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An innovative method for computing static corrections using seismic reflection horizons analysis

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Abstract

Seismic exploration faces significant challenges due to the physical parameters and geometric complexity of near-surface layers, making their modeling essential for accurately calculating static corrections. These corrections are crucial for preserving the image of geological structures represented by seismic reflectors. However, obtaining key physical parameters, such as the replacement velocity of the substrate and the velocities and thicknesses of near-surface layers, remains challenging. This study proposes a novel approach that addresses the issue in an alternative way. The innovative calculation method allows the direct computation of static corrections, relying solely on the structural analysis of seismic horizons in the near-trace section. Notably, this approach does not require prior knowledge of the weathered zone model. The application of this method to both simulated and real reflection seismic data demonstrates its potential and effectiveness. The static corrections derived from this approach significantly improve seismic image quality and eliminate abnormal regional static corrections compared to calibrated refraction static corrections. Furthermore, this method does not require calibration with borehole data, simplifying the process and representing a significant advantage over traditional methods. In summary, this innovative approach provides an effective solution to the challenges of near-surface layer modeling, delivering substantial improvements quantitatively—through time and effort savings, and reduced error—and qualitatively by enhancing data quality, ensuring consistency with geological realities, and enabling more reliable geological interpretations.

Keywords: Static corrections; Weathered zone model; Near-surface layers; Near-surface structures; Near-trace section; Seismic horizons; Frequency decomposition

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1. Introduction

In seismic exploration, the heterogeneity and anisotropy associated with velocity variations, along with the geometric and lithological complexity of near-surface layers, significantly influence the arrival times of seismic waves. As a result, these factors affect imaging characteristics such as continuity, coherence, resolution, and particularly the shape of seismic horizons and the geological information obtained.[1-4]

Computing static corrections is a processing operation that involves aligning the source and receiver points on the same reference plane. This is achieved by filling the gap between the datum plane and the bedrock of low-velocity layers with a replacement velocity close to or equal to that of the consolidated layer.[1,4]

The refraction statics method is the most commonly used approach for determining static corrections in seismic processing centers. It calculates statics by modeling near-surface layers, a process that remains challenging. Existing methods utilize the travel times of refracted waves to generate a model of the weathered zone (WZ) for computing static corrections. However, these refraction statics methods require picking the first arrivals on seismic reflection records, which consumes time and necessitates significant human intervention.[5-9]

Near-surface structures often coexist with low-quality first arrivals, particularly in scenarios involving complex geometries, which complicates the picking process.[10] Constructing accurate surface models requires high-quality first arrivals; however, results from the refraction method based on these data are not always satisfactory. Therefore, calibrating static corrections with borehole information is essential to achieve reliable values.[11] In regions with poor-quality refractors and terrestrial areas with intricate surface features, the correction process is often complicated, making it time-consuming. To tackle these challenges, automatic picking techniques for first arrivals have been developed.[12-16] However, low-quality first arrivals frequently coincide with complex near-surface structures, further complicating the picking procedure.[10,17] In addition, surface conditions and the characteristics of the near-surface layer—such as heterogeneity, anisotropy, discontinuities, geological uplifts, velocity inversions, and variations in interface shape and dip—affect the recorded refraction waves. These factors contribute to the difficulties in modeling the WZ.[1,4]

The challenges faced when using refracted waves from reflection seismic acquisition underscore the limitations of static refraction corrections and raise the question of whether these first arrival waves are truly suitable for modeling the WZ.

In this work, we introduce a novel technique for computing primary static corrections from the travel time of reflected waves, eliminating the need for first arrival picking and the requirement to model the WZ. This technique utilizes near-trace sections to facilitate the rapid and straightforward identification of seismic horizons (reflectors) affected by static anomalies. The potential, performance, and effectiveness of this method are confirmed and validated through its application to simulated data, followed by real seismic data.

It is well established that one of the quality control procedures for static corrections involves verifying the data from seismic sections post-stacking.[11] Using this criterion, the quality control was conducted on seismic profile data measuring 68 km, characterized by clearly variable surface conditions and morphology.

The seismic sections of the profile were processed using two static correction solutions: the proposed technique and the diminishing residual matrices (DRM) refraction statics method.[18] A comparison of the results was then performed on both obtained seismic sections.

