

# Research on Imaging Methods based on Passive Source Surface Waves

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**Abstract:** Surface waves can be categorized into active-source surface waves and noise-source surface waves based on their signal sources, corresponding to active source exploration and passive source exploration methods, respectively. Active source exploration requires artificial excitation, which not only damages the surrounding environment but is also susceptible to interference from ambient noise, thus demanding very high requirements for the measurement site. In contrast, passive source exploration does not require seismic source excitation, does not harm the environment, and has relatively simple data collection, making it cost-effective and environmentally friendly, with significant research value. This paper mainly introduces the imaging principle of ambient noise exploration methods. Under certain circumstances, ambient noise recorded over long periods between two stations can be used to derive dispersion curves through Green's functions, thus enabling the inversion of subsurface structures. To validate the method's effectiveness, Tessler was used to establish a model (a simple horizontal layered model) to obtain noise data from different source locations and densities. Surface wave records were extracted and compared to analyze the intensity of surface wave records from different strata and source locations, studying the impact of different source densities and locations on surface wave imaging, and exploring the feasibility of the research. Then, high-quality fundamental mode dispersion curves from each group were extracted to analyze the reasons for varying quality in fundamental mode surface waves across different dispersion images, and the subsurface structure was inverted. Finally, practical data were used to test the applicability of the fundamental mode dispersion curve inversion.

**Keywords:** Ambient Noise; Dispersion Curves; Passive Source Imaging; Velocity Structure.

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## 1. Introduction

Passive seismic imaging, utilizing background noise for imaging, offers an effective supplement to conventional exploration methods, particularly in complex geological areas. By correlating long-term noise records, seismic records can be synthesized to extract surface wave records for dispersion imaging and ultimately invert subsurface velocity structures. This innovative approach reveals local features of complex geological structures that conventional methods may miss. It also provides flexibility and simplicity compared to traditional seismic exploration techniques. If widely adopted, passive seismic imaging could potentially replace conventional methods involving artificial explosives, especially in areas unsuitable for conventional seismic exploration. This technology holds promise for various applications, including monitoring heavy oil thermal recovery and mapping urban underground spaces in environments where traditional methods are impractical.

In recent years, numerous seismologists have made significant contributions to the field of seismic interferometry. Professor Claerbout is one of the pioneers of seismic interferometry. In 1968, Claerbout [1] first performed autocorrelation on noise records generated by underground seismic sources, obtaining the Green's function that describes the relationship between seismic sources and the seismic field. In 1989, Zhang et al. [2] demonstrated the feasibility of "daylight imaging" in a three-dimensional homogeneous medium. In 1990, Katz [3] applied Claerbout's one-dimensional autocorrelation imaging technique to vertical seismic profiles, obtaining one-dimensional geological inversion interface images. In practical applications,

Daneshvar et al. [4] and Cole [5] attempted to use passive seismic records for research but faced issues such as short recording times and poor coupling capabilities. In 1996, Rickett and Claerbout synthesized seismic records using the phase-shift method, validating the coherent imaging theory. In 2000, Schuster and Rickett [6] further developed seismic interferometry, completing the reflection imaging of the underground medium.

After 2007, domestic scholars such as Qi Cheng and Chen Qifu [7] first proposed using ambient noise for seismic imaging. He Zhengqin et al. [8] successfully extracted surface wave information from noise records to probe the shallow crustal velocity structure. There have also been breakthroughs in other areas. For instance, in 2016, Liu Qinghua et al. [9] used the spatial autocorrelation method to process ambient noise records, obtaining accurate dispersion curves and deriving the S-wave velocity structure. These studies have provided crucial support for the development of seismic interferometry.

Many scholars both domestically and internationally have researched and validated the theory and reliability of seismic background noise imaging, enabling the accurate determination of surface wave velocities and shear wave velocity structures in the study area. Compared to other tomographic imaging techniques, seismic background noise has three main advantages: Firstly, it does not rely on seismic activity. Seismic background noise imaging utilizes continuous background noise from long-period station recordings, eliminating the need for seismic event data and thus not being constrained by geographical limitations. Secondly, it offers high-resolution imaging. By utilizing continuous background noise beneath stations as data sources,

the imaging results have higher resolution, with more random and denser station distribution. Lastly, it is cost-effective and not geographically constrained. In regions unsuitable for artificial seismic activities, such as rugged mountain ranges and dams, utilizing underground or surface noise for imaging is cost-effective, without collection constraints, and effectively addresses safety, environmental, and specific environmental monitoring issues.

The article is mainly divided into five sections: Section One Introduction outlines the research purposes of shallow imaging using background noise, the current situation of domestic and foreign research, and the advantages of noise imaging; Section Two introduces the theoretical research on passive source surface wave imaging, including the principles of the cross-correlation-based Green's function method and the phase-shift method for dispersion imaging; Section Three analyzes the influencing factors of passive source surface wave imaging, including the effects of source density, distribution position, and recording duration on imaging accuracy; Section Four validates the theoretical research content through practical data application, demonstrating the practicality and feasibility of the method; Section Five concludes the research content, summarizes the findings, and provides prospects for future research directions.

## 2. Passive Source Surface Wave Imaging Method Theoretical Research

### 2.1. Cross-correlation-based Green's Function Method

Passive source surface wave imaging method theory mainly involves the utilization of background noise for underground structure imaging. By cross-correlating background noise, the Green's functions between seismic sensors can be obtained, akin to the pulse response received at one sensor after applying a pulse excitation at another sensor. This method originates from early conjectures among seismologists, aiming to employ noise for underground structure investigation. Analyzing the cross-correlation function of background noise enables underground structure imaging, thereby complementing conventional imaging methods.

