Factors influencing microtremor data collected using nested-triangular array configurations

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Abstract. The availability of microtremor data is potentially affected by various external factors. By combining field data and artificial interference, this work aims to determine the correlation between these factors and the dispersion curve of fundamental-mode Rayleigh waves extracted from microtremors. The first step was to obtain real, high-quality microtremor records using a triangular ten-station array of 48-m radius. Secondly, a series of artificial or semi-artificial interferences of varying type, duration, amplitude, etc., were generated and combined with the real records to imitate actual interferences. Thirdly, all the dispersion curves of the fundamental-mode Rayleigh waves of these modified microtremor records were estimated using the extended spatial autocorrelation method (ESAC). Finally, by comparing the experimental dispersion curves with the original curve, in terms of overlap ratio, we obtained useful conclusions that can be directly applied to microtremor data collection and analysis.

1. Introduction
Microtremors are ground vibrations with displacement amplitudes of between 1 and 10 microns and velocity amplitudes of 0.001–0.01 cm/s. They can be detected by seismographs with high magnification[1]. Since the pioneering work of Horike[2] and Okada[3], microtremor-array measurement has been recognized as an appealing and convenient exploration method for determining S-wave velocity[4]. Successful applications of microtremor exploration in engineering and resource exploration have been achieved[5-7]. Microtremor applications for the evaluation of the liquefaction potential of particular soils have also been reported[8,9]. A combination of these two methods has also been presented by many authors, with the aim of achieving high-accuracy results in both high and low frequency ranges[10,11].

Most researches focus on the application of microtremor method in different fields. However, little work has been done to study the method itself. In practice, field microtremor data are inevitably contaminated with various types of noise, which may result in a violation of the basic assumption that wavefields must be spatially and temporally stationary. In addition, it is relatively common for the collected data to be unsuitable, due to unavoidable circumstances such as equipment failure. How these factors affect result has not been clearly revealed. This is because the microtremor related
method is based on stochastic theory and the data have random characteristics which cannot easily be studied analytically and quantitatively via direct simulation of wavefields. In this paper, efforts are made to quantitatively and semi-quantitatively determine how the microtremor exploration method is affected by noise and other potential factors.

2. Microtremor records and data analysis
Data collection for this research was carried out on September 3, 2017 on a plain region of Zhejiang Province, China. The site was approximately 30 km from the nearest gulf coastline. The array consisted of ten WD-1 2-Hz vertical-component geophones, calibrated and adjusted to a critical damping of 0.8. Microtremors were observed for more than 30 min at a frequency sampling of 200 Hz. Figures 1(a) shows one of the raw datasets, where each trace consists of 209,920 data points. The Fourier spectra of this dataset are shown in Figures 1(b)–(k).

![Figure 1.](image)

3. Factors influencing microtremor data collection

3.1. Impact of regular noise on microtremors
In the first experiment, the impact of regular noise on microtremors was studied. To simulate regular noise, we simultaneously cut out microtremor segments from other real datasets recorded from a nearby site which had similar time-frequency characteristics to the experimental data. The length of the cut segments selected were 6000, 12000, 18000, 24000, and 30000 data points, which accounted for 2.86%, 5.72%, 8.58%, 11.44%, and 14.30% of one single trace length, respectively. The amplitudes of the segments were enlarged by 2, 4, 6, 8 and 10 times before used respectively. These two parameters lead to a total of 25 different cases. For all the experiments, we selected the 400s time point of the records to add these noise segments.
Figures 2(a) and (b) show two of the 25 modified experimental datasets, where the datasets in the rectangles are the segments truncated from another record with data lengths of 6000 and 24000 points, respectively. Moreover, their amplitudes were magnified by 2 and 8 times respectively. Figure 2(c) compares the 25 azimuthally-averaged ESAC coherency curves at geophone distance r₄, where the curves have a high degree of coincidence, especially in the main frequency range. For other radii, the data (not shown) were identical to that in Figure 2(c). Figure 2(d) displays the 26 corresponding dispersion curves, including the original one. As is illustrated, the experimental results correspond with the original curve and all the correlation coefficients between the experimental curves and the original curve exceed 0.99. From this experiment we conclude that the impact of regular noise on the dispersion curve is slight if the noise has similar frequency characteristics to that of the microtremor records and if the noise duration does not exceed 15% of the length of a single trace.

