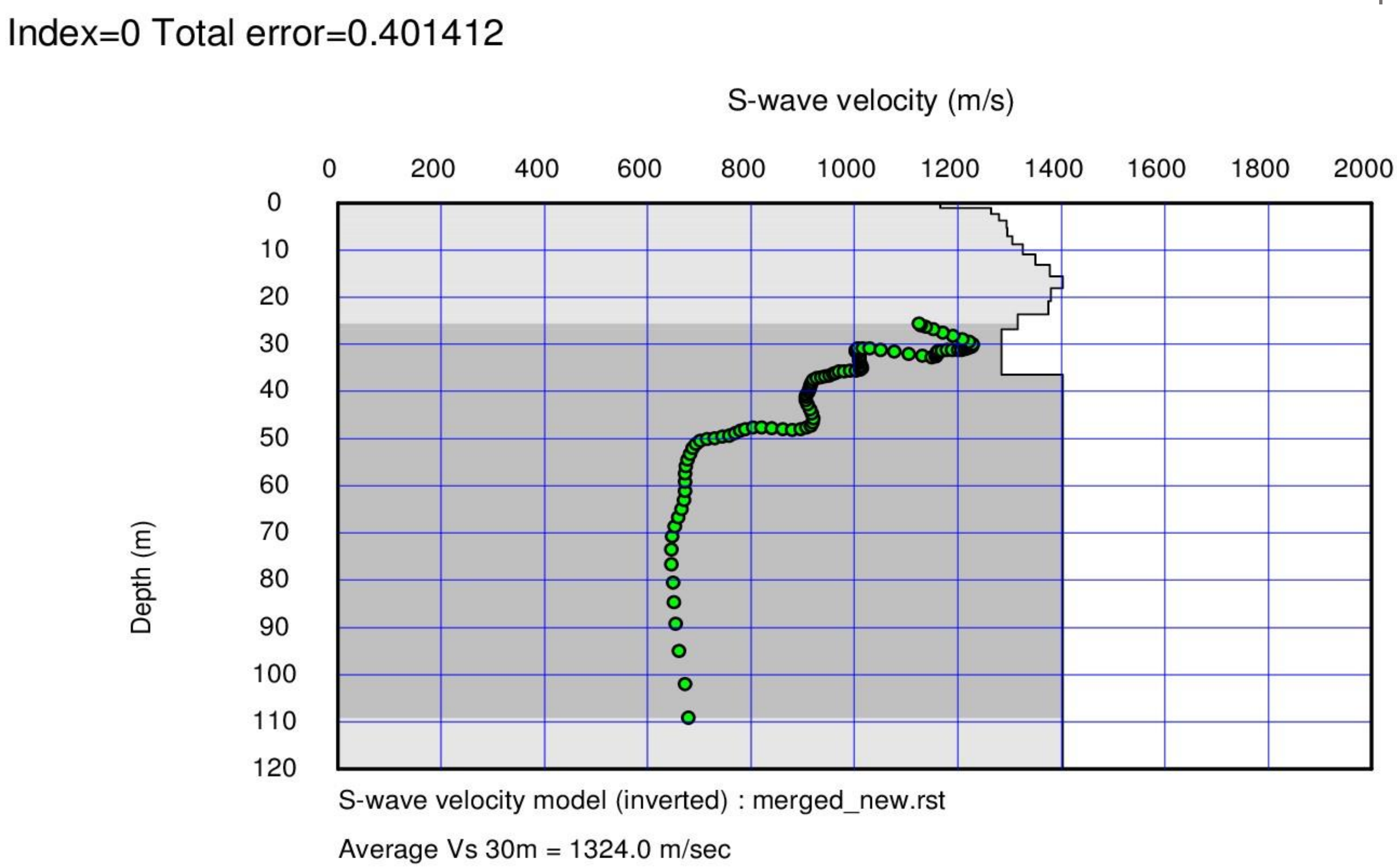


Figure 4.8: The 1-D Shear Velocity Model (Vs30)

CHAPTER 5
DISCUSSION AND CONCLUSION

5.1. Discussion

5.1.1. Interpret the resulting shear-wave velocity profile at the Boles site.

The geophysical investigation employed the Multichannel Analysis of Surface Waves (MASW) technique to acquire shear wave velocity (Vs) data at two chosen locations, Jan-Meda and Bole Homes.