### 2.2. Phase-shift Method Dispersion Imaging

The phase-shift method was introduced by Park [10] at the 1998 SEG Annual Meeting. When extracting dispersion curves using this method, seismic data is first subjected to dispersion imaging, resulting in the energy distribution in the F-VR domain. Subsequently, the energy peak lines are extracted to obtain the dispersion curve of surface waves. The final phase velocity dispersion curve, as depicted in Figure 1, is derived from the surface wave recordings and phase velocity dispersion energy map generated by 400 randomly distributed seismic sources, recorded over a duration of 10,000 seconds, and stacked 11,000 times.

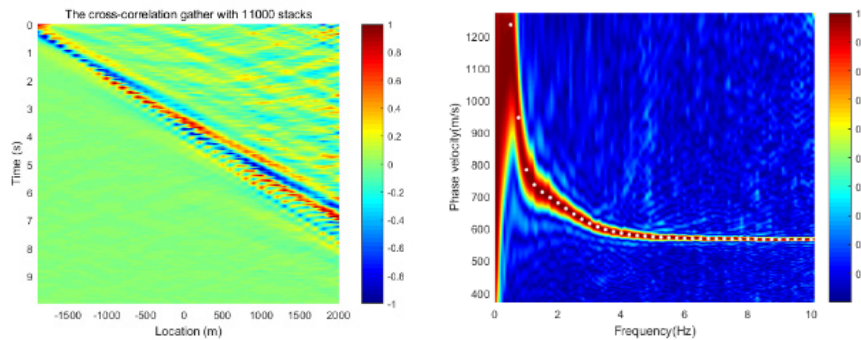


Figure 1. (a) Shallow surface wave recordings from 400 shots; (b) Dispersion imaging of shallow layers from 400 shots.

## 3. Analysis of Influencing Factors in Passive Source Surface Wave Imaging

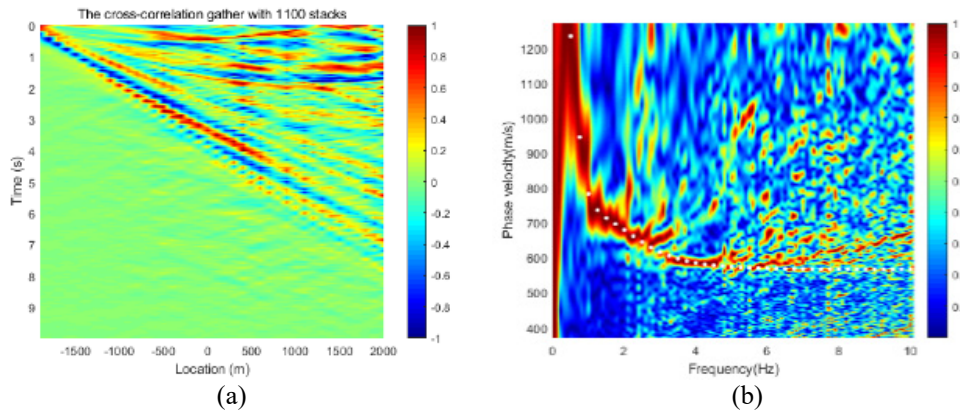
Background noise imaging is an emerging underground passive imaging method. Utilizing long-period background noise data from regional seismic stations, it employs cross-correlation to extract Green's function and dispersion curves, facilitating velocity model inversion. Widely applied in Earth science, this technique offers continuous stability, broad coverage, and high-resolution imaging of subsurface structures without the need for seismic distribution constraints. Additionally, the reasonable density and distribution of seismic sources are crucial for obtaining high-quality imaging results, enabling the inference of finer underground structures.

### 3.1. The Impact of Seismic Source Distribution

Through simulations of the distribution of noise sources in passive dispersion imaging, noise sources were randomly placed within different depth ranges of the model, including shallow (0-300m), intermediate (300-600m), deep (600-1000m), on both sides of the model (left side less than 1100m, right side greater than 2500m, with sources on both sides), and at the central position of the model (vertical 600-1000m, left side greater than 1100m, right side less than 2500m, with a central source below). The recording durations were set to three time periods: 50 minutes, 100 minutes, and 1000 minutes. With the source density fixed at 100 shot points and a recording time of 100 minutes, we compared the synthetic surface wave records and dispersion energy under different noise source distributions. Among these distributions, random source dispersion curves showed superior performance, exhibiting more continuous dispersion energy and higher

phase velocity resolution, resulting in more accurate and clear dispersion curves.

### 3.1.1. Comparison and Analysis of Deep-source Surface Wave Records and Dispersion Imaging

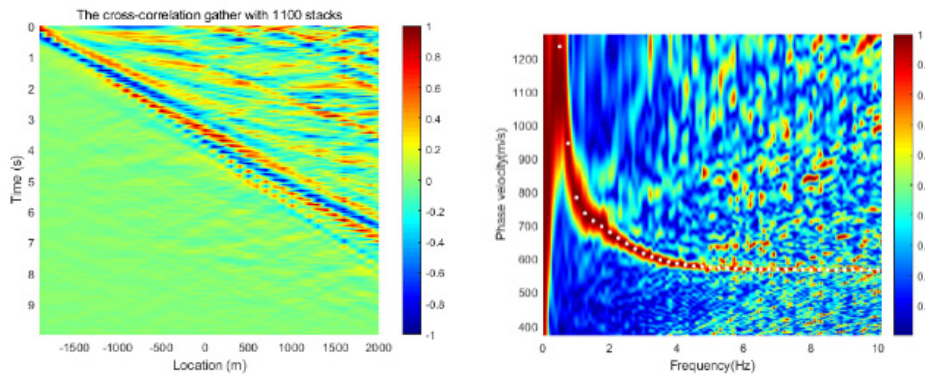


**Figure 2.** (a) Deep-source surface wave records; (b) Deep-source dispersion imaging.

The random distribution of noise sources in the 600-1000m depth range affects the dispersion imaging. Figure 2(a) Deep-layer surface wave records exhibit weak energy with backscatter. Figure 2(b) Deep dispersion imaging reveals discontinuous energy and dispersion phenomena, reducing