### 3.2. Impact of random noise on microtremors

In this section, we study the impact of random noise on microtremors. The experimental procedure was the same as that described above except that the amplitude amplification factors were reduced to 1, 2, 3, 4, and 5 respectively. The random noise segments were computer generated and set to be distinct for different traces. There remained 25 parameter combinations in this experiment. Figure 3(a) shows one of the records, where each trace was suppressed by a 24000-point random noise. Figure 3(b) presents the 25 azimuthally-averaged ESAC coherency curves at geophone distance r₄. In this experiment, all the curves deviate from each other notably. Although in the dominant frequency range the deviation is relatively slight, their coincidences are weak when compared to Figure 2(c). In addition, the deviation becomes more severe with increasing data point numbers and random noise amplitude. The main reason for this finding lies in the serious spectrum damage of the microtremor caused by the random noise.
3.3. Impact of amplitude change of the whole single trace

In practice it is quite common that microtremor records show significant differences in amplitude between different traces. This may be caused by natural factors, equipment failure, improper placement of geophones. In this section we studied how dispersion curves are affected as a microtremor dataset shows no balance in average amplitude among different traces.

In the single-trace cases, the first, second, fifth and ninth geophones were selected. In double-trace cases, geophone pairs were selected according to their distances, e.g., the combination of the first and the second geophones. Amplitude modification included four situations: reduced by two or ten times and amplified by five or ten times. In this study, a total of 24 independent experiments were carried out. Figures 4(a) and (b) exhibits two of the 24 cases. Figure 4(c) shows the 25 (the standard curve is also included) averaged values of the ESAC coherency curves at radius $r_4$; (d) comparison of the ultimate Rayleigh wave dispersion curves of the 24 cases.

Based on the results of this experiment, we concluded that amplitude differences between different traces do not affect the final dispersion curve.
3.4. Replacement of one trace by random noise

In this section, we discuss the consequences when one or more geophones don’t work correctly during data acquisition. First we suppose that only one trace, that has the geophone number 1, 2, 6, and 8 respectively, is invalid, which was replaced by computer-generated random noise in this experiment. Hereafter, for the sake of brevity, modified microtremor records will not be displayed. Figure 5 shows all the ESAC coherency curves of the nine different geophone distances when the first trace (the center of the array) is entirely replaced by random noise. As is illustrated, all values of the three curves at \(r_1\) become zero (also seen at \(r_3\) and \(r_6\)), which should be Bessel functions of varying frequencies. This is because all ESAC coherencies under these three radii were heavily dependent on the first trace, whose replacement by random noise would destroy the related Bessel functions completely. Figures 5(j)–(r) present the nine azimuthally-averaged ESAC coefficients, corresponding to Figures 5(a)–(i), respectively. It is possible that the curves under \(r_1\), \(r_3\), and \(r_6\) are zero-valued, which eventually leads to a distorted dispersion curve.

**Figure 5.** (a)–(i): All the ESAC coherency curves at radii from \(r_1\) to \(r_9\) when the whole-trace microtremor data collected from the center of the array were replaced by random noise; the corresponding azimuthally-averaged coefficients are displayed in (j)–(r).

**Figure 6.** Comparison of the real (original) dispersion curve with dispersion curves when the first, second, sixth and eighth trace of the experimental data were replaced by random noise.