This comparison demonstrates that the proposed method significantly reduces the errors associated with the DRM approach. Consequently, the results highlight the advantages of this new technique and provide a comprehensive evaluation of its impact on the interpretation of seismic data.

2. Methodology

Sedimentary basins have generally undergone multiple tectonic phases, significantly altering sedimentation patterns and basin morphology. The impact of tectonic forces on the formation and evolution of geological layers and sedimentary environments highlights the geological deformations from the Paleozoic to the Cenozoic eras.[19-26] Consequently, geological layers did not form simultaneously. These layers have experienced syn-sedimentary deformations, resulting in geological interfaces that are globally uncorrelated and linearly independent of one another. This characteristic serves as a valuable criterion for evaluating the accuracy of the structural image represented by the seismic reflection horizons in the near-trace section.[27] Thus, in a zero-offset seismic section without applied static corrections, it can be observed that all seismic horizons, from top to bottom, are influenced by the same deformation. This deformation manifests as a common curve among the seismic horizon curves in the zero-offset seismic section, corresponding to the total static corrections. Consequently, calculating this common curve provides the requisite static corrections for accurate interpretation.[28]

This study aims to extract this common curve, or common solution, from the seismic horizons selected on the near-trace section. The principle of the method is illustrated on simulated data, corresponding to a geological model with three synthetic horizons, before and after removing the common curve (Figure 1).

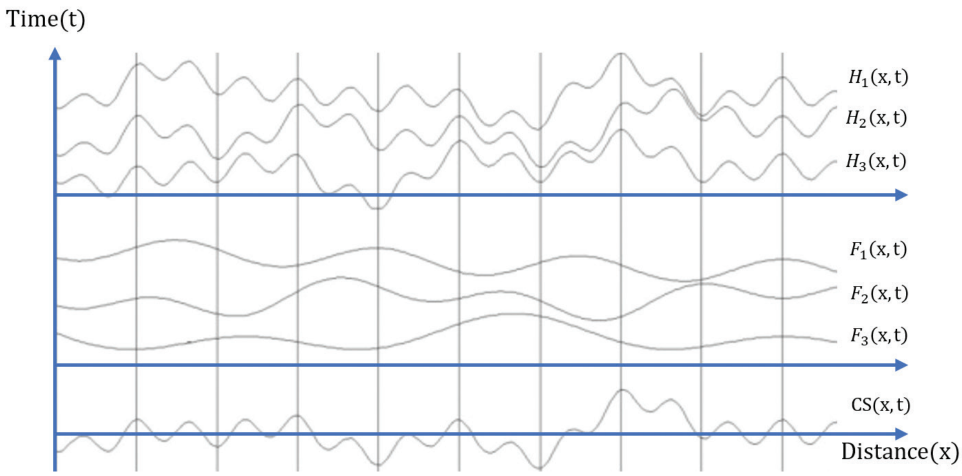

Figure 1. Synthetic model of seismic horizons on the near-trace section, with and without effects of elevation and near-surface layers.
Abbreviation: CS: Common solution.

$$\begin{cases} H_1(\mathrm{x},\mathrm{t}) = F_1(\mathrm{x},\mathrm{t}) + CS(x,t) \\ H_2(\mathrm{x},\mathrm{t}) = F_2(\mathrm{x},\mathrm{t}) + CS(x,t) \\ H_3(\mathrm{x},\mathrm{t}) = F_3(\mathrm{x},\mathrm{t}) + CS(x,t) \end{cases} \quad \text{(I)}$$

In Equation I, H_1, H_2, and H_3 refer to the horizons before application of static corrections (time geological model), F_1, F_2, and F_3 refer to the horizons after application of static corrections, CS refers to the common solution (static corrections model), and (x, t) is the spatiotemporal localization.

The process applied the Fourier transform to the mathematical functions representing the horizon curves selected on the seismic section of the near-trace section into several frequency classes.[4,27-29] Then, these frequency classes were constructed and used as matrix data to calculate the separation operator matrix and, consequently, the common solution curve, $CS(x, t)$.

The computational procedure employed by the proposed method for calculating static corrections is summarized in Table 1.