the resolution of phase velocity, thus impacting the acquisition of clear dispersion curves.

### 3.1.2. Mid-layer Source Surface Wave Records and Dispersion Imaging Analysis

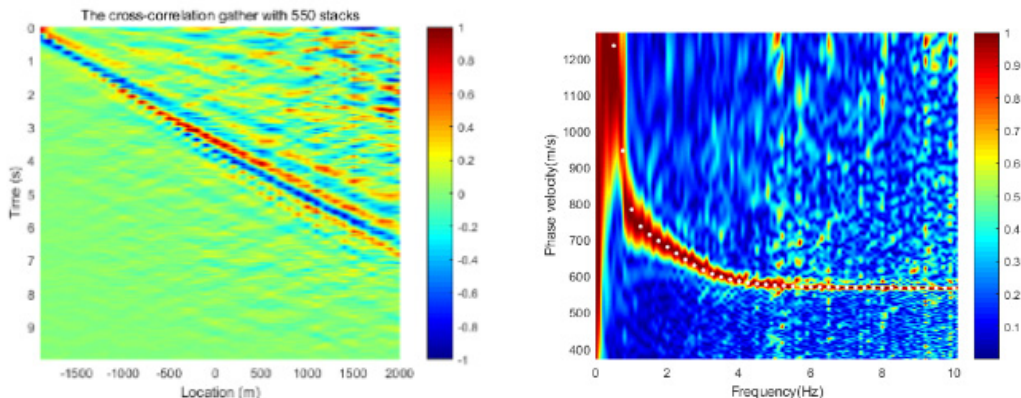


**Figure 3.** (a) Mid-level surface wave records; (b) Mid-level dispersion imaging

Simulating noise sources randomly distributed between 300-600m (mid-level noise sources), single-shot noise records were obtained through cross-correlation stacking, and surface wave records were extracted. Figure 3 (a) shows that the mid-level surface wave records exhibit noticeable backscattered surface waves with moderate energy. Figure 3 (b) shows that the mid-level dispersion energy is relatively continuous, but energy dispersion is still present. The

fundamental mode surface wave dispersion energy axis is clear, with energy converging towards the axis, likely due to insufficient stacking. The phase velocity resolution is high, allowing for the extraction of clear dispersion curves.

### 3.1.3. Comparison and Analysis of Shallow Source Surface Wave Records and Dispersion Imaging



**Figure 4.** (a) Shallow surface wave records; (b) Shallow dispersion imaging

The simulated noise sources are randomly distributed in the

depth range of 0-300 meters, defined as shallow noise sources.

After cross-correlation and superposition of the noise records, individual shot noise records are obtained, from which surface wave records are extracted. From Figure 4(a), it can be clearly seen that the shallow surface wave records exhibit significant backscattering and relatively strong energy; Figure 3-9(b) shows that the energy of shallow dispersion imaging is concentrated, with a clear axis line appearing on the

fundamental surface wave dispersion energy axis, and the resolution of phase velocity is relatively high, enabling clear dispersion curves to be obtained.

### 3.1.4. Analysis of Surface Wave Records and Dispersion Imaging with Sources Placed on Both Sides

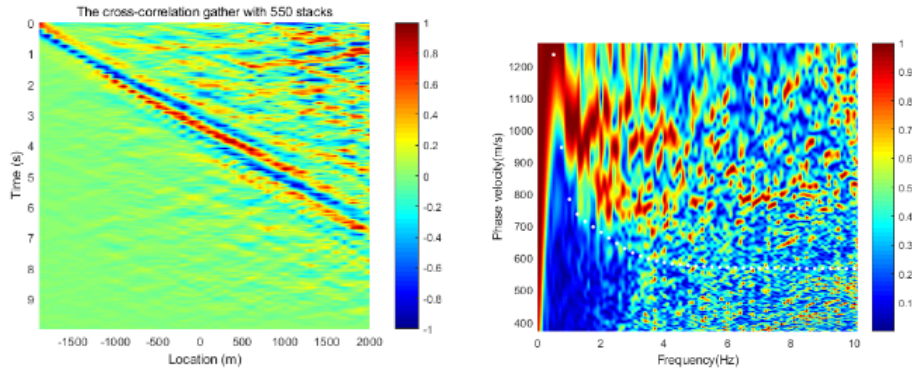


Figure 5. (a) Surface wave records with sources on both sides; (b) Dispersion imaging with sources on both sides

Simulated random noise sources are distributed on both sides, with the left side less than 1100m and the right side greater than 2500m. After cross-correlation processing, single-shot noise records are obtained and surface wave information is extracted. Figure 5(a) shows pronounced backscattered surface waves with significant energy, while Figure 5(b) presents dispersion imaging of sources on both

sides, with discontinuous energy distribution and chaotic dispersion energy axis of fundamental surface waves, affecting phase velocity resolution.

