Study on the crustal velocity structure of the Dunhua-Mishan fault based on the dense seismic array by ambient noise tomography

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Abstract. The Dunhua-Mishan fault is a component of the Tanlu fault zone, and it is also a major regional fault structure in Liaoning area. The study area is located in Fushun area of the Dunhua-Mishan fault. In order to study the crustal velocity structure in this region, we used 60 sets of three-component short-period seismographs and laid out two temporary profiles in Fushun, Liaoning from Nov. 3 to 25, 2019. Each temporary profile is about 12 km long that is composed of 30 seismometers, which nearly vertically cross the Dunhua-Mishan fault where the survey lines are 6 km apart. The installation stations spacing distance from 200 to 400 m use the external GPS time service to record frequency range of 0.2 to 150 Hz in the instrument. The crustal structure characteristics of the fault zone are studied by ambient noise cross-correlation method. In order to efficiently extract high and low frequency surface wave dispersion signals at the same time, we adopt the Extended Range Phase Shift (ERPS) method. Finally, we use ERPS method to process the collected data and invert the S-wave velocity structure. We initially obtained the S-wave velocity structure of the upper crust below 5 km in the area, which matches well with the local geological data. The S-wave velocity structure has significant lateral inhomogeneity of the Dunhua-Mishan fault in Fushun area. The S-wave velocity is obviously lower on the Dunhua-Mishan fault, while with the existence of ancient mixed granite the velocity on both sides of the fault is obviously higher.

Key words. Dunhua-Mishan fault; Dense seismic array; Ambient noise tomography; Extended Range Phase Shift method
1. Preface

Dunhua-Mishan fault is one main branch of Tanlu fault zone, which starts from the southwest of Shenyang in the West and extends to Jilin through Fushun and Qingyuan. Dunhua-Mishan fault (also called Hunhe fault in Liaoning section) strike 50°-80° with the total length of 195km. Dunhua-Mishan fault is an ancient fault structure, which was formed as early as Archean. The faults controlled the stratigraphic distribution of Archean-Proterozoic, Mesozoic Jurassic-Cretaceous and Cenozoic. The Dunhua-Mishan fault experienced multiple tectonic activities and controlled the modern Dunhua-Mishan landform, forming a river valley from NEE to nearly EW direction.

Most of the researches on Dunhua-Mishan fault focus on the activity, deformation characteristics and risk assessment of the fault[1-2]. In recent years, many geological disasters have occurred in Dunhua-Mishan fault, especially due to the surface subsidence caused by coal mining in Fushun area, and the frequent occurrence of mine earthquakes[3], which has aroused great attention. In addition, there are different understandings about the activity of Dunhua-Mishan fault. Therefore it is necessary to understand the underground geological structure of the area clearly, so as to provide the basis for the subsequent risk assessment of Dunhua-Mishan fault. Due to the lack of geological drilling data and the weak seismic activity in this area, the study of the shallow underground structure on both sides of Dunhua-Mishan fault is relatively weak. Based on the short-period surface wave technique, the velocity structure on both sides of Dunhua-Mishan fault is inversed by using the background noise imaging method, which further reveals the structural characteristics and seismic risk of Dunhua-Mishan fault.

Background noise imaging technology has been widely used in the study of near surface three-dimensional velocity structure in recent years. The basic idea is to approximate the empirical Green's function by calculating the noise cross-correlation function between stations. Previous background noise imaging studies focused on the long-period frequency band, which was used to retrieve the structure of the crust and upper mantle. In recent years, significant progress has been made in inversion of near surface underground structures using high-frequency surface wave information extracted from background noise[4]. In general, high frequency surface waves are more sensitive to shallow structures, while low frequency surface waves are more sensitive to deep structures[5]. In order to improve the ability of traditional phase-shifting method to extract low-frequency signals, we use Extension Range Phase-Shifting method (ERPS)[6] in this study. In Fushun area of Dunhua-Mishan fault, we set up two dense array profiles perpendicular to Dunhua-Mishan fault, and conducted continuous data acquisition for 23 days from November 3, 2019 to November 25, 2019. After extracting the dispersion curve, the S-wave velocity structure is inversed. In this paper, the general situation of geological structure, cross-correlation calculation, frequency dispersion extraction, velocity structure inversion and geological interpretation are described.