- At the Bole Homes site, our interpretation of the shear wave velocity measurements is summarized in tables. The analysis identified five distinct subsurface layers, with the table highlighting a broad range of Vs values, signifying notable variations in the subsurface conditions across the surveyed areas.

Tables 5.1. MASW-derived Shear Wave Velocity Profile on Bole site.

Depth (m)	Shear wave velocity vs, m/s	Soil discerption
0 - 10	>200	loose sands, silts, or soft clays
10 - 20	>400	denser sands and stiffer clays
20- 30	>500	very dense sands or stiff clays.
30 - 40	≤600	weathered rock or partially compacted sediments
40 - 50	≥600	dense clays, siltstone, or weathered bedrock

The shear wave velocity profile for the Bole site, derived from inverting the dispersion curve, reveals a gradual increase in velocity with depth, suggesting the presence of different subsurface materials.

- Based on subsurface characterization, the measured Vs values show a distinct spatial variation between Jan-Meda and Bole. In the Bole Homes area, lower Vs values (approximately 200–600 m/s) were recorded, suggesting the presence of soft, saturated sediments with low shear strength. In contrast, higher Vs values (above 500 m/s) were found on the Jan-Meda hillslopes, indicating very stiff soil or possibly weathered rock formations. These Vs variations align well with existing geological maps, which depict recent lake deposits in the lowlands of Bole and weathered volcanic rock outcrops in the Jan-Meda hills.

- The Vs profile indicates a steady increase from 200 m/s at the surface to 500 m/s at a depth of 20 meters (Figure 4.3). This pattern suggests a uniform layer of well-consolidated soil that becomes denser with depth. The alignment between the measured and modeled dispersion curves is excellent, signifying reliable data.

- **The limitation is in this study: At 10 meters**, measurements can be influenced by factors such as soil moisture content. Vs alone may not be sufficient to definitively determine soil type, and it is advisable to incorporate additional information, such as soil classification tests, for confirmation. **At 20 meters**, the VS values may overlap with those of other soil types. It is important to consider using supplementary data for accurate identification. **At 30 meters**, Vs values at this depth can indicate certain types of weathered rock. **At 40 meters**, there is an overlapping range with some weak rock types. **At 50 meters**, higher Vs values typically suggest the presence of rock; however, some very dense soils can also reach these values.

5.1.2. Interpret the resulting shear-wave velocity profile at the Jan-Meda site

The shear wave velocity profile for the Jan Meda profile reveals significantly higher velocities at all depths, suggesting a stiffer and more homogeneous subsurface. What we have interpreted is summarized in tables and characterized by the material type.

Table 5.2. MASW -derived shear wave velocity profile 1 on Jan-Meda

Depth (m)	Shear wave velocity, Vs (m/s)	Soil description
0-15	not shown (very low)	loose sand, silt, or soft clay
15-20	1400-1500	very stiff
20-25	1500- 1600	very stiff
25-30	1600-1700	Hard rock
>35	>1800	Very Hard rock

Tables 5.3. MASW-derived Shear Wave Velocity Profile 2 on sites Jan -Meda

Depth in (m)	Shear wave velocity vs, (m/s)	Soil description
0 - 25	Very low	This shallow layer likely consists of soft, unconsolidated materials such as loose sand, silt, or soft clay. These soils are highly compressible and provide minimal resistance to shear waves.
25 - 50	1000 – 700	This depth range indicates a transition to much stiffer materials, such as dense sand, stiff clay, or weathered rock. The soil here is more compact and provides greater resistance to shear waves.
50- 75	800 - 700	The materials in this layer may consist of very stiff clays, dense sands, or weakly cemented rock. These soils are strong but slightly less stiff than the layer above.
75 – 100	>600	At this depth, the materials are likely very stiff soils or transitioning into rock formations. The layer might consist of dense, compacted soils or weathered bedrock, providing high resistance to seismic waves.

What we detected From The investigation understand of Vs profile shows a starting at 25-meter depth and below that not shown the shear wave velocity.

