Improved High-Resolution 3D Vs Model of Long Beach, CA: Inversion of Multimodal Dispersion Curves From Ambient Noise of a Dense Array

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Abstract
Ambient noise recorded by a dense seismic array provides an opportunity to resolve detailed 3D shear wave velocity (Vs) structures. We utilize the frequency-Bessel transform (F-J) method to compute the dispersion spectrogram for ambient noise recorded by the Long Beach seismic array, extract multimodal dispersion curves with a deep learning approach, and invert multimodal dispersion curves with a gradient algorithm. The addition of higher-mode dispersion curves reduces nonuniqueness and provides an improved high-resolution 3D Vs model that shows good correlations with the known stratigraphic sequence and geologic features in the study area. Furthermore, the Richard fault between the Pacific Coast Highway and Newport-Inglewood faults, which have never been discussed in previous studies, is resolved. Our study demonstrates the potential of using the F-J method to extract multimodal dispersion curves and consequently retrieve an improved high-resolution 3D Vs model from a dense seismic array.

Plain Language Summary
A seismometer not only records earthquake events but also records weak vibration signals in the environment. Researchers use the seemingly irregular ambient vibration recorded by a dense seismometer to obtain the shear wave velocity (Vs) structure underground. In this study, the ambient vibration recorded by the Long Beach seismic array is analyzed with a recently developed frequency-Bessel transform method, which can effectively extract higher-mode dispersion curves. For each subarray, we measure the dispersion curves with this recently developed method and simultaneously invert the fundamental and higher-mode dispersion curves to obtain a 1D Vs model. Then, we merge all 1D Vs models at each subarray to construct a 3D Vs model. Our model shows high-resolution features in both lateral and vertical directions, which correlate well with known geological backgrounds. In addition, the Pacific Coast Highway fault, Newport-Inglewood fault, and Richfield fault never discussed in the previous velocity model, are clearly resolved in this study.

1. Introduction
Ambient noise technology (Sabra et al., 2005; Shapiro et al., 2005) uses cross-correlation to extract the empirical Green's function between station pairs and has become a common tool to obtain underground structures. It is widely used in continental (Bensen et al., 2008; Ritzwoller et al., 2011; Ward et al., 2013; Yang et al., 2007), regional (Behm et al., 2016; Stehly et al., 2009; Wilson et al., 2002), and urban (Dai et al., 2021; Li et al., 2016; Mordret et al., 2013) geophysical studies. Inverting the dispersion curves extracted from ambient noise or earthquake events is used to image the shear wave velocity (Vs) structure. Traditionally, only the fundamental-mode dispersion curve is inverted to obtain the Vs model (Yao et al., 2006), since it is difficult to effectively extract higher-mode surface-wave dispersion curves from real seismic data (especially seismic ambient noise). However, studies have shown that adding higher-mode surface-wave dispersion curves to inversion processing can improve the accuracy and obtain a more reliable underground Vs model (Beaty et al., 2002; Maraschini et al., 2010; Xia et al., 2003). For example, Beaty et al. (2002) used a simulated annealing method to simultaneously invert multimodal Rayleigh-wave dispersion data.

Recently, Wang et al. (2019) developed a frequency-Bessel transform (F-J) method that could effectively extract higher-mode dispersion curves, especially from seismic ambient noise data. Numerical examples (Wang...
et al., 2019) and real applications (Hu et al., 2020; Wu et al., 2020; Zhan et al., 2020) have shown that the F-J method is an effective tool for ambient noise multimodal dispersion curve extraction. Subsequently, Li, Shi et al. (2021, 2022) verified the application of extracting normal mode and leaking mode dispersion curves by this method on earthquake records and ambient noise cross-correlations. Currently, short-period dense seismic arrays have been widely deployed for shallow structure imaging (Ma et al., 2020; Xie et al., 2021).