2. Geological structure of the study area

The Archean and Early Proterozoic migmatite, as well as the mixed granite and Archean metamorphic rock series are well developed in Dunhua-Mishan fault zone. There are also Mesozoic and Cenozoic strata exposed in the fault depression belt and its adjacent areas. In addition, the fault basin formed along Dunhua-Mishan fault controlled the Paleogene coal
deposits such as Jurassic-Cretaceous of Mesozoic and Fushun Coal Basin of Cenozoic, and it also controlled the intrusion and eruption of basic magma.

The Dunhua-Mishan fault experienced many periods of tectonic activity in Mesozoic and Cenozoic. The thrust activity of the fault was strong in the Yanshanian period, but it was mainly extensional since Neogene. The fault activity is not obvious in Quaternary.

The Fushun Basin formed by Dunhua-Mishan fault is mainly composed of Southern branch fault (F1, F1a and F1b) and Northern branch fault (F2). The basement of the basin is composed of Archean Early Proterozoic Anshan Group metamorphic migmatite where the Mesozoic and Cenozoic strata deposits (see Fig.1a and Fig.6).

Figure 1. (a) Location of temporary seismic stations and Dunhua-Mishan fault; (b) Distribution of the enlarged temporary seismic stations and station number. The black line is the Dunhua-Mishan fault; (c) Velocity models used in the study.

3. Data acquisition and analysis

3.1. data acquisition

The study area is located in Dongzhou District, Fushun City, Liaoning Province, with an altitude of 100m-180m, where the Donglutian coal mine is located in the east of the study area, and Dahuofang reservoir is located in the west. We deployed 60 short-period (5 s-150 Hz) ALLSEIS-3CL seismic stations with two lines (Line1 and Line2 profiles) with 30 stations respectively, perpendicular to Dunhua-Mishan fault. The two 12-kilometer lines with average station spacing of about 400m are distributed in parallel, whose distance is 5 km (see Fig. 1b and Fig. 6). From November 3, 2019 to November 25, 2019, continuous data acquisition was conducted for 23 days. One dimensional velocity model was obtained by referring to exploration, drilling data[7] and regional one-dimensional model [3].

3.2. background noise data processing

The data processing basically follows the background noise data processing flow introduced by Bensen [8]. Firstly, the single station data is preprocessed to check the quality of the continuous waveform and eliminate the bad traces. The data segments are divided into single hour data segments, which are processed by de averaging, de linearization, filtering, spectral
whitening, time domain normalization, etc. Considering the same type of seismic instruments used in each survey, we do not need to remove the instrument response. Then, all stations on the same line are combined in pairs. For each station pair, the cross-correlation is calculated by using the corresponding single hour segment, and the cross-correlation function is obtained by superposition. As shown in the figure 2, we show the partial cross-correlation function of line2. It can be seen that the collected signal has a high signal-to-noise ratio, but the positive and negative half axis signals are not completely symmetrical, and the positive half signal is obviously stronger than the negative half signal, which is mainly caused by the uneven distribution of noise sources.

![Figure 2](image_url)

**Figure 2.** Partial cross-correlation function of line2 in 0.1-3s period (signal-to-noise ratio greater than 5), in which the red dotted line represents the time interval line with the speed of 1.5km/s and 5km/s.

### 3.3. Extracting dispersion curve

The empirical Green's function can be extracted from the cross-correlation function by Hilbert transform. We use the ERPS method to process the cross-correlation function, calculate the dispersion energy diagram and extract the phase velocity dispersion curve. The ERPS method consists of two parts: internal array phase shift method and external array phase shift method. The internal array phase shift is easy to extract high frequency signals, while the external array phase shift is easy to extract medium and low frequency signals. According to a certain method, the medium-and-low frequency dispersion and high frequency dispersion are integrated into a complete dispersion curve, and then the velocity structure is obtained by inversion of the dispersion curve. In general, the method of adding and averaging the positive and negative branches is used to suppress the influence of uneven noise sources. However, considering that the cross-correlation positive and negative branches of the linear array represent the noise sources from two different end sources, this processing calculates the dispersion energy in three ways: the positive branch, the negative branch, and the plus and minus branches, so as to provide more choices for the dispersion extraction to avoid the effective signal being annihilated by the noise when the plus and minus branches are averaged.
Figure 3 and Figure 4 shows the result of the line1 and line2 phase-velocity dispersion curves. We extracted 0.2-3.3s phase velocity dispersion curve for line1 and 0.2-4s phase velocity dispersion curve for line2. In this frequency band, we merge the internal array dispersion curve with the external array dispersion curve. The short period is dominated by the intra array dispersion curve, and the long period is dominated by the external array dispersion curve. The integrated broadband dispersion curve is obtained by weighted superposition, which is used to inverse the shear wave velocity structure of underground media.

