A Superior Seismic Data Preprocessing Technique to Improve the Resolution of Surface wave Velocity Spectrums

Tarun Naskar (tarunnaskar@iitm.ac.in)
Indian Institute of Technology Madras
Mrinal Bhaumik
Indian Institute of Technology Madras
Sayan Mukherjee
Indian Institute of Technology Madras

Research Article

Keywords: high-resolution surface wave velocity spectrum, dispersion image, seismic survey

Posted Date: July 15th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-712071/v1

TITLE PAGE

A superior seismic data preprocessing technique to improve the resolution of surface wave velocity spectrums

Tarun Naskar[1]*, Mrinal Bhaumik[1+] and Sayan Mukherjee[1+]

[1]Indian Institute of Technology, Madras-600036, India.

Email: tarunnaskar@iitm.ac.in *

[+]these authors contributed equally to this work

A superior seismic data preprocessing technique to improve the resolution of surface wave velocity spectrums

Abstract

A high-resolution surface wave velocity spectrum, also known as dispersion image, is of paramount importance for any seismic survey to accurately predict subsurface earth's properties. The presence of diversified noise in the field acquisition and dissimilar attenuation due to mechanical and radial damping makes it challenging for different wavefield transformation algorithm to produce a detailed and precise velocity spectrum. Standard seismic data preprocessing technique like trace normalisation or bandpass filter fails to address all issues appropriately. Here we have presented a new superior preprocessing technique that can eradicate most of the shortcomings adequately. Experimental field data and published results are used to demonstrate the accuracy of the proposed method. The proposed method also found to produce superior results when compared against the popular commercially available software package Surfseis 6. Overall, the proposed method improves the quality of the velocity spectrum significantly, and it produces a sharper dispersion image even for the extremely noisy data. The work presented here enhances our ability to interpret the surface wave data precisely and help explore accurate properties of the subsurface earth.

Introduction

Surface waves such as Rayleigh or Love waves get generated in the elastic half space from disturbances due to natural events like earthquake, tsunami, landslide etc., or from disruption due to man made events like blasting, construction activities and vehicular movements. The Rayleigh wave attenuates much slowly compared to body waves but carries almost 67% of the source's input energy[1]. Therefore, surface waves are an excellent choice for exploring the earth's properties up to a shallow depth. The surface waves based tests are relatively simple, non destructive in nature, cost-effective and considerably faster when compared to conventional testing methodologies like SPT, seismic cross-hole, up-hole and down-hole test etc. The surface wave testing technique can be divided into three major parts: namely, i) the acquisition of experimental field record with the help of geophones, ii) processing the field data to obtain the experimental dispersion image, and iii) performing inverse analysis to predict the subterranean earth's properties[2–4]. Many wavefield transforms available to generate high resolution multimodal dispersion image from the field seismogram data with varying degree of accuracy. The two dimensional Fourier transform or frequency-wave number (*f-k*) transform[5], the slant stack transform or time intercept-phase slowness (τ-p) transform[6], Park's wave field transform or phase shift method (ω–c)[3] and high-resolution linear Radon transform (HRLRT)[7], are few prominent ones. Park's ω–c method is currently the most popular choice among researchers due to its high accuracy[3] and ability to generate relatively high-resolution dispersion plots especially when limited numbers of traces and offset range is used[3,8–10]. The *f-k* transform and, to an extent, the τ-p transform has broader application and are readily available as an inbuilt toolbox among all the coding platforms. Past researchers have demonstrated the phase-shift method's superiority over *f-k* and τ-p transform[3,8,9]. Even after applying different processing techniques, *f-k* and τ-p transform failed to produce a velocity spectrum on par with the phase-shift method[3,8]. A relatively recent development is high-resolution linear Radon transform (HRLRT) which reported producing a relatively sharper velocity spectrum than the phase shift method [7,11,12]. However, the HRLRT is a computationally expensive method and it also struggles when poor quality data is used. To this end, we propose a superior seismic data preprocessing technique that can be easily implemented for any wavefield transformation method. The potential outcomes are, (i) the proposed technique normalises each traces against dissimilar attenuation due to mechanical and radial damping, (ii) superior handling of field data contaminated by noise, and (iii) it eliminates the primary shortcomings associated with different wavefield transformation algorithm, thus produces superior velocity spectrum. The proposed technique is simple, and it can be easily implemented. To illustrate the efficacy of the proposed technique, experimental and published results were compared. The proposed method produced a significantly better result for the *f-k*, τ-p method even for the extremely noisy data. Furthermore, using HRLRT, the proposed method produced a superior result against the latest version of commercially available software Surfseis 6, which uses its own processing tool and traditional trace normalisation. The proposed scheme unable to improve the quality of the dispersion image for the phase shift method, which is known to be insensitive towards the data preprocessing technique[8].