In this study, we present the application of the F-J method to measure the multimodal dispersion curves of the seismic ambient noise recorded by the Long Beach seismic array. We calculate the spectrograms for each subarray by the F-J method and efficiently extract the multimodal dispersion curves with a deep learning approach. To obtain a reliable Vs model, the density and Vp/Vs ratio in a previous study were used as constraints in the multimodal dispersion curve inversion. All individual 1D Vs models are merged to construct the final 3D Vs model. The results are consistent with the geological unit and stratigraphic profile.

2. Data and Methods

Between January and June 2011, more than 5,200 high-frequency velocity sensors were deployed in the Long Beach area with an average station spacing of 0.1 km, denoted by the gray triangles in Figure 1a. Long Beach is home to several major faults including the Pacific Coast Highway (PCH) denoted by purple lines, and Newport-Inglewood (NI) faults denoted by black dotted lines. Several wells at Pier F, Pier C, LBCH, and LB Webster elementary school are used to identify the stratigraphic profile (Ponti et al., 2007) in Figure 5a. Signal Hill is located at the center of the seismic array. We present a workflow (Figure 1) to retrieve an improved high-resolution 3D shear wave velocity (Vs) model from ambient noise recorded by the Long Beach seismic array.

The cross-correlation functions (CCFs) between all station pairs are calculated from the seismic ambient noise recorded during the period of 5–25 March 2011. For each 1-hr noise segment, Lin et al. (2013) performed spectrum whitening and subsequently calculated the temporal normalization before cross-correlation but normalized each 1-hr noise cross-correlation by its maximum amplitude. The CCFs in this study are provided by Lin et al. (2013), and the CCFs for subarray S are shown in Figure 1b, which are used to generate dispersion spectrograms for reference location S. The dispersion spectrogram calculated with the frequency-Bessel transform (F-J) method (Wang et al., 2019) is shown in Figure 1c. Then, the multimodal dispersion curves in Figure 1d are extracted from the F-J spectrogram with a deep learning approach named DisperNet (Dong et al., 2021). Transfer learning (Text S1 in Supporting Information S1), which incorporates dozens of manual pickings, is essential for accurate auto-picking with DisperNet on the Long Beach data set. A gradient method with Broyden-Fletcher-Goldfarb-Shanno (BFGS) optimization (Byrd et al., 1995; Pan et al., 2019) by fitting the observed and predicted multimodal dispersion curves is adopted in this study. To avoid the solutions trapped in a local minimum, we adopt a multistarting strategy and invert multimodal dispersion curves with 80 different starting Vs models, which are randomly generated with the given lower and upper Vs boundaries. The final estimated Vs model (the red curve in Figure 1e) is obtained by implementing a weighted average (Pan et al., 2019; Wu et al., 2020) over the first 40 solutions with minimum misfits. The derivation of the 40 inverted Vs models is used to evaluate the uncertainty of the final estimated Vs model. We move the reference location to each station, repeat the workflow mentioned above for each subarray, and finally construct a 3D Vs model by merging all 1D Vs models.

3. Results

The phase velocity maps of the fundamental mode at 0.6 and 1.0 Hz are shown in Figures 2a and 2b, respectively, and reference locations with station numbers less than 240 are trimmed off to remove the edge effect (Figure S1 in Supporting Information S1). High-velocity anomalies basically emerge along the NI fault zone (indicated by the black dotted lines) in deeper structures. Figure 2c shows the phase velocity map of the fundamental mode at 2 Hz, which corresponds to a shallower depth structure. High-velocity anomalies appear along the NI fault zone and on the northern side of the fault, which implies strong lateral velocity vibration for the shallow structure. Figures 2d and 2e show the phase velocity maps of the first-higher mode at 2.0 and 3.0 Hz, respectively. High-velocity anomalies also appear along the NI fault zone. Figure 2f shows the Rayleigh-wave phase velocity map for the second-higher mode at 3.0 Hz.
Higher-mode dispersion curves are not extracted for all reference locations. The blue and green dots in Figure S2 in Supporting Information S1 show the reference locations where the first- and second-higher-mode dispersion curves are extracted, respectively. The first-higher mode dispersion curves are extracted at ∼5,140 reference locations. The remaining ∼60 reference locations without first-higher-mode extraction are basically near the NI fault zone. This result implies that the local velocity model here is complicated and deviates from the 1D layered model assumption. The second-higher-mode dispersion curves can only be extracted from the southwest part (∼540 reference locations) of the seismic array, which implies that the stratum in the southwest tends to be a more horizontally layered medium.