Table 1. The algorithm to calculate static correction using seismic reflection horizons

Input	Data input and preprocessing
1	Construction of a near-trace seismic section with no applied static corrections
2	Selection of significant seismic horizons
3	Spectral decomposition of selected horizons
4	Matrix computing
4.1	Construction of a binary matrix, the "separation operator," by normalizing and stacking all the frequency classes
4.2	Obtaining the common matrix through outer multiplication of the separation operator with each decomposed horizon
4.3	The common curve is the stacking of all columns of the common matrix
4.4	The total statics curve is obtained by averaging stacks of all common curves
End	Separation of source and receiver statics

3. Results

3.1. Application to simulated data

To demonstrate the potential of the suggested technique, it was applied to simulated data.[30-33] For this purpose, a four-layer model was constructed and a known static anomaly containing high- and medium-frequency components was introduced. The obtained results are shown in Figures 2 and 3. The separation operator was applied to all the decomposed selected horizons. The obtained curves of the common solutions were consistent and comparable (Figure 3). The average stack of all common solutions was considered to improve the solution accuracy.

The effectiveness of the method was further validated through a comparison of the original (theoretical) static model and the static corrections calculated post-separation. This comparison revealed a negligible discrepancy between the two curves, as illustrated by the error curve (Figure 4). In addition, the successful application of this method on simulated data confirmed its high calculation accuracy, highlighting its reliability and potential for application to real seismic data processing.

3.2. Application to real data

The shape of the time seismic horizons in the near-trace section indicated good geological interfaces deformed by

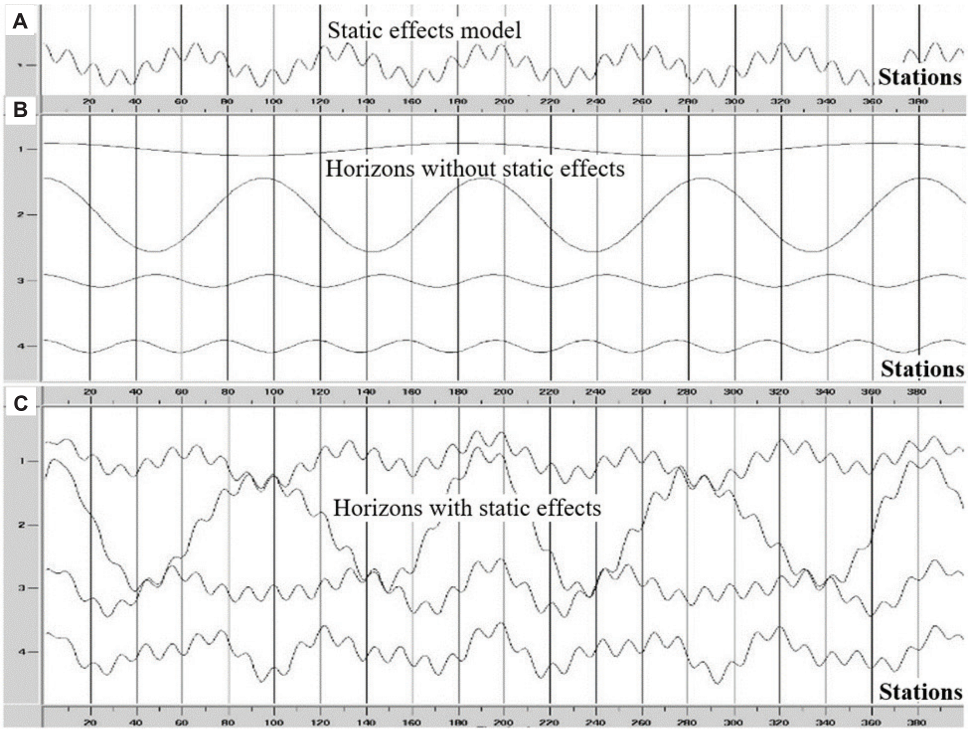

Figure 2. Model of synthetic seismic horizons on near-trace section. (A) Static anomalies model at 15 Hz, summing to 90 Hz. (B) Horizons unaffected by statics at 5 Hz, 10 Hz, 20 Hz, and 25 Hz. (C) Horizons with static effects.