At Top Layer Low Vs, the Vs profile shows that the very shallow layer (0–25 meters) has a very low Vs, possibly below the reliable detection limit of the MASW method. This low Vs could indicate that soft**,** unconsolidated materials, such as very loose sands, organic soils, or highly disturbed near-surface layers, might have Vs values too low to be accurately captured by MASW. Air or water: if the top layer is filled with air (e.g., gaps between large rocks) or water, Vs would be very low and difficult to measure with MASW.

In this study, during a survey at the Jan-Meda site, an observed decrease in shear wave velocity (Vs) with depth can be attributed to several factors. These include the presence of softer, less consolidated, or more weathered geological layers beneath denser surface layers, increased water saturation at deeper levels reducing material stiffness, extensive weathering or fracturing in deeper layers, man-made disturbances such as excavation or construction activities, organic-rich or clay-rich deposits with inherently lower stiffness, and a lack of compaction or the presence of highly compressible materials. A detailed analysis of the subsurface geology, water table levels, and supplementary data from boreholes or other geophysical surveys is necessary to accurately determine the causes of this decrease in Vs.

5.1.3. Site Classification According to Eurocode8(EC8) and National Earthquake Hazard Program (NEHRP)

are crucial for evaluating the seismic response of a site. These classifications are based on the characteristics of the soil and rock layers at the site, primarily focusing on parameters such as shear wave velocity, standard penetration test (SPT) blow count, and undrained shear strength. These classifications are essential for determining the design seismic action of structures, influencing the seismic design coefficients used in engineering applications.

Tabel 5.4. Comparison between EC8 and NEHRP

Parameter	Eurocode 8(EC8)	NEHRP
Class A	Vs30 > 800m/s	Vs30 > 1500 m/s
Class B	360 < Vs30≤800m/s	760 < Vs30 ≤ 1500m/s
Class C	180 < Vs30≤360m/s	360 < Vs30 ≤ 760m/s
Class D	Vs30 ≤ 180m/s	180 < Vs30 ≤ 360m/s
Class E	Vs30 ≤ 180m/s	Vs30 ≤180 m/s
Class F	Special conditions, requiring detailed studies	Special conditions, requiring detailed studies

The measured Vs values were correlated with the site classification system outlined in the Eurocode 8 (EC8). The EC8 classifies sites based on Vs30, the average shear wave velocity within the top 30 meters of the subsurface. Table 4.4 presents the site classification for each investigated location based on the measured Vs and the EC8 criteria.

Table 5.5 Site Classification of Investigated Location.

Location	***Average shear wave velocity $V_{S,30}$***	***EC8 site classification***
Bole Homes	353.8 m/s	C (Moderately Stiff)
Jan-Meda	1324.0 m/s	A (Rock/Stiff)

5.1.4. Comparison between Bole and Jan-Meda sites

The shear wave velocity data clearly indicate that Jan Meda exhibits significantly higher subsurface shear wave velocities compared to Bole across all measurement methods. This disparity reflects geological variations between the two areas: Jan Meda has more consolidated and rigid materials, while Bole's subsurface is softer and more heterogeneous.

The inclusion of dispersion images, dispersion curves, and shear wave velocity models in MASW data analysis was crucial for accurately interpreting subsurface conditions. These components provided a comprehensive understanding of the underlying materials. These findings are pivotal for seismic hazard assessment, urban planning, and construction in these regions. Visual representations effectively communicate these findings, facilitating informed decision-making regarding infrastructure development and risk mitigation.

Seismic Response Implications: The assigned site classes have significant implications for seismic response during earthquakes. Areas classified as C (soft to stiff soil) in Bole Homes are likely to experience greater ground shaking amplification compared to areas with stiffer soils or rock (Class A) like Jan-Meda. This underscores the need for rigorous design considerations for structures on soft-soil sites. Engineers can use their knowledge of site classes to design earthquake-resistant structures with appropriate foundation systems. For instance, structures on soft soils (Site Class C) may require deep pile foundations to mitigate ground shaking amplification effects.