Improvement for *f-k* and τ-p method

The present consensus among geophysicists is that the ω–c method generates far superior dispersion image compared to *f-k* transform and τ-*p* transform. Against this long-cherished belief, the proposed preprocessing technique enables the *f-k*, τ-*p* method to produce a dispersion image on par with the ω–c method. To demonstrate the effectiveness of the proposed preprocessing technique, velocity spectrums published by Dal Moro *et al.*[8] are compared with velocity spectrums obtained using the proposed approach (Fig. 1). The original seismogram was digitised to reproduce the published results, and the velocity spectrums were reconstructed using our own Matlab code. Dal Moro *et al.*[8] compared the efficacy of the different data preprocessing techniques such as trace normalisation, high pass filter, lowpass filter and bandpass filter using the three most popular wavefield transformation algorithms, namely, *f-k* transform, τ-*p* transform and Park's ω–c method. They had used 24 channel common receiver shot data with a source to first sensor distance of 5m and sensor spacing of 2m. Dal Moro *et al.*[8] observed that the ω–c method outperformed the other two wavefield transform algorithm and generated the best quality velocity spectrums in terms of accuracy. In

Fig. 1 we have compared the result published by Dal Moro *et al.*[8] with the result obtained using the proposed preprocessing technique. For *f-k* and *τ-p* transform, the proposed method significantly improves the quality of the velocity spectrum. By implementing preprocessing technique proposed in this paper, both *f-k* and *τ-p* transform produced velocity spectrums on par with Park's *ω–c* method. Furthermore, Dal Moro *et al.*[8] reported that compare to *ω–c* method the *f-k* and *τ-p* method suffers from spatial aliasing and noises, which leads to ambiguous interpretation. Using the proposed approach, we have observd no sign of such spatial aliasing and noises are relative low. Dal Moro *et al.*[8] also concluded that Park's phase shift transform is poorly sensitive to any data preprocessing technique. For Park's phase shift algorithm, trace normalisation and the proposed approach produced identical velocity spectrum (Fig 1a,b). This outcome is in accordance with the observation made by Dal Moro *et al.*[8]

Superior preprocessing of noisy data

In the seismic field data acquisitions, noise contamination is an unavoidable issue that can occur due to low energy sources, non-source generated waves, defect in sensors, faulty connections etc. Each of these issues will affect the individual traces and corresponding seismic data uniquely. The proposed method can effectively preprocess the noisy data better than any methods currently in use. To demonstrate the efficacy of the proposed approach, 48 channel common receiver shot gathered with the help of 4.5 Hz vertical geophones was employed. The source was kept at a distance of 2.5m from the first sensor and 0.5 m sensor spacing was used. Different types of field noises are added on 12 randomly selected traces to represent assorted noisy field acquisitions on the ground. The velocity spectrum for this noisy acquisition is generated using the *τ-p* method with the help of the proposed preprocessing technique and trace normalisation technique. Finally, velocity spectrums for original and noisy data are compared (Fig. 2). As expected, the proposed method produced a superior result than the trace normalisation method for both initial acquisitions and noisy data. However, it is noisy data where the proposed method notably outperforms the trace normalisation method (Fig. 2c,d). For noisy data with trace normalisation, only a few modes are visible and the modes are not clearly distinguishable. On the other hand, the proposed method produced a velocity spectrum more or less similar to velocity spectrums without noise. Almost all the seven modes are visible and they are clearly distinguishable. The dispersion image created using the proposed method for noisy data is marginally superior to the dispersion image produced using trace normalisation for original data without noise. From the dispersion image produced using the proposed method, the fundamental mode and first mode can be separately identified, while it is not possible in the case of trace normalisation. The results indicate that the proposed technique is promising. It is worth mentioning that no frequency filtering technique such as low pass, high pass or bandpass filter is used to obtain the present results.

