Urban near-surface imaging from ambient noise tomography using dense seismic networks

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Abstract. It is of scientific and engineering significance to extract surface wave signals from urban ambient noise for fine-scale three-dimensional velocity structure imaging of underground medium. A series of issues such as ambient noise characteristics in urban environment, observation system design and resolution of small-scale imaging, have put forward a lot of new requirements and challenges to traditional methods and technologies. We utilized the dense array with its aperture extend below hundred meters in Hangzhou urban area, to carry out the ambient noise data acquisition experiments within one day. Based on the time-frequency analysis of noise cross-correlations, we conducted surface wave travel time tomography. Finally, the phase velocity slices were inverted to build a three-dimensional S-wave velocity structure, and the profiles were compared with the drilling data for validations. We concluded that these geometry and processing parameters adopted in the urban environment are feasible for near-surface tomography and can meet the demands of three-dimensional geological survey in cities efficiently.

1. Introduction

With the urgent need for urban underground resource extraction, space exploitations and geological survey and evaluations, which are closer to serving the economic and social development. In recent years, researches on seismic ambient noise tomographic of local or reservoir-scale imaging are in the ascendant. The success of seismic interferometry in large-scale imaging firstly motivated the oil and gas exploration community to use this method to extract body waves [1]. However, there are still many challenges to achieve this goal since special requirements are often imposed on the medium (such as the mode conversion caused by the anisotropy [2]) and processing methods (such as deconvolution [3]). Surface wave is the strongest and most easily collected signal component in ambient noise. The particularity of high-frequency surface wave response and imaging in urban areas is largely reflected in the frequency band of noise signals. Based on this, it brings about the design of observation systems (detectors, station spacing, recording time, etc.) and data processing methods. Microseism (0.15 ~ 2Hz) originates from the ocean tides and the vibration generated by atmospheric activity on the earth's surface. The coherent signal components of human noise (2 ~ 25Hz) are mainly based on surface wave energy. They complement each other to realize multi-scale imaging of urban underground space.

The researches on ambient noise and its application in shallow exploration have been carried out in cities of China, especially in the use of noise recordings with ultrashort-period observation to extract high-frequency surface wave in urban environment [4-6]. Based on the noise cross-correlation techniques, multichannel analysis of passive surface wave was proposed [7] to extract high-frequency
surface wave dispersion energy up to several tens of hertz from urban traffic noise after the slant stacking of virtual source gathers [8-9], which is common used to image the shear wave velocity structure within depth of 100 meters.

Further study on obtaining high-resolution surface wave energy maps for ultra-short ambient noise recordings in towns and cities is underway. For example, Pang [10] developed a signal-to-noise-ratio screening algorithm to improve the quality of dispersion energy imaging. In addition, the surface wave waveform inversion algorithm and the tomography using a linear array [11] are also very useful for reference. The common feature of these studies is that high-frequency geophones are used to form dense arrays, but still obvious surface wave signals can be observed in lower frequency bands. In this kind of small-scale shallow velocity structure research, tomographic imaging algorithms mostly use the direct ray path integration in the Cartesian coordinate system [12]. Here we impose the ray tracing eikonal solver under spherical coordinates in order to take medium heterogeneities into consideration [13], which is more consistent with Fermat principle than the conventional straight ray tomography under Cartesian coordinates, to conduct tomographic inversion for the imaging of underground velocity structures in Hangzhou urban area. and the final inverted three-dimensional S-wave velocity model is combined with two well logs to reveal and interpret different lithologies for subsurface fine stratification and bedrock surface characterization.

2. Data observation and processing

The target zone for ambient noise surface wave tomography is shown in Figure 1 with its diameter expands as close as 150m, and totally 182 nodes equipped with 5Hz three-component geophones were used to build a dense seismic network with the average adjacent station interval about 10m. The synchronized observation started at 5:30 pm, June 15th and ended at 5:15 pm, June 16th, 2019 (totally 23 hours 45 minutes) with the sampling frequency 1000Hz.

There are also two wells that provide shear wave velocity logging data, the nearest well #1 is about 50 m away from the networks, and the another well #2 that about 500m along the northeast direction of this highway is not shown here. Two well log data is basically the same in terms of the shear wave velocity shallower than 40m. There is an obvious high-speed gravel interlayer in this section, and the position corresponding to the maximum velocity gradient of the bedrock is also relatively consistent.

We focus on the vertical-component ambient noise data, and didn’t apply instrument response removal since there are same sensors within the whole network. To reduce the data redundancy and to avoid the sampling aliasing, the raw noise dataset was firstly low pass filtered and then decimated to 50Hz. Data preprocessing was inspired by Bensen [14]. We apply seismic interferometry between the given virtual sources and all other stations regarded as receivers, and finally obtain the cross-correlation functions through linear stacking to average the effect of noise temporal variations.