- Additionally, in MASW results, a decrease in shear wave velocity with depth is often unexpected at the Jan-Meda site. Typically, shear wave velocity increases with depth as soils or rocks become denser and stiffer. However, several factors could contribute to a decrease in shear wave velocity, such as the presence of soft volcanic ash layers or hidden soft layers like loose sand or organic materials beneath a stiffer surface layer. This temporary decrease in Vs may transition to an increase with depth once bedrock is encountered. The water table also plays a crucial role; saturated soils tend to be less stiff and exhibit lower Vs values compared to dry soils. Detailed insights into the impact of the water table on shear wave velocity can be found in the Federal Highway Administration's (FHWA) document, "Geotechnical Engineering Circular No. 7: Recommended Practice for the Use of Shear Wave Velocity for Evaluating Seismic Hazards."

5.2. Conclusion

This study employed shear wave velocity measurements to investigate the subsurface characteristics and seismic response of two specific sites: Jan-Meda and Bole Homes. The analysis of average shear wave velocity underscored a significant contrast, emphasizing the importance of site-specific characterization in enhancing seismic resilience.

- At Bole Homes, the average shear wave velocity was measured at 353.8 m/s, indicating Site Class C conditions according to Eurocode 8 (EC8) and the National Seismic Hazard Program (NSHP) classification. This suggests the presence of stiff soil profiles and alluvial soils typical of this area. The relatively low shear wave velocity implies heightened susceptibility to seismic events, potentially leading to significant ground shaking amplification and liquefaction. These risks have been observed in past earthquakes in Addis Ababa under similar soil conditions. Consequently, construction practices in Bole Homes should prioritize deeper pile foundations and seismic isolation techniques, as mandated by building codes for high-risk zones.

- In contrast, at Jan-Meda, the average shear wave velocity was significantly higher at 1303.7 m/s, classifying it as Site Class A according to Eurocode 8 (EC8) and the NSHP. This classification indicates very stiff soils or rock formations typical of the mountainous regions surrounding Addis Ababa. The higher shear wave velocity suggests a more favorable response to seismic activity, with lower amplification of ground shaking and increased stability during earthquakes. Consequently, construction practices in Jan-Meda may allow for shallower foundations and less stringent seismic design requirements compared to Bole Homes. This approach can potentially lead to more cost-effective and efficient construction while maintaining adequate safety standards.
- The study observed a clear correlation between shear wave velocity and geomorphological features. Areas with lower velocities generally coincide with alluvial plains and recent lake deposits, while higher velocities are associated with bedrock outcrops and older formations. This knowledge empowers stakeholders to make informed decisions regarding construction practices, land-use planning, and seismic risk mitigation strategies. Ultimately, it contributes to the development of a more resilient any structure for communities in Bole Homes and Jan-Meda.
- It is important to acknowledge study limitations, such as the number of survey points and the depth of the investigation. Future studies can address these limitations to gain a more comprehensive understanding by focusing on key improvements like increasing the number of survey points, extending the depth of investigation, improving data resolution, and applying advanced methods. These enhancements will not only improve the understanding of seismic responses but also provide practical benefits for stakeholders, such as those involved in urban planning and disaster mitigation.

5.3. Recommendation

The generated site classification map is a valuable tool for various stakeholders involved in construction and development and land planning within Jan-Meda and Bole Homes.

a) Developers**:** The map can guide decisions regarding construction practices and materials suitable for the seismic risk of the area.
b) Researcher: Further analysis could be conducted to investigate that selected site more using different methods, like electrical resistivity tomography (ERT), to conduct more detailed assessments.
c) In terms of engineering and design considerations:

    i. The varying subsurface conditions suggest that Bole may be more susceptible to differential settlement and soil-structure interaction issues. Special attention should be given to the design of foundations and the potential for liquefaction if soft layers are present.
    ii. Implement soil improvement techniques and consider the use of base isolation or energy dissipation devices to enhance the seismic performance of structures.
    iii. The stiffer and more homogeneous subsurface at Jan Meda indicates better support for structures, with less risk of differential settlement. Standard foundation designs are likely to be sufficient.
    iv. Ensure that the design takes into account the higher seismic forces that might be transmitted through the stiffer soil or rock.

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