First, we invert only the fundamental-mode dispersion curve. Although compressional wave velocity (Vp) and density can affect the phase velocities, their sensitivities to the phase velocity are much lower than that of Vs (Pan et al., 2019; Wu et al., 2020; Xia et al., 2003). Here, we invert only for the Vs model, while the density and Vp follow an empirical relation (Lin et al., 2013). The inversion results for subarray S are shown in Figures S3a–S3c in Supporting Information S1. The black curves in Figure S3a in Supporting Information S1 are the inverted Vs models with 80 randomly generated initial Vs models, and the red curve is the final estimated Vs model. The uncertainties of the Vs model at depths less than 0.8 km are approximately 0.02 km/s, while the uncertainty increases to 0.07 km/s at half space. Since only the fundamental-mode dispersion curve is used in the inversion, the predicted fundamental-mode dispersion curve matches well with the observed curve. However, there are mismatches between the predicted and observed higher-mode dispersion curves. For comparison, we simultaneously invert multimodal dispersion curves. The black and red curves in Figure S3d in Supporting Information S1 are the inverted and final estimated Vs models. The corresponding Vs uncertainties (Figure S3e in Supporting Information S1) are shown in Figures S3a–S3c in Supporting Information S1.
Information S1) are approximately 0.01 km/s at depths less than 0.8 km and increase to 0.05 km/s at half space. A sharp boundary at depths between 0.3 and 0.4 km is constrained by incorporating higher-mode dispersion curves. In addition, the predicted dispersion curves for all modes in Figure S3f in Supporting Information S1 well match with the observed curves.

Then, we invert the multimodal dispersion curves for all reference locations to obtain 1D Vs models and merge the Vs models for all reference locations to construct the 3D Vs model. A Gaussian smoothing filter with a radius of 200 m is applied to obtain the final 3D Vs model. Representative depth slices of the final 3D Vs model are shown in Figure 3. For comparison, the representative depth slices of the final 3D Vs model from the inversion of fundamental-mode dispersion curve are also shown in Figure S4 in Supporting Information S1. The velocity patterns in Figure 3 are basically identical to those in Figure S4 in Supporting Information S1, although there are slight structural differences.

We compare the two inverted 3D Vs models with the previous eikonal tomographic results of Lin et al. (2013). Figures S5a–S5c in Supporting Information S1 show the Vs models at a depth of 0.1 km from the eikonal tomography, inversion of the fundamental-mode and multimodal dispersion curves, respectively. The long wavelength features in the eikonal tomography are basically identical to those observed in the inversion of the fundamental-mode and multimodal dispersion curves. However, more detailed velocity variations near the NI fault zone are observed in Figures S5b and S5c in Supporting Information S1. For the depth slice comparisons at a depth of 0.3 km (Figures S7d–S7f in Supporting Information S1), a high-velocity anomaly (>0.9 km/s) emerges in the Signal Hill area in Figure S5f in Supporting Information S1, while a high-velocity anomaly with a Vs value of 0.8 km/s appears southwest of the NI fault in Figure S5d in Supporting Information S1. The final estimated 3D
Vs model from the inversion of multimodal mode dispersion curves shows a more detailed lateral velocity change that correlates well with the main geological structural features of the region. The high-velocity anomalies (in the Signal Hill region) resolved in Figure S5f in Supporting Information S1 may be related to deeper earth material exhumed due to the deformation process (Lin et al., 2013).