Similar results can be obtained for the *f-k* and HRLRT method, but we have not included them in the present manuscript due to the limitation on the number of display items.

Improvement for HRLRT method

The previous sections' results are a clear indicator of the significant improvements over the conventional data preprocessing technique. In addition to these popular algorithms, we tested our method against the latest commercially available software package, Surfseis 6. The Sursfeis is one of the most popular and frequently used software and 6 indicates the latest release which incorporates the HRLRT algorithm and trace normalisation. The HRLRT method is arguably the most advanced wavefield transform and it generates the highest quality velocity spectrum[7,11–13]. Using our experimental data, we have compared the proposed data processing technique's efficacy for the HRLRT method. Fig. 3a represents the velocity spectrum produced using Surfseis 6 with HRLRT and trace normalisation, Fig. 3b illustrates the velocity spectrum produced by HRLRT and trace normalisation using our Matlab code and finally, Fig. 3c represent the velocity spectrum produced by HRLRT with the proposed method using our own Matlab code. The proposed preprocessing technique produced the best quality velocity spectrum, while Surfseis produced relatively an inferior quality velocity spectrum. The velocity spectrum produced by Surfseis has lots of noise, especially at higher frequencies and between 0 to 500m velocity ranges. Moreover, the different propagation modes are not clearly identifiable and separable. Our HRLRT code using trace normalisation produced a relatively better quality velocity spectrum compared to Surfseis; with no visible noises present, different modes are identifiable and separable except a few. Our HRLRT code with the proposed preprocessing technique produced the best quality velocity spectrum. There are no visible noises present; all the modes are clearly identifiable and separable. It should be noted that Surfseis software does not display different preprocessing technique they have used while implementing the HRLRT algorithm. For Surfseis, we have used the default integrity factor value of 2 as it produced the best possible results.

Conclusions

A new seismic data preprocessing technique is proposed to process noisy field data and compensate for the losses due to mechanical and radial damping. The accuracy of the proposed approach has been demonstrated using published results as well as using experimental data. The present method works well with all the available wavefield transform algorithms except ω–c method. In agreement with the literature, the present study found that the ω–c method is poorly sensitive to the data preprocessing technique. It is noted that the proposed approach improves the quality of the dispersion image significantly when compared to a traditional preprocessing technique like trace normalisation. The present method produced a sharper velocity spectrum containing multiple easily separable modes with little to no noise. The proposed method performs better than the latest commercially available software package, Surfseis 6. Overall, the seismic data preprocessing technique proposed in this paper will help in producing sharper dispersion image and predicting accurate layer properties of subsurface earth.

Methods

Although the traditional trace normalisation improves the dispersion image quality by compensating losses due to radial damping, it can not compensate for the mechanical damping. The mechanical damping tends to dissipate the energy through molecular friction inside the material. Unlike radial damping, which affects the wave as per distance travelled, mechanical damping effects the wave as per the number of the cycle completed while travelling unit distances. As the higher modes or high frequency wave has to complete more number cycle for travelling the same lengths, mechanical damping affects them severely. The traditional data preprocessing techniques are ineffective against these type of energy losses. Furthermore, the traditional techniques perform poorly for high noise contaminated data. In this paper, we have proposed a new seismic data preprocessing technique that normalises the traces in such a way that the energy losses due to radial damping and mechanical damping can be compensated. It also suppresses the noise present in the data more effectively. Furthermore, the proposed method preserves the phase information of each frequency; thus, it can be applied to all the available transformation techniques. Let $u(x,t)$ is the seismogram data in the distance (x) - time (t) domain . The proposed normalisation technique can be achieved by reconstructing the data in the following way :

$$U(x,t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\left[\int_{-\infty}^{+\infty}\frac{u(x,t)}{\left|\int_{-\infty}^{+\infty}u(x,t)e^{-i\omega t}dt)\right|}e^{-i\omega t}dt\right]e^{i\omega t}d\omega \quad (1)$$