### 3.1.5. Comparison Analysis of Surface Wave Records and Dispersion Imaging from the Central Lower Source

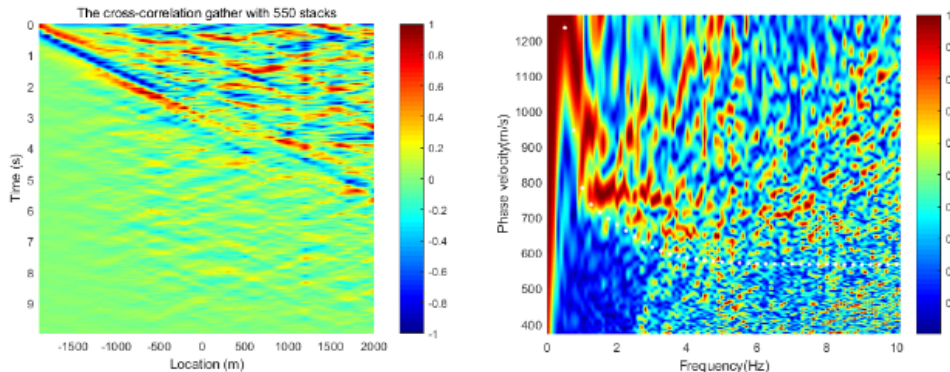


Figure 6. (a) Lower central source surface wave records; (b) Lower central source dispersion imaging

Simulated random noise sources are located at the central position, and after cross-correlation processing of the noise records followed by superposition, surface wave information is extracted. As observed in Figure 6(a), weak backward-scattered surface waves are evident. Figure 6(b) reveals discontinuous dispersion energy from the sources on both sides, with a chaotic dispersion energy axis for the fundamental surface wave, resulting in poor phase velocity resolution, significantly impacting the subsequent acquisition of clear dispersion curves.

In summary, based on the analysis of the dispersion imaging results from five different source positions, ranked from best to worst quality: shallow source dispersion imaging > middle source dispersion imaging > deep source dispersion imaging > dispersion imaging from sources on both sides > dispersion imaging from the central lower source. Therefore, for the subsequent experiments, shallow source data will be selected for extracting dispersion curves and conducting the next step of inversion work.

## 3.2. The Influence of Seismic Source Density

To test the impact of noise source density on passive source imaging, we simulated the actual distribution of 100 and 400 shot noise sources. After comparing the effects of five different source distributions on passive source surface wave imaging, we selected the shallow source position with the best imaging quality for further discussion. Now, the noise sources have been randomly placed within the depth range of 0 to 300 meters in the model, with a recording duration of 50 minutes as an example.

### 3.2.1. Analysis of Surface Wave Records and Dispersion Imaging Contrasting 100 Shot Points

Simulating 100 noise sources, we applied cross-correlation and stacking to obtain single-shot noise records and extracted surface wave information. From Figure 7(a), the shallow surface wave records show distinct backscattering waves with moderate energy. Figure 7(b) illustrates that the shallow dispersion imaging has concentrated energy, with a clear fundamental mode dispersion energy axis. However, the low source density results in low phase velocity resolution,

affecting the clarity of the dispersion curves.

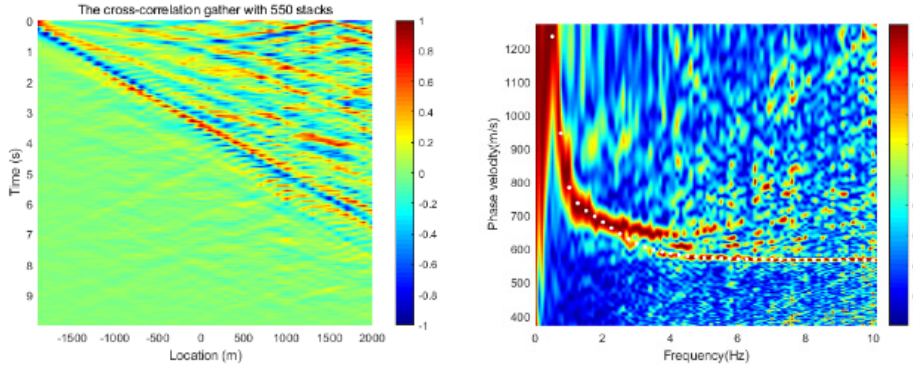


Figure 7. (a) Shallow Surface Wave Records of 100 Shot Points; (b) Shallow Dispersion Imaging of 100 Shot Points

### 3.2.2. Analysis of Surface Wave Records and Dispersion Imaging for 400 Shots

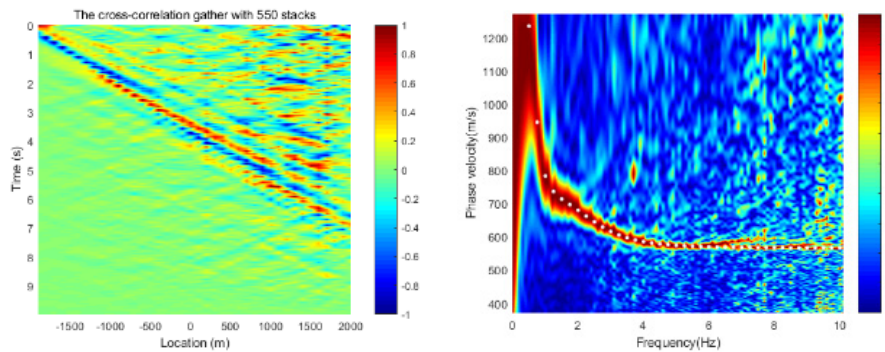


Figure 8. (a) Surface wave records for 400 shallow shots; (b) Dispersion imaging for 400 shallow shots.