The vertical slices of the final 3D Vs model with the inversion of multimodal dispersion curves at different longitudes are shown in Figure 4. The absolute Vs slices are shown in Figures 4a1–4f1. The relative perturbations of Vs slices are plotted in Figures 4a2–4f2, where an average 1D Vs model in Figure 4g is removed. The black and purple dashed lines denote the surface projections of the NI and PCH faults, respectively. The lateral velocity discontinuities in each slice correlate well with the known surface projections of NI and PCH faults. In addition, a minor fault (red dashed line) between the NI and PCH faults is resolved from the lateral velocity discontinuities. The lateral velocity discontinuities and minor faults are also resolved in the vertical slices (Figure S6 in Supporting Information S1) with the inversion of the fundamental-mode dispersion curve, although the resolution in Figure S6 in Supporting Information S1 is less than that in Figure 4. We also compare the relative perturbation with the eikonal tomographic results (Lin et al., 2013) in Figure S7 in Supporting Information S1. The velocity patterns, including the high-velocity anomaly and lateral velocity variation, are basically identical. However, the
vertical resolution of the Vs perturbation with multimodal dispersion curve inversion is much higher than that of the eikonal tomographic results. The use of the F-J method for the Long Beach data set and incorporating multimodal dispersion curves during inversion resolves an improved high-resolution 3D Vs model, which shows more detailed lateral and vertical structural patterns than previous tomography.

Figure 4. Representative vertical slices of the final 3D Vs model from the inversion of multimodal dispersion curves. The absolute Vs slices are plotted in (a1–f1), and the relative perturbation of Vs slices are plotted in (a2–f2) with the average 1D model in (g) removed. The black and purple dotted lines denote the surface projections of the Newport-Inglewood and Pacific Coast Highway faults, respectively. The red dashed line represents a minor fault revealed in this model.
Figure 5. (a) The modified stratigraphy along the ∼N-S profile in Figure 1a, with 4 deep wells used as constraints. The wells are located at Pier F, Pier C, LBCH, and LB Webster elementary school, approximately 1 km west of the Long Beach seismic array, (b) vertical Vs slice DD’ from the inversion of multimodal dispersion curves, (c) interpreted stratigraphy based on the Vs profile in (b), and (d) Vs perturbation with the 1D Vs model in Figure 4g removed. The purple and black arrows indicate the surface projections of the Pacific Coast Highway and Newport-Inglewood faults, respectively.
4. Discussions

We compare the observed and predicted multimodal dispersion curves in Figure S8 in Supporting Information S1. The predicted dispersion curves (red curves) based on the Vs model from the multimodal inversion well match with the observed curves (black curves). However, the predicted dispersion curves based on the Vs model from fundamental mode inversion deviate from the observed ones. Thus, incorporating higher modes in the surface-wave dispersion curve inversion reduces the nonuniqueness and improves the final model accuracy.

To intuitively understand the stratigraphic structure, a modified stratigraphy profile (Ponti et al., 2007), ~1 km west of the Long Beach seismic array, is plotted in Figure 5a. The inferred stratigraphy is constrained by four deep wells, marked by solid white lines. The vertical purple line in Figure 5a is the PCH fault, and the red curve is the Richfield fault. More detailed geological explanations are shown in the lower left panel in Figure 5a.

The Vs slice from the inversion of multimodal dispersion curves for the DD’ (Figure 1a) profile is shown in Figure 5b, where the purple and black arrows denote the surface projections of the PCH and NI faults, respectively. The dashed red curve represents the minor fault location between PCH and NI faults, which is resolved in the final 3D Vs model in Figure 4. Obviously, the fault between PCH and NI faults is the Richfield fault.