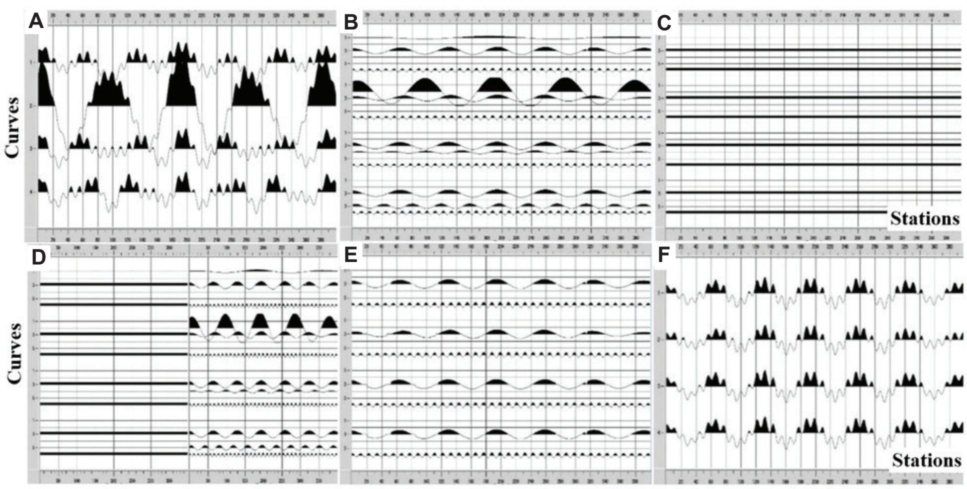

Figure 3. Graphical illustration of the static correction process, showing the decomposed horizons, the separation operator, and the common solution pre-stack and post-stack curves. (A) The geological model is affected by static effects. (B) Decomposed horizons. (C) Separator operator. (D) Operator versus decomposed horizons. (E) Common components. (F) Computed statics model.

the effects of surface elevation and the properties of the near-surface layers (Figure 5). A near-trace seismic section was constructed by selecting the near-offset traces without applying static corrections, using data that had already been preprocessed (Figures 5 and 6). Five seismic horizons were identified and picked from top to bottom (Figure 5).

The common curve was determined based on the spectral decomposition of seismic horizons selected on a near-trace section. The elementary decomposition of each seismic horizon curve was performed within a common frequency band, established through the spectral frequency analysis of all horizon curves.

The curves were converted into traces with an inter-common medium point of 12.5 m, and the sampling rate was set to 2 ms to adapt to the frequency range (0.1–60 Hz) for software processing (Figure 7). High frequencies

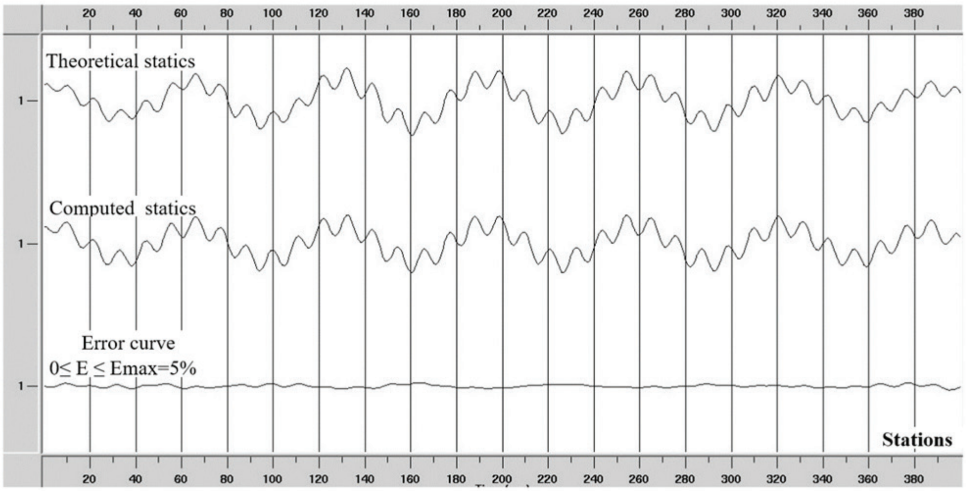

Figure 4. Comparison between the theoretical static model and the computed static corrections. The error curve indicates a maximum deviation of 5% (Emax=5%).

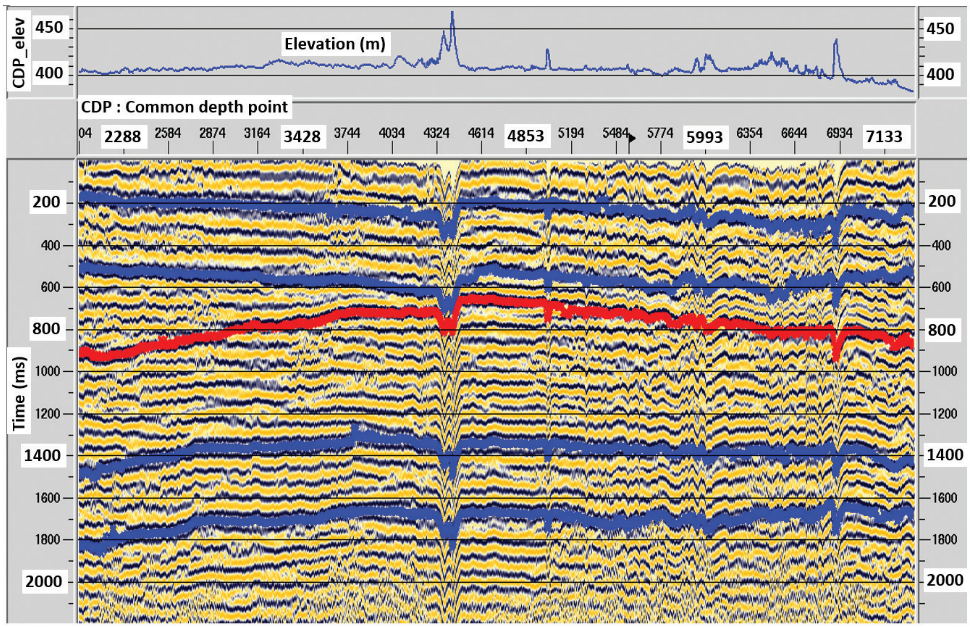

Figure 5. Seismic reflection horizons interpreted on the near-trace section without applying static corrections.

exhibited low amplitudes, which helped determine the maximum frequency limit for effective processing. The frequency analysis of each horizon revealed that high-frequency components have low amplitudes (Figure 7E), aiding in determining the optimal maximum frequency and the overall frequency band for the subsequent elementary frequency decomposition (Figures 7 and 8).

Each curve was decomposed into elementary frequencies and sorted into frequency classes. The selected horizon curves, non-stationary signals, were individually decomposed using the short-time Fourier transform and then categorized into their respective frequency classes (Figure 9).

Each elementary trace was normalized, and a separation operator matrix was constructed. The common curve was then obtained by multiplying the operator matrix by each decomposed horizon matrix. The total statics curve was calculated as the average stack of all resulting curves. The common curve, derived from all horizons, was generated through element-by-element matrix multiplication of the normalized frequency elementary components, followed by summation to produce a common global solution curve (Figure 10).

When applied to all selected horizons, the operator matrix yielded consistent and comparable results with

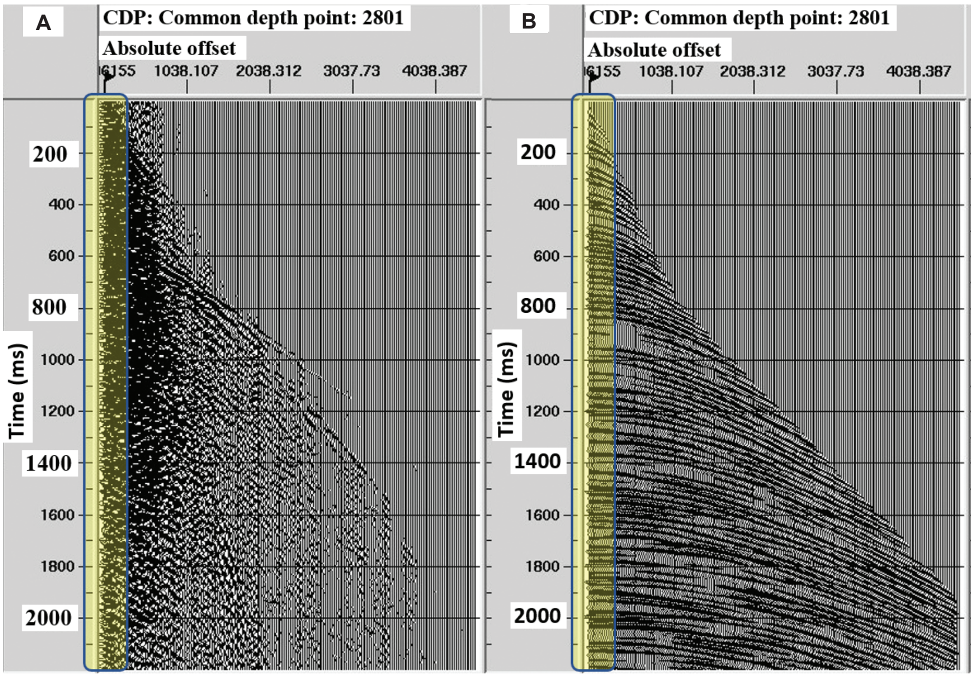

Figure 6. CDP gathers traces. (A) Raw CDP gather traces compared to (B) filtered CDP gather traces, illustrating the enhancement in signal clarity following preprocessing.
Abbreviation: CDP: Common depth point.

acceptable accuracy (Figure 10). To enhance the precision of the total static correction, the average of all common solution curves was computed (Figure 11).

An approximate calculation (Equations II–IX) was proposed to separate the source and receiver static corrections from the total static corrections using the elevations of the source and receiver to deduce a mean velocity. It considers the difference between source and receiver elevations, as well as the mean elevation of the entire seismic line (Z_{mean} = 400 m in this case) (Figures 12 and 13).

$$\delta_z = Z_r - Z_S \quad \text{(II)}$$

where δ_z is the difference between source and receiver elevations (in m), Z_s is the source elevation (in m), and Z_r is the receiver elevation (in m).

$$Z_m = (Z_S + Z_r)/2 \quad \text{(III)}$$

where $Z_m = Z_{CMP}$, in which Z_m is the mean elevation between the source and the receiver (in m), also referred to as the common midpoint elevation (Z_{CMP}). Z_{CMP} is the elevation of the common medium point between the source and the receiver (in m).

$$V_m = 2\,(Z_m - Z_{mean})/CS_T \quad \text{(IV)}$$

Where V_m is the average velocity between the mean elevation Z_m and the reference elevation Z_{mean}.

$$\delta_T = {}^{\delta_z}\!/_{V_m} \quad \text{(V)}$$

where δ_T is the time difference between the source and the receiver static corrections (in s).

$$CS_T = 2\,(Z_m - Z_{mean})/V_m \quad \text{(VI)}$$

where CS_T is the total static correction (in m), and Z_{mean} is the mean elevation of the entire seismic line (400 m).

$$CS_T = CS_S + CS_R \quad \text{(VII)}$$

$$CS_S = (CS_T - \delta_T)/2 \quad \text{(VIII)}$$

$$CS_R = CS_T - CS_S \quad \text{(IX)}$$

Where CS_s is the source static correction, and CS_R is the receiver static correction.

We present a novel technique for computing static corrections directly from the travel times of reflected waves. This approach calculates total static corrections by identifying seismic reflection horizons on the near-trace section. The static corrections for both the source and the receiver are derived from elevation values. To illustrate the effectiveness and efficiency of this method, the results were compared with those obtained from refraction statics based on the DRM method (Figures 14-17).

The suggested technique was applied to a 68-km seismic profile, and the results obtained were compared to those

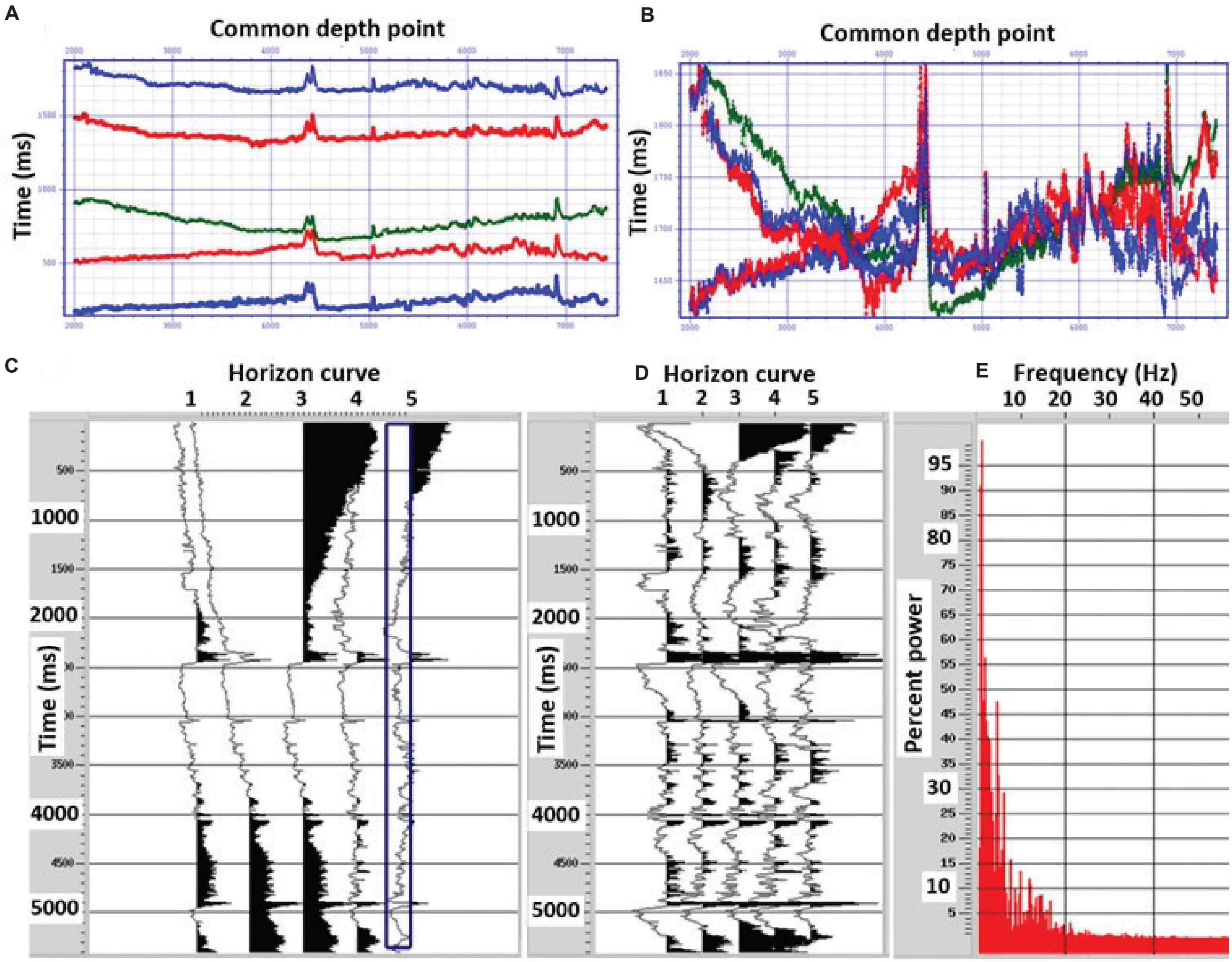

Figure 7. Conversion and processing of horizon curves. (A) Selected horizon curves. (B) Superposition of selected horizon curves. (C) Horizon curves converted into traces. (D) Traces with a common frequency band. (E) Frequency spectrum of all the traces (percent power).

derived using the DRM-based refraction statics method.[18] The refraction statics solution was computed by picking the first arrivals in the offset range of 150–1100 m, using V0=800 m/s and V1=2,400 m/s (Figure 14).

The curves of the refraction static corrections and the proposed corrections displayed a similar global trend; however, notable differences were observed in the regional, medium, and short wavelengths (Figures 14 and 15). The differences in values (10–20 ms) between the static curves from the receivers over distances ranging from 10 km to 20 km (Figure 15) suggest the presence of significant errors that could result in misleading and erroneous structural interpretations, thereby distorting the overall geological interpretation.

This comparison demonstrated that the proposed method significantly reduced the errors associated with the DRM method (Figures 14 and 15). In addition, it enhanced the quality of seismic data and ensured accurate interpretation of geological structures (Figures 16 and 17). Consequently, the results highlighted the advantages of the proposed approach and offered a comprehensive evaluation of its impact on the interpretation of seismic data.

One quality control procedure for static corrections involves checking the data on the seismic section after stacking.[11] The proposed method improved the seismic image and provided more precise and accurate static corrections. The horizons were clearer in the seismic section obtained. In addition, the comparison with calibrated refraction statics revealed significant improvements in seismic imaging and regional static anomalies removal (Figures 16 and 17).

Unlike static corrections derived from refraction methods, which require calibration with borehole