We simulated 400 shot points of noise sources, obtained single shot noise records by cross-correlation, and extracted surface wave information. As seen in Figure 8(a), the shallow surface wave records exhibit distinct backscattered waves with strong energy. In Figure 8(b), the shallow dispersion imaging shows concentrated energy with a clear axis of dispersion energy for the fundamental mode, indicating high resolution of phase velocity.

In conclusion, the comparison between the dispersion imaging obtained from 100 shot points and 400 shot points reveals significant differences in the axis of dispersion energy for the fundamental mode, indicating a noticeable impact of the number of shot points. Therefore, the dispersion imaging

from 400 shot points in the shallow layer is selected for subsequent inversion work.

### 3.3. The Influence of Recording Duration

To test the effect of recording duration on passive source imaging, we simulated three groups of recordings with different lengths: 50 minutes, 100 minutes, and 1000 minutes. A comparative analysis was conducted on these three sets of experiments, discussing the specific impact of recording duration on imaging features. Now, taking the actual distribution of 100 shot points as an example, the noise sources were randomly placed within the depth range of 600 to 1000 meters in the model (deep noise source).

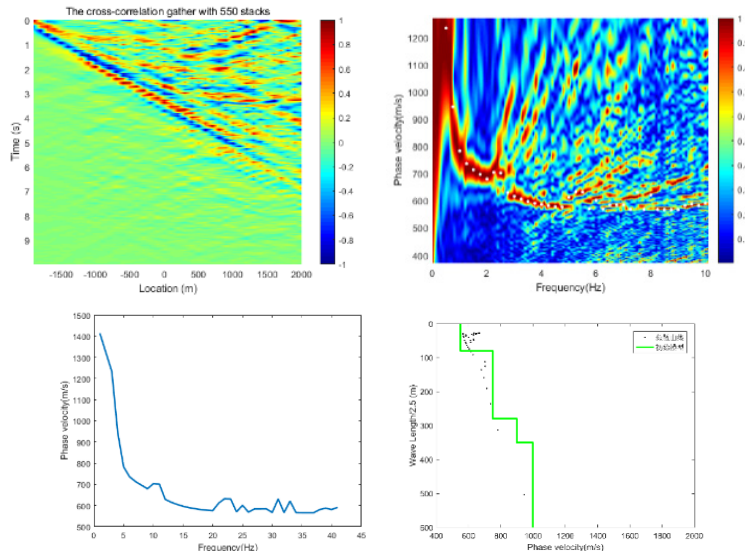
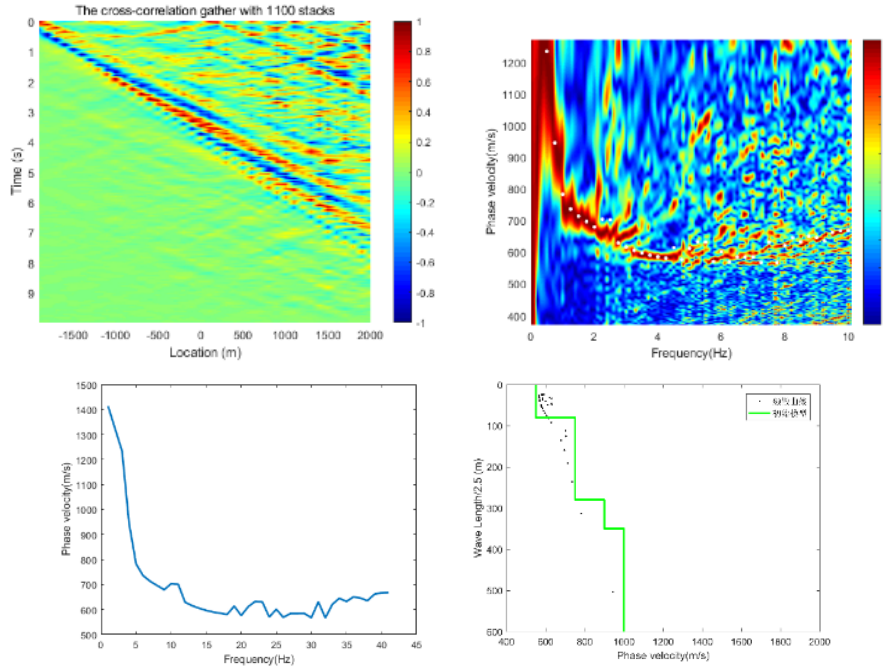


Figure 9. (a) 50-minute deep-layer surface wave record; (b) 50-minute deep-layer dispersion imaging; (c) 50-minute dispersion curve; (d) Depth-domain dispersion curve

The analysis of the 50-minute surface wave record, obtained by cross-correlating and stacking noise records to extract single-shot noise records, reveals discernible back-scattered surface waves but with inconsistent energy levels, varying in intensity. As depicted in Figure 9(a), the 50-minute deep-seated surface wave record exhibits pronounced back-scattered surface waves, albeit with discontinuous energy levels, ranging from strong to weak. In Figure 9(b), the 50-minute deep-seated dispersion imaging displays energy