**Figure 3.** The phase-velocity dispersion curves for Line1. The gray lines represent the merged dispersion curves, the bold red line is the average dispersion curve for the phase velocity, and black lines represent the two standard deviations.

**Figure 4.** The phase-velocity dispersion curves for Line2. The gray lines represent the merged dispersion curves, the bold red line is the average dispersion curve for the phase velocity, and black lines represent the two standard deviations.

4. Results and discussion
We take Line1 temporary profile as an example. The north endpoint is set as the coordinate origin. It is obvious from Figure 6 that the shear wave velocity of Dunhua-Mishan fault is high on both sides and low in the middle.

The fault basin shows low velocity characteristics due to the thick sedimentary layer, as well as the reveal of Archean plagioclase, plagioclase migmatite and Anshan Group migmatite crystalline basement in the study area. The crystalline basement formed by these ancient rocks shows high-velocity characteristics due to high degree of metamorphism, especially at the north and south ends of Dunhua-Mishan fault. The Dunhua-Mishan fault basin is characterized by medium-low velocity because of the existence of Tertiary Paleocene basalt sandstone, Eocene shale and Quaternary Holocene sandstone.

In addition, the S-wave velocity increases with the increase of depth. At the same time, the shear wave velocity is obviously related to the landform, and the velocity is also high in the area with higher elevation showing in Figure 5.

According to the geological data and previous research results, Dunhua-Mishan fault has experienced the tectonic activities of thrusting in Yanshanian period, followed by extensional activity in Neogene, and no activity since late Pleistocene. It can be seen from Figures 5 and 6 that the shallow surface thickness is about 0-200m, which shows the low velocity with a Quaternary sedimentary layer consisted of sandstone and conglomerate. Especially the range of 3-9km along the profile line1 from the north endpoint beginning is characterized by the low velocity. It can be seen that the lateral velocity does not change basically, which indicates that the stratum has not experienced the influence of the tectonic movement of Dunhua-Mishan fault, which agrees well with the conclusion that the regional tectonic movement of Dunhua-Mishan fault is not obvious since Quaternary and the seismic activity level of the fault is weak[2]. Considering the large scale reveal of Archean metamorphic rocks at the both end of Dunhua-Mishan fault, the low velocity seems due to the weathering on the surface.

At depth of 200m-1000m, the lateral velocity inhomogeneity on both sides of the fault is obvious. Because the strata are mainly composed of the Tertiary Paleogene shale, basaltic sandstone and shale, it is characterized by medium-high velocity. The faulted basin formed by the extensional action of the fault has obvious control over the stratigraphic deposition.

About the 1000m below, the Archean crystalline metamorphic rocks and Mesozoic Cretaceous-Jurassic rocks were mainly experienced by the Yanshanian compression, the velocity structure changed large laterally. At the same time, the velocity fluctuation of the faulted basin becomes large, which may have experienced the compressional action in the Yanshanian period and the extensional action in the Tertiary period. In some sections, due to the Yanshanian thrust-dominated tectonic activities, the velocity structure of the fault rocks is shown that the high velocity layer is inserted into the low-speed layer, while the low-speed layer is inserted into the high-speed layer. For example, the velocity structure characteristics of high velocity body and low velocity body inversion can be seen near the depth of 1.0km at 8 kilometers from the north end of the survey line1. It may be due to strong tectonic compression, the rocks of high velocity body reverse to the low velocity layer, forming a complex velocity structure. It is also possible that the reversed high velocity body is a residual body of basic magma rich in iron, showing high velocity characteristics.
As for the Dunhua-Mishan fault, it can be seen from the lateral velocity variation map of the section that below 1000 meters, the Archaean metamorphic rocks and Mesozoic rocks experienced complex compression, and the velocity fluctuation is obvious. In particular, the obvious velocity variation zone is located at about 4km point and 8km point to the north end of the survey line1, which is supposed to be the location of the north branch (F2) and south branch (F1) of the Dunhua-Mishan fault with steep dip angle and deep extension downward (see Fig.5 two inverted triangle locations).