where the circular frequency $\omega = 2\pi f \ and \ i = \sqrt{-1}$. In the above expression, $U(x,t)$ is the normalised form of the original data $u(x,t)$. To generate the dispersion image for different wavefield transform, one need to use $U(x,t)$ instead of $u(x,t)$. Fig. 4 represents the seismogram corresponds to original data, trace normalised data and data processed using the proposed method. From these images (Fig. 4), we can observe that, compared to the original seismogram, trace normalisation amplifies the signal associated with the furthest sensor while the proposed method does the best job. The trace normalisation can only raise the amplitude of the dominating waves travelling close to median velocities, while the proposed method can augment the amplitude of waves travelling with the entire velocity spectrum. Therefore, the proposed method can obtain an enhanced dispersion image with low noise.

Data availability

All the data used for this research fndings are available and can provided based on the request to the corresponding authors.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Ministry of Human Resource and Development, Govt. of India. Grant No. SB20210856CEMHRD008957.

Reference

1. Miller, G. . & Pursey, H. On the partition of energy between elastic waves in a semi-infinite solid. *Proc. R. Soc. London. Ser. A. Math. Phys. Sci.* **233**, 55–69 (1955).
2. Tokimatsu, K., Tamura, S. & Kojima, H. Effects of Multiple Modes on Rayleigh Wave Dispersion Characteristics. *J. Geotech. Eng.* **118**, 1529–1543 (1992).
3. Park, C. B., Miller, R. D. & Xia, J. Imaging dispersion curves of surface waves on multi-channel record. in *SEG Technical Program Expanded Abstracts 1998* 1377–1380 (Society of Exploration Geophysicists, 1998). doi:10.1190/1.1820161.

4. Kumar, J. & Naskar, T. A fast and accurate method to compute dispersion spectra for layered media using a modified Kausel-Roësset stiffness matrix approach. *Soil Dyn. Earthq. Eng.* **92**, 176–182 (2017).

5. Yilmaz, Ö. *Seismic Data Analysis*. *Seismic Data Analysis* (Society of Exploration Geophysicists, 2001). doi:10.1190/1.9781560801580.

6. McMechan, G. A. & Yedlin, M. J. Analysis of dispersive waves by wave field transformation. *GEOPHYSICS* **46**, 869–874 (1981).

7. Luo, Y., Xu, Y., Liu, Q. & Xia, J. Rayleigh-wave dispersive energy imaging and mode separating by high-resolution linear Radon transform. *Lead. Edge* **27**, 1536–1542 (2008).

8. Dal Moro, G., Pipan, M., Forte, E. & Finetti, I. Determination of Rayleigh wave dispersion curves for near surface applications in unconsolidated sediments. in *SEG Technical Program Expanded Abstracts 2003* vol. 22 1247–1250 (Society of Exploration Geophysicists, 2003).

9. Park, C. B. Imaging dispersion of MASW data - Full vs. Selective offset scheme. *J. Environ. Eng. Geophys.* **16**, 13–23 (2011).

10. Naskar, T. & Kumar, J. A faster scheme to generate multimodal dispersion plots for Rayleigh wave propagation. *Soil Dyn. Earthq. Eng.* **117**, 280–287 (2019).

11. Luo, Y. *et al.* Rayleigh-wave mode separation by high-resolution linear Radon transform. *Geophys. J. Int.* **179**, 254–264 (2009).

12. Shen, C., Wang, A., Wang, L., Xu, Z. & Cheng, F. Resolution equivalence of dispersion-imaging methods for noise-free high-frequency surface-wave data. *J. Appl. Geophys.* **122**, 167–171 (2015).

13. Ivanov, J., Miller, R., Feigenbaum, D. & Schwenk, J. Benefits of using the high-resolution linear Radon transform with the multichannel analysis of surface waves method. in *SEG Technical Program Expanded Abstracts 2017* 2647–2653 (Society of Exploration Geophysicists, 2017). doi:10.1190/segam2017-17793766.1.