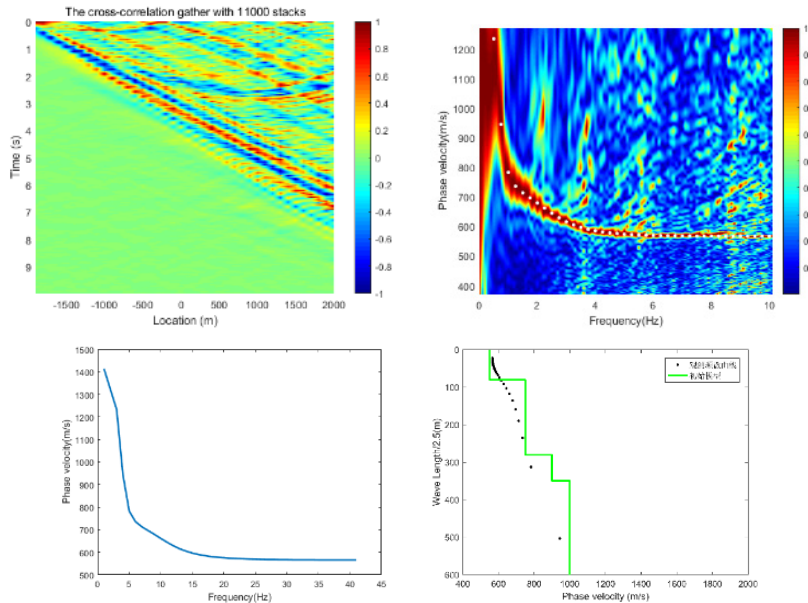
distribution consistent with the surface wave record, yet the energy levels are not entirely continuous. The axis of the dispersion energy for the fundamental surface wave exhibits a clear line, surrounded by dispersed energy. This inconsistency significantly impacts the subsequent acquisition of precise dispersion curves. Therefore, extending the recording duration could yield higher-quality dispersion curves, facilitating more accurate inversion of shear wave velocity structures, as illustrated in Figure 12(a).



**Figure 10.** (a) Deep-seated surface wave record for 100 minutes; (b) Dispersion imaging for 100 minutes; (c) Dispersion curves for 100 minutes; (d) Depth-domain dispersion curves

Analyzed the surface wave records for 100 minutes, extracted single-shot noise records through cross-correlation of noise records, and obtained surface wave information. From Figure 10(a), it can be observed that the deep-level surface wave records for 100 minutes exhibit distinct backward-scattering surface waves, with moderate energy. Figure 10(b) indicates that the deep-level dispersion imaging

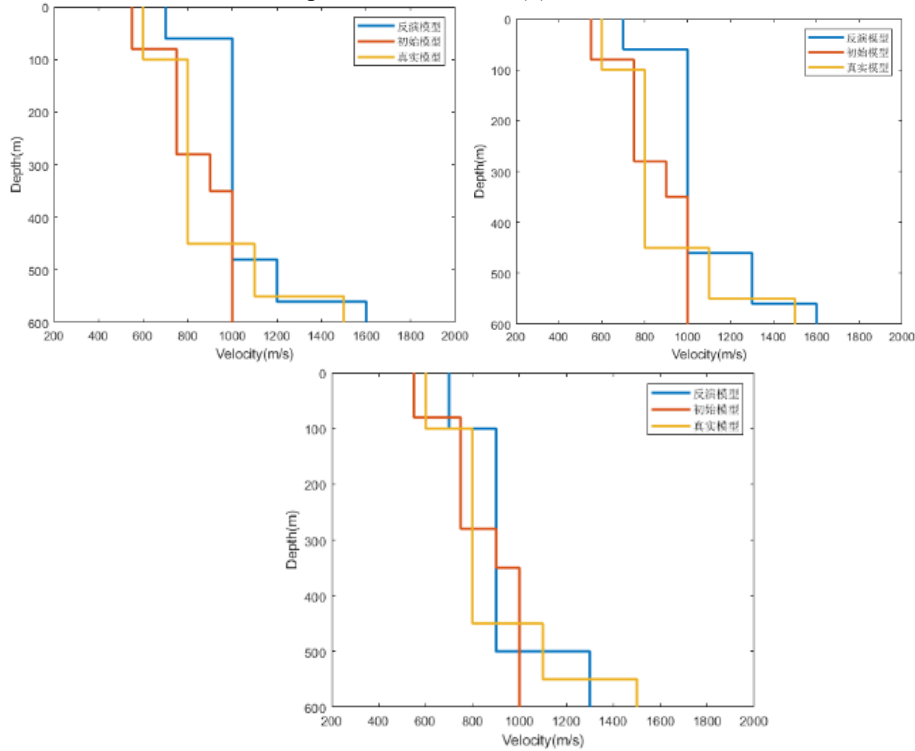
for 100 minutes is better compared to the 50-minute records, although the continuity of energy and energy approximation around the axis still need to be considered. Therefore, it may be considered to extend the recording time to improve imaging quality. The phase velocity resolution is good, affecting the subsequent acquisition of dispersion curves, but still meets the requirements, as seen in Figure 12(b).



**Figure 11.** (a) Deep-level surface wave record for 1000 minutes; (b) Deep-level dispersion imaging for 1000 minutes; (c) Dispersion curves for 1000 minutes; (d) Depth-domain dispersion curves

Analysis of the 100-minute surface wave recordings, obtained by cross-correlating and stacking single-shot noise recordings to extract surface wave information, revealed evident backscattered surface waves with moderate energy in Figure 10(a). Figure 10(b) indicates that the deep-frequency dispersion imaging for 100 minutes is better compared to the

50-minute recordings, yet the continuity of energy and clarity of the fundamental mode dispersion energy axis still need to be considered. It is suggested to extend the recording duration to improve imaging quality, although the phase velocity resolution still meets the requirements, as shown in Figure 12(b)



**Figure 12.** (a) Velocity structure for 50 minutes; (b) Velocity structure for 100 minutes; (c) Velocity structure for 1000 minutes

In summary, the recording duration of noise sources has a significant impact on passive source imaging. In this study, we found that with an increase in the number of cross-correlation stacking, the imaging quality gradually improves. Despite the different recording durations, they all basically meet the requirements for extracting dispersion curves and can infer relatively accurate shallow subsurface velocity structures.