According to the stratigraphic profile in Figure 5a, the Upper Wilmington (UW) sequence (dark gray), north of the PCH fault, is approximately 0.15–0.2 km thick at depths of approximately 0.2–0.4 km. We interpret the yellow section (0.73 < Vs < 0.86 km/s) in Figure 5b as the Upper Wilmington sequence. In addition, the Tertiary Undiv. (TU) sequence (dark green) is approximately 0.8 km deep, so we interpret the blue section (Vs > 1.23 km/s) in Figure 5b as the TU sequence. The stratigraphic sequences above UW and the sequences between the UW and TU are interpreted in detail in Figure 5c based on the Vs contour map in Figure 5b and average thickness for each sequence.

The average shear-wave velocity for the upper 30 m depth (Vs30) is a key parameter to classify sites in many building codes (Code, 2005; Council, 2003). It has also been used to estimate site amplification factors in recent ground-motion prediction equations (Boore & Atkinson, 2008). The method to calculate Vs30 in this study is described in Text S2 in Supporting Information S1. The calculated Vs30 from the inverted 3D Vs models by inverting the fundamental-mode and multimodal dispersion curves are shown in Figure S9a and S9b in Supporting Information S1, respectively. According to (Building Seismic Safety Council, 1988), the site with 360 < Vs30 < 760 m/s corresponds to very dense soil and soft rock. The areas with average Vs larger than 0.50 km/s in the Signal Hill region and southern part should be correlated with soft rock. The areas with average Vs less than 0.50 km/s and larger than 0.42 km/s should be very dense soil. The areas with average Vs less than 0.42 km/s may be stiff soil. We can see that the basic features are nearly identical; however, the Vs30 contour map derived from the improved high-resolution 3D Vs model shows more detailed heterogeneities.

5. Conclusion

In this study, we construct an improved high-resolution 3D Vs model by inverting multimodal dispersion curves extracted from ambient noise in Long Beach, CA. More specifically, we compute the dispersion spectrograms for each subarray with a radius of ~1 km by the frequency-Bessel transform (F-J) method. The F-J method can effectively and accurately extract the dispersion curves of the fundamental and higher-mode dispersion curves. Traditional manual or semi-autopicking methods are time consuming. In this study, a deep learning method named DisperNet is used for vast dispersion curve picking. For each subarray, we simultaneously invert the multimodal dispersion curves with 80 randomly generated initial Vs models, then, a final estimated Vs model is obtained by implementing a weighted average over the first 40 solutions with minimum misfits. The final 3D Vs model is obtained by merging all 1D Vs models at each subarray.

Compared to earlier studies in the region using Rayleigh wave eikonal tomography (Bianco et al., 2019; Lin et al., 2013) and body wave tomography (Castellanos et al., 2020), the 3D Vs model from the inversion of multimodal dispersion curves resolves much more detailed structural patterns in both lateral and vertical directions. The velocity discontinuities in the vertical Vs slices correlate well with the PCH and NI faults. The Richfield fault between NI and PCH faults, which has never been discussed in previous studies, is also well resolved. The 3D Vs model shows good correlations with the known stratigraphic sequences and geologic units. Moreover, the Vs30 derived from the multimodal dispersion curves shows more detailed heterogeneities. The use of the F-J method
to extract multimodal dispersion curves and incorporate them in the inversion provides an improved high-resolution 3D vs model in this study.

Data Availability Statement

The authors thank Prof. Fanchi Lin for providing the cross-correlation functions (CCFs) and eikonal tomography results in this study. The CCFs used in the study are available in Lin et al. (2013) and were requested by contacting the corresponding author of the paper. The original data from Lin et al. (2013) is the property of Signal Hill Petroleum Inc. The dispersion curves in this study can be accessed from https://doi.org/10.7910/DVN/VIIFI. The F-J spectromgram calculation is implemented by CC-FJpy (Li, Zhou et al., 2021), which can be accessed from https://doi.org/10.1785/02202101402.

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