![Figure 1. The observation system consists of 13×14=182 nodal sensors, which are represented by white triangles in the left panel. And only the nearest well #1 is shown here with their borehole data of shear velocities given in the right panel](image-url)
3. Phase velocity Tomography

Frequency-Phase velocity dispersions were measured through Time frequency analysis of empirical Green’s functions based on the image transform techniques [15]. One representative phase velocity dispersion result in Figure 2 is shown for example. Moreover, the cluster of total dispersion curves extracted in this subnet is also presented. We compare the averaged dispersion curve with the theoretical dispersion curve synthesized from the borehole data, and find well consistency with their RMS error of 15.72 m/s.

The phase travel times were inverted by ray-tracing tomography under spherical coordinates which is consistent with Fermat principle to take medium heterogeneities into consideration. Figure. 3 shows the phase velocity maps of 16 frequencies. In general, these maps show smooth velocity variations from lower to higher frequency, which reveal the trend that high-velocity basement underlies the low-velocity shallow strata and indicate stable tomographic results though they are inverted individually. From these maps, the phase velocity drops from about 700 m/s to 300 m/s in the frequency band of 1.5~2.5 Hz, while in the 2.5 Hz ~ 9 Hz frequency band, the speed decreases from 300 m/s to 180 m/s. The general trend is same as the borehole data which shows that the velocity above the bedrock changes gently, while the velocity below the bedrock increases sharply. At the same time, the lateral velocity distribution of maps above 2.5 Hz is relatively uniform, and the maps of lower frequencies reflect the non-uniformity of phase velocity, which is also consistent with the comparison between two boreholes.

As is shown in Figure 3, 18 stations (red triangles) are chosen as virtual sources, meanwhile as receivers too, that they cross-correlate with other stations (blue triangles) to make up the customized station pairs. Since the chosen reference stations act as seismic sources, we hope to allocate them to be azimuthally homogenous to average the real variations of noise source distribution, and multiple interstation distances vary from the nearest 10 m and the farthest 150 m are also considered to retrieve signals with different wavelength. Undoubtedly, these operations enhance the work efficiency and still can achieve quite high path densities within this 150×150 m area, and lateral resolution is roughly equal to the average station interval (10 m) according to the checkerboard tests.

![Figure 2](image)

*Figure 2.* Left panel: phase velocity dispersion image under certain station-pair expansion. Right panel: dispersion curve clusters of all given virtual sources. Gray lines represent the extracted dispersion curves, black dashed lines indicate the number of dispersion curves varies in different frequencies, and blue lines represent the averaged dispersion curves. Red line is the dispersion curve forwarded from the borehole shear-wave velocities.
Figure 3. Phase velocity slices after tomographic inversions. In this study, we follow the convention of near-surface representations that the cool color (blue) indicates low velocity while the warm color (red) indicates high velocity. The given 18 virtual sources are highlighted by red triangles.

4. Discussion and conclusion

Although the reliable phase velocity maps have confirmed the primary trend of velocity gradient, and qualitatively implied a few of details about depth variations, we further rely on the shear-wave slices at exact depth extent, and to intuitively compare them with existing shear-wave well log data.

We invert the dispersion curve below each measurement point to obtain the shear wave velocity, and then take an average, which is shown in Figure 4 (the green curve). Compared with the shear wave velocity curves of the two wells (the blue and the red curve), the numerical range and trend are in good agreement, which also validates reliability of our inversion results.

From the comparison of the drilling lithology histogram data, the shear wave velocity slices of different depths corresponding to different lithologies (Figure 5). The stratum can be divided into four units: surface silt layer, clay layer with gravel layer, weathered bedrock layer, and the relatively high-speed slice at the position of 45m clearly corresponds to the gravel layer.

The velocity structure within a depth of 100m in this survey area corresponds to the geological situation which can be summarized as two parts in Figure 6: the soil cover layer and the bedrock section. Combing with the drilling data, we can infer from the shallow to deep formations that, the soil cover is composed of silt (2~20m), clay (20~42m), gravel interlayer (42~50m), and bottom clay layer (50~56m), the soil cover is shallow in the range of about 60m, and the speed of the silt layer approximately positive correlates with depth in the range of 150~200m/s. Fluctuating within the range of 200~210m/s, velocity distribution of the clay layer is relatively uniform. Velocity of the gravel layer is 400m/s on average, and the velocity gradient is significantly different from that of the upper and lower clay layers. The lithology and particle size of the unearthed samples indicate that no transition layer exists.
Three-dimensional geological survey is a pioneering work in the process of urbanization. A reliable and efficient observation and processing plan should be designed for urban noise, terrain, and underground structure characteristics. The experimental results in the surrounding urban areas of Hangzhou show that it is possible to use dense arrays with short-period observations, and perform batch processing for shallow surface fine imaging, so as to efficiently complete the area scanning of geological surveys. The pair of stations formed by the virtual-source node and the receiver node are used to extract the phase travel time, and the ray path coverage is sufficient to meet the requirement of horizontal resolution by checkerboard check, and the data processing efficiency of the station is reasonably improved.

**Figure 4.** Comparison between shear wave velocities from two well logs and the averaged inversion result.

**Figure 5.** Comparison between lithologies and the inverted shear wave velocity slices.
Figure 6. Interpretations and stratifications of isosurface in 3-D shear wave velocity model: (a) soli covers; (b) weathering bedrock

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