#### 4. Application of Field Data

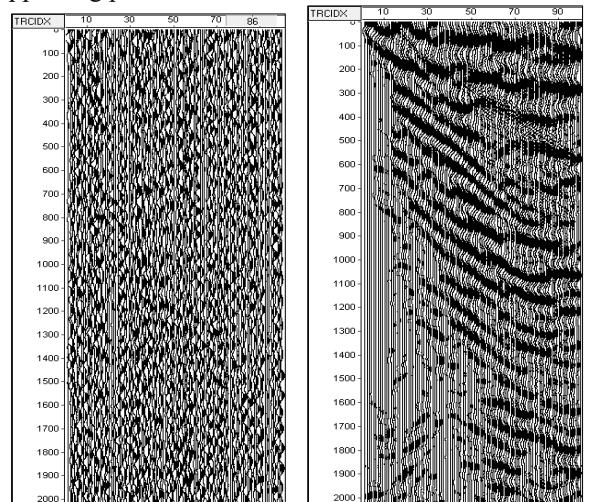
Passive imaging of background noise is a novel method that can substitute traditional active seismic sources. It directly utilizes background noise records to obtain subsurface geological information, particularly suitable for regions with low seismic activity.

This section applies the theory of passive source surface wave imaging to practical data processing, including collecting long-term underground background noise data, preprocessing, cross-correlation stacking, extracting surface wave records and dispersion curves, and inverting for shear wave velocity models.

The field data originates from seismic background noise records in China. Detectors are placed on the ground surface, and the noise sources include nearby wind blowing grass and ground traffic vehicle vibrations. To eliminate interference sources such as earthquakes and equipment responses, preprocessing of the raw data is necessary, including mean removal, trend removal, bandpass filtering, and time-domain normalization.

The noise records from different channels are shown in

Figure 13. The processed data are cross-correlated and stacked. The single-shot noise records from different channels are presented in Figure 14. Two sets of single-shot records, labeled as 1 and 2, are taken, with time on the vertical axis and channel number on the horizontal axis. In Figure 13(b), the energy of data 1's surface waves is strong, with a continuous distribution and high resolution. In Figure 14(b), the energy of data 2's surface waves is generally good, but there are local instances of energy crossovers and weakening or disappearing phenomena.



**Figure 13.** (a) Background noise records of Data 1; (b) Single-shot noise records of Data 1

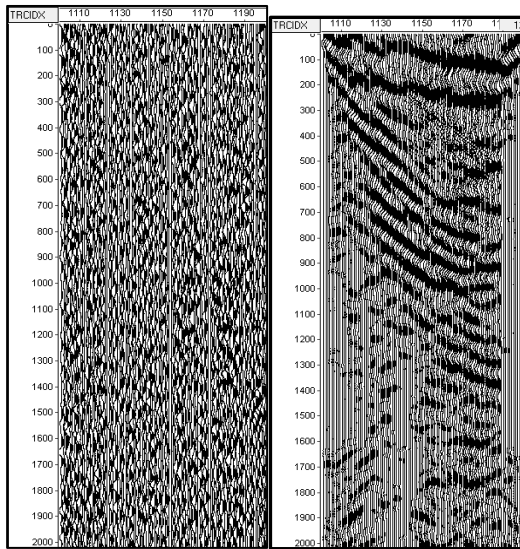


Figure 14. (a) Background noise records of Data 2; (b) Single-shot noise records of Data 2.

Extract surface wave information from single-shot noise records and perform surface wave dispersion imaging. The dispersion energy is mainly concentrated in the low-frequency range of 2Hz to 4Hz, consistent with the low-frequency characteristics of surface waves. By highlighting

peak values in local regions and manually removing scattered points, the dispersion curve is picked, as shown in Figure 15(b) and Figure 16(b). The original dispersion diagram is plotted, and dispersion curves are drawn in the depth domain to invert the velocity structure.

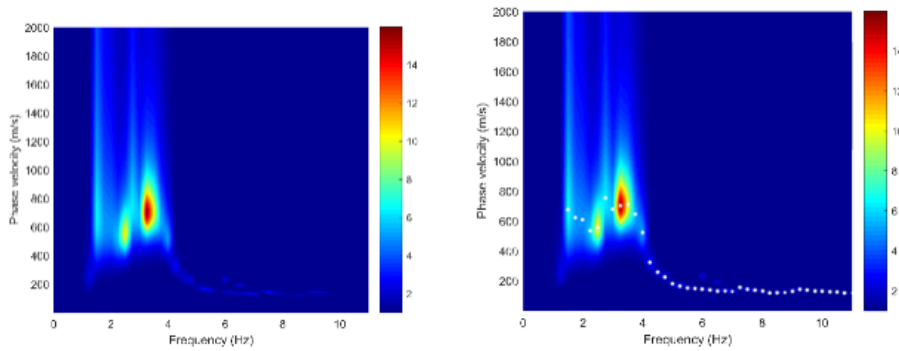


Figure 15. (a) Dispersion Imaging of Data 1; (b) Picking of Dispersion Curves for Data 2.