FIGURE CAPTIONS

Fig. 1| Comparison of the velocity spectrum obtained by, a, Phase shift transform with trace normalization (Dal Moro et al.). b, Phase shift transform with proposed normalization. c, f-k transform with trace normalization (Dal Moro et al.). d, f-k transform with proposed normalization. e, τ-p transform with trace normalization (Dal Moro et al.). f, τ-p transform with proposed normalization.

Fig. 2| Dispersion image obtained by τ-p transform for, a, Original data with proposed normalization. b, Original data with trace normalised. c, Noisy data with proposed normalization. d, Noisy data with trace normalization.

Fig. 3| Dispersion image by HRLRT method using, a, Surfseis software with trace normalization. b, Our own HRLRT code with trace normalization. c, Our own HRLRT code with proposed normalization.

Fig. 4| 48 channel common shot gather. a, Recorded field seismogram. b, Trace normalised seismogram. c, Seismogram obtained after employing the proposed normalization.

Figures

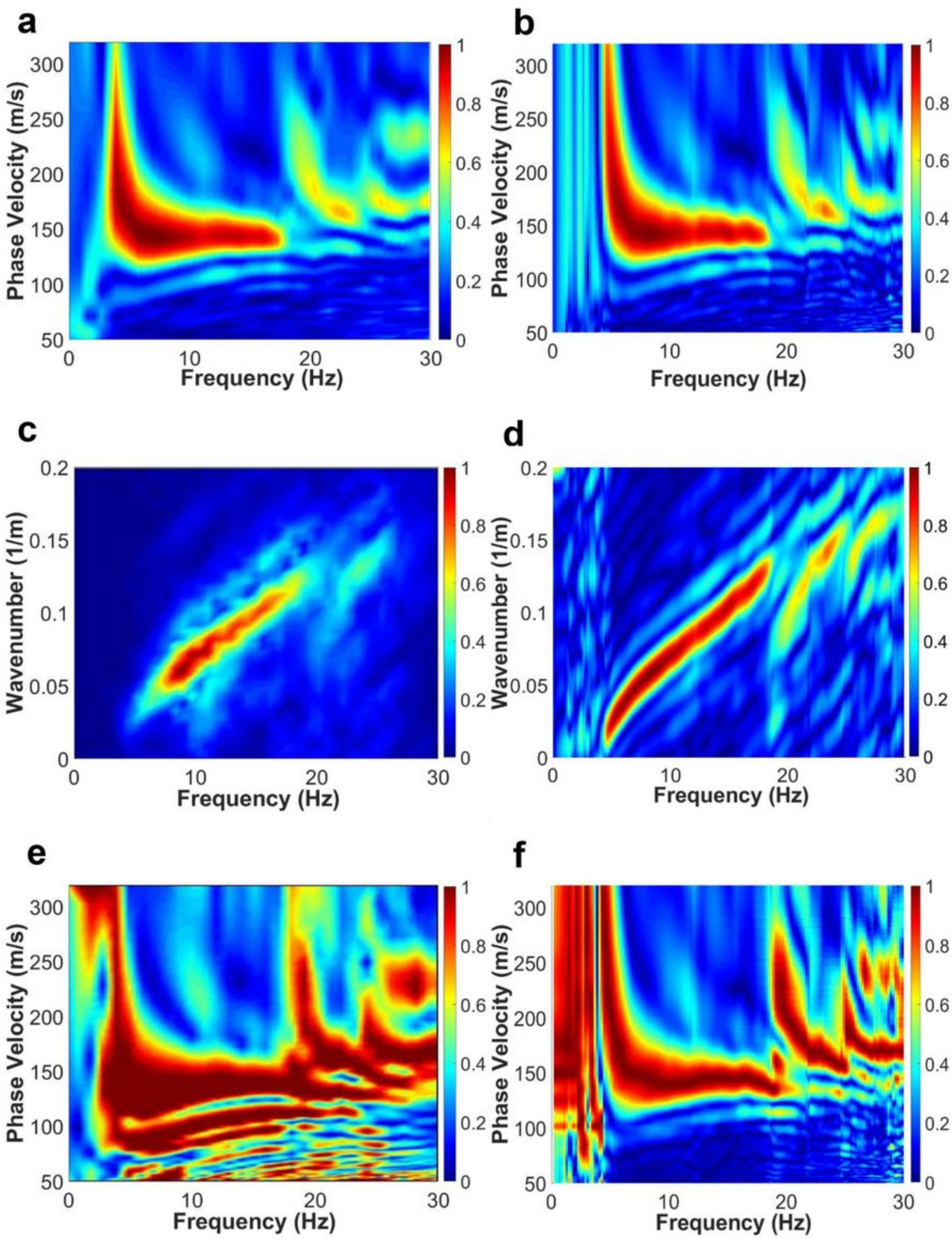

Figure 1

Comparison of the velocity spectrum obtained by, a, Phase shift transform with trace normalization (Dal Moro et al.). b, Phase shift transform with proposed normalization. c, f-k transform with trace normalization (Dal Moro et al.). d, f-k transform with proposed normalization. e, τ-p transform with trace normalization (Dal Moro et al.). f, τ-p transform with proposed normalization.