In addition, the velocity structure inversion results are associated with the gravity and electromagnetic anomalies[9]. The gravity negative anomaly and the gravity positive anomaly on both sides of the faulted basin reflect that the bottom of the two ends of the fault has a higher velocity value due to the high density of ancient metamorphic rocks, while the basin has a lower velocity due to the low density of Mesozoic and Quaternary sedimentary rocks. In addition, the existence of Anshan-type magnetite in the south side of the fault leads to the positive electromagnetic anomaly, which may be an explanation for the high velocity anomaly caused by the inversion of high velocity body into low velocity layer in the south section of Dunhua-Mishan fault in line1 profile. In general, Dunhua-Mishan fault controls the stratigraphic distribution, tectonic evolution and velocity distribution of the area.

**Figure 5.** S-wave velocity with depth and elevation of Line1 profile with distance (The two inverted triangles are the location of the north and south branch of Dunhua-Mishan fault respectively)
Figure 6. Geological and structural map of the study area. Line1 and Line2 are the array station profiles

5. Conclusion
The underground velocity structure of Dunhua-Mishan fault was studied by noise imaging method. Overall, our results agree well with the local geology. The following conclusions were drawn:

1) The imaging results show that the shear wave velocity structure of Dunhua-Mishan fault has obvious lateral heterogeneity, which is characterized by high velocity on both sides and low velocity in the middle. Besides, the velocity distribution characteristics are basically consistent with the surface geological structure.

2) The velocity of S-wave is obviously related to the topography. The velocity is higher in the area with higher elevation, and the velocity is lower in the area with lower elevation due to the thicker overburden. In addition, the velocity inversion results are in good agreement with the actual gravity and electromagnetic observations.

3) Based on the results of velocity inversion and geological observation, the spatial location of the North-South branch of Dunhua-Mishan fault is further defined. The Dunhua-Mishan fault controls the stratigraphic distribution, tectonic evolution and velocity distribution of the area.

4) In view of the uniform transverse distribution of S-wave velocity structure in Quaternary sediments, it can be considered that Dunhua-Mishan fault is inactive in Quaternary, which is consistent with the conclusion that Dunhua-Mishan fault is inactive since Late Pleistocene.

Acknowledgments
Thanks for the software of ERPS provided by Prof. Li Junlun and calculation by Ni Hongyu. This research is supported by Science and Technology Program of Liaoning Province (Grant No. 2019010223-JH8/103) and supported by Research grants from National Institute of Natural Hazards, Ministry of Emergency Management of China (Grant No. ZDJ2019-16) and the China Earthquake Science Experimental Field Project (Grant No. 2019CSES0106).

Reference
[1] Wan B, Jin C Y and Suo R 2017 J. Journal of Disaster Prevention and Mitigation. 33(01) 1-11
[2] Lei Q Q, Wang C, Zhao X H and Qu L 2007 J. Technology for Earthquake Disaster Prevention. vol.2. No2 128-36
[3] Zhang B, Zhang G W, Jiao M R, Zhang Z H and Shu M C 2021 J. Chinese Journal of Geophysics. 64(04) 1227-35
[4] Lin F C, Li D and Clayton R W 2013 J. Geophysics. 78(4) Q45-56
[5] Li C, Yao H J and Fang H J 2016 J. Seismol. Res. Lett. 87(4) 882-92
[6] Deng B 2020 Study on two new methods in surface-wave tomography using seismic ambient noise, Anhui: University of Science and Technology of China. A
dissertation for bachelor degree, 7-12

[7] Liao X, Zhao B M and Huang H 2008 *J. World Seismological Engineering*. 24(4) 64-9
[8] Bensen G D, Ritzwoller M H and Barmin M P, et al. 2007 *J. Geophys. J. Int.* 169(3) 1239-60
[9] Zhang Z Y, Wang B, Peng H and Tian D X 2020 *J. Global Geology*. Vol.39 No1 176-84