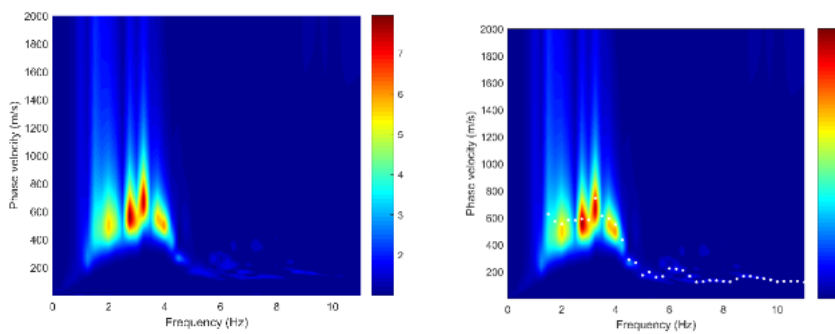


Figure 16. (a) Dispersion Imaging of Data 1; (b) Picking of Dispersion Curves for Data 2

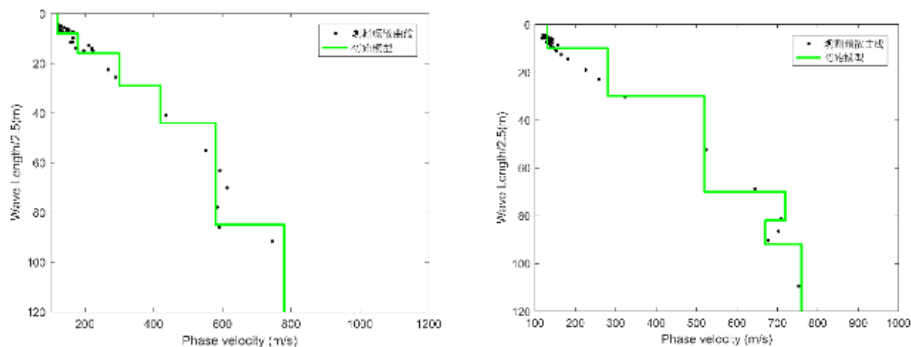


Figure 17. (a) Depth-domain Dispersion Curve of Data 1; (b) Depth-domain Dispersion Curve of Data 2.

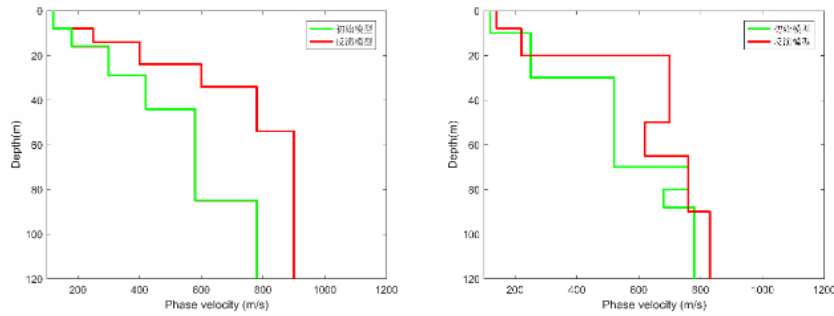


Figure 18. (a) Velocity Structure of Data 1; (b) Velocity Structure of Data 2.

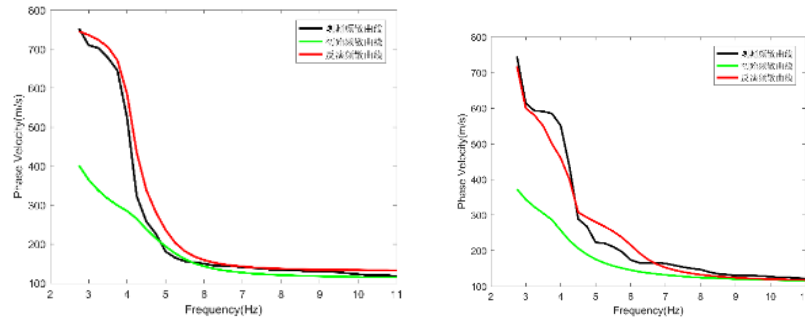


Figure 19. (a) Dispersion Curve of Data 1; (b) Dispersion Curve of Data 2

Read the acquired dispersion curves and plot the original dispersion images, converting the three dispersion curves into the depth domain as shown in Figures 17(a) and 17(b). After establishing two different six-layer horizontal initial models and setting the inversion control parameters, we used the least-squares method for simultaneous inversion of lateral wave velocity and thickness. After 8 iterations, we obtained the inverted strata velocity structure results, as shown in Figures 18(a) and 18(b). It is evident that the fit between the inverted dispersion curves and the true dispersion curves of the strata is better for Data 1 compared to Data 2, as shown in Figures 19(a) and 19(b), suggesting that the inversion results for Data 1 provide a more accurate estimate of the strata velocity.

## 5. Conclusion

Based on the above content, it can be inferred that firstly, the density and distribution of seismic sources significantly impact the imaging results. Therefore, when collecting data, one should consider the random distribution of seismic sources and choose an appropriate distribution. Secondly, longer recording durations yield more effective information, which is advantageous for subsequent processing.

The practical application of background noise imaging method demonstrates its rationality and feasibility. Extracting Green's functions from seismic background noise will greatly advance seismology. It is important to continue monitoring the progress of this method and conduct further related research to explore its deeper potential.

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