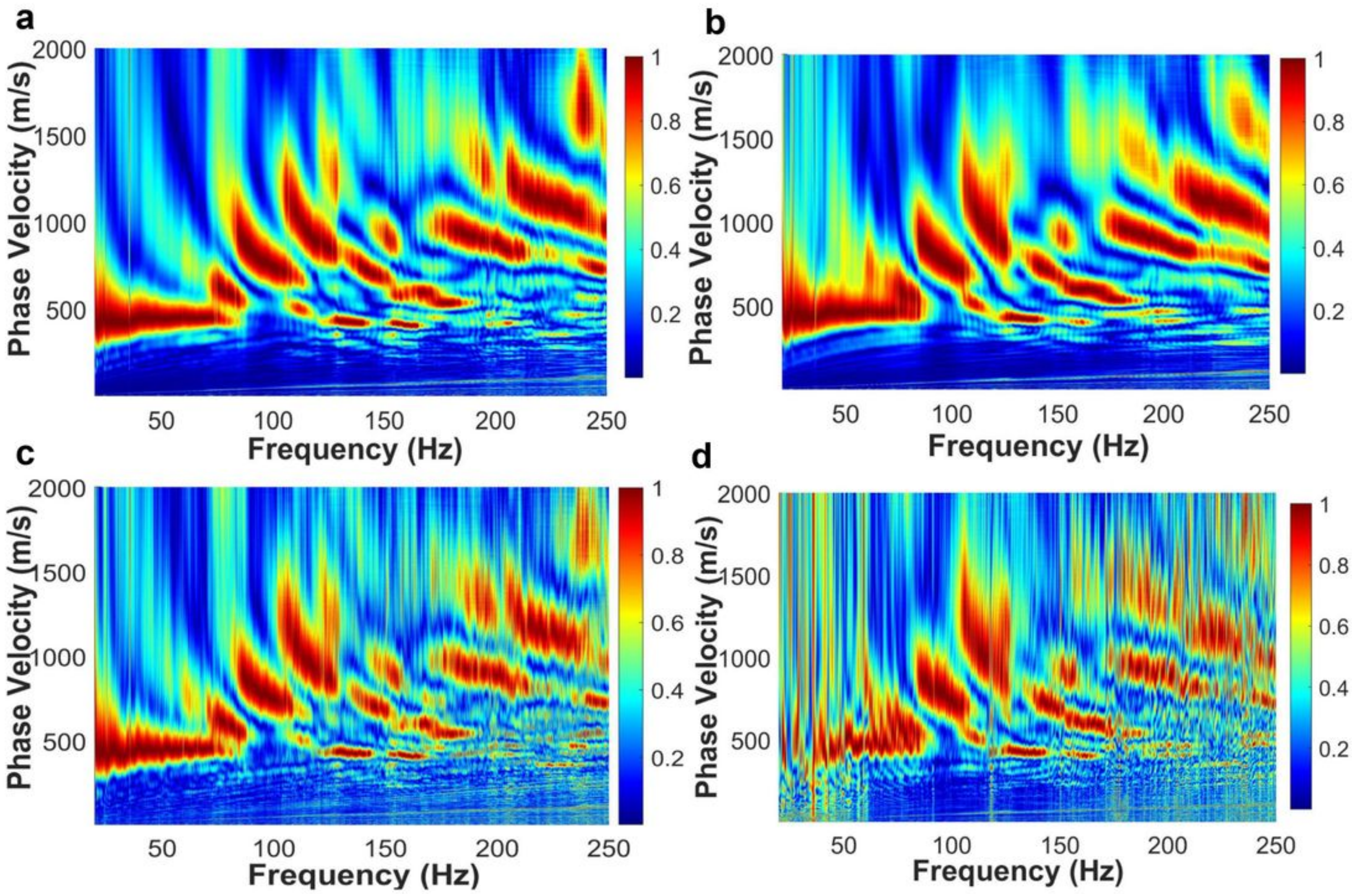

Figure 2

Dispersion image obtained by □ – □ transform for, a, Original data with proposed normalization. b, Original data with trace normalised. c, Noisy data with proposed normalization. d, Noisy data with trace normalization.

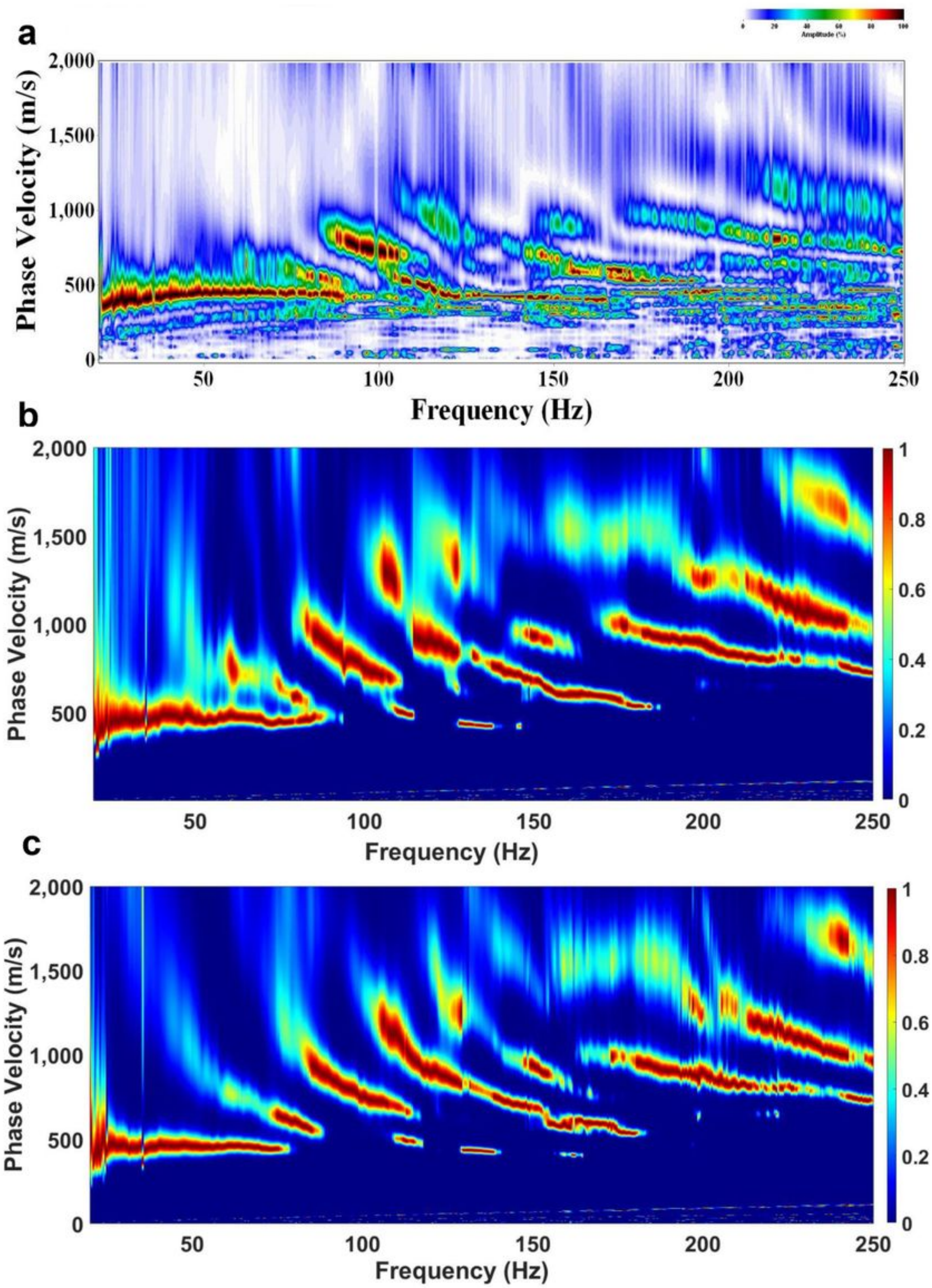

Figure 3

Dispersion image by HRLRT method using, a, Surfseis software with trace normalization. b, Our own HRLRT code with trace normalization. c, Our own HRLRT code with proposed normalization.

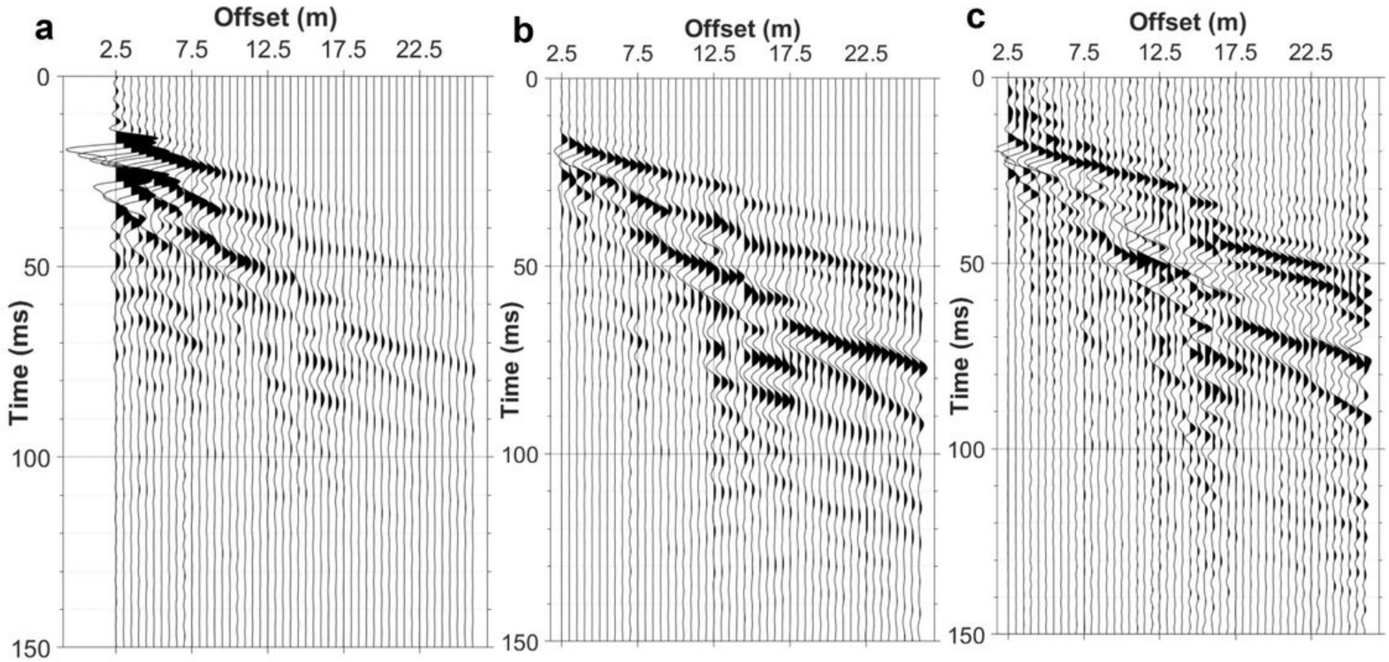

Figure 4

48 channel common shot gather. a, Recorded field seismogram. b, Trace normalised seismogram. c, Seismogram obtained after employing the proposed normalization.