Figure 6 compares the dispersion curves obtained from the four experiments detailed above. In Figure 6(a), the experimental curve completely deviates from the real curve, specifically in the main frequency range. The correlation coefficient between the two curves is as low as 0.2709. In Figures 6(b), (c), and (d), the experimental curves agree well with the real curve; no unacceptable deviation was found. The correlation coefficients were all above 0.98. Based on these results, we can conclude that the geophone in the center of a circular configuration plays a significant role in achieving a high-accuracy dispersion curve. Therefore, during data acquisition, effective data collection by the geophone in the center of a circular array should be ensured. However, if the trace with invalid data was from any of the other geophones, its influence on the dispersion curve was lower than that of the trace from the center geophone; these effects seem to be the same irrespective of which vertex of the geophone was fixed.
3.5. Replacement of two traces by random noise

In this section, two traces were entirely replaced by random noise. In a nested-triangular array configuration, geophones distributed in the same regular triangle have the same status; that is, the number of independent geophone pairs decreases from 45 to 12. Previous research has shown that the replacement of the center geophone results in totally incorrect dispersion curve. Thus there is no need to consider the cases involving the center geophone. Therefore, the final number of independent geophone pairs we should research is on four.

Figures 7(a)–(i) show all the ESAC coherency curves at radii from \( r_1 \) to \( r_9 \), respectively, when the second and fourth traces were replaced by random noise. It is observed that the affected curves distribute at \( r_1 \), \( r_2 \), \( r_4 \), and \( r_7 \). Compared with the previous experiment, the number of influenced radii (four) did not increase. However, the total number of adversely affected curves increased to 15 when only one trace was modified, i.e., 2, 7, 4 and 2, respectively. The percentage of damaged curves at each radius was 66.7%, 77.8%, 66.7%, and 66.7%, respectively, which would leave greater impact on the azimuthally-averaged ESAC coefficients. As shown in Figures 7(j), (k), (m), and (p), the averaged curves at \( r_1 \), \( r_2 \), \( r_4 \), and \( r_7 \) are obviously compressed toward zero from both the positive and negative directions. These distortions of the averaged curves lead to the invalid dispersion curve, as shown in Figure 8(b).

Figures 8(c)–(i) compare the other dispersion curves with the real curve when different geophones pairs are replaced by random noise. No fatal deviation between the experimental dispersion curves and the standard curve can be fund, despite mismatches at some frequencies.

Figure 7. (a)–(i): All ESAC coherency curves at radii from \( r_1 \) to \( r_9 \) when the second and fourth traces were replaced by random noise; the corresponding azimuthally-averaged coefficients are displayed in (j)–(r).

Figure 8. Comparison of the real (original) dispersion curve with dispersion curves of the nine cases where two traces of the raw microtremor data were replaced by random noise.
4. Conclusion
A series of experiments based on field microtremor data were designed and executed to study how the dispersion curve of a fundamental-mode Rayleigh wave extracted from microtremor data is affected by unavoidable factors such as noise, instrument problems and site restrictions. According to the results, we draw some conclusions as follows.

1) If microtremors were contaminated by high-amplitude noise that has a similar Fourier spectrum as the effective data, meanwhile the time duration of the noise does not exceed 15% of a single trace, then the impact of the noise on dispersion curve is slight and may be ignored. 2) If the time duration of random noise is less than 14% of a single trace and the amplitude level is no more than double of the microtremor data, then its impact on the dispersion curve is also negligible. 3) Compared with time duration, amplitude variation has a greater impact on dispersion curve. 4) Simultaneously change amplitude of a single trace has no impact on dispersion curve, which demonstrates that geological information contained within microtremor data does not change with ground surface motion. 5) When multiple-circular array measurements are used, the data collected from the center of the array plays a very important role in the estimation of a reliable dispersion curve. 6) If two abnormal geophones exist within the same array, the greater the distance between them, the more negligible the impact on the results will be.

The above conclusions are specifically based on a circular array configuration and as such they may not be applicable to other configuration shapes. In addition, although several other major factors that may affect dispersion curves were considered, it was not practical to test for all these scenarios. Future research efforts will focus on more diverse and thus complicated array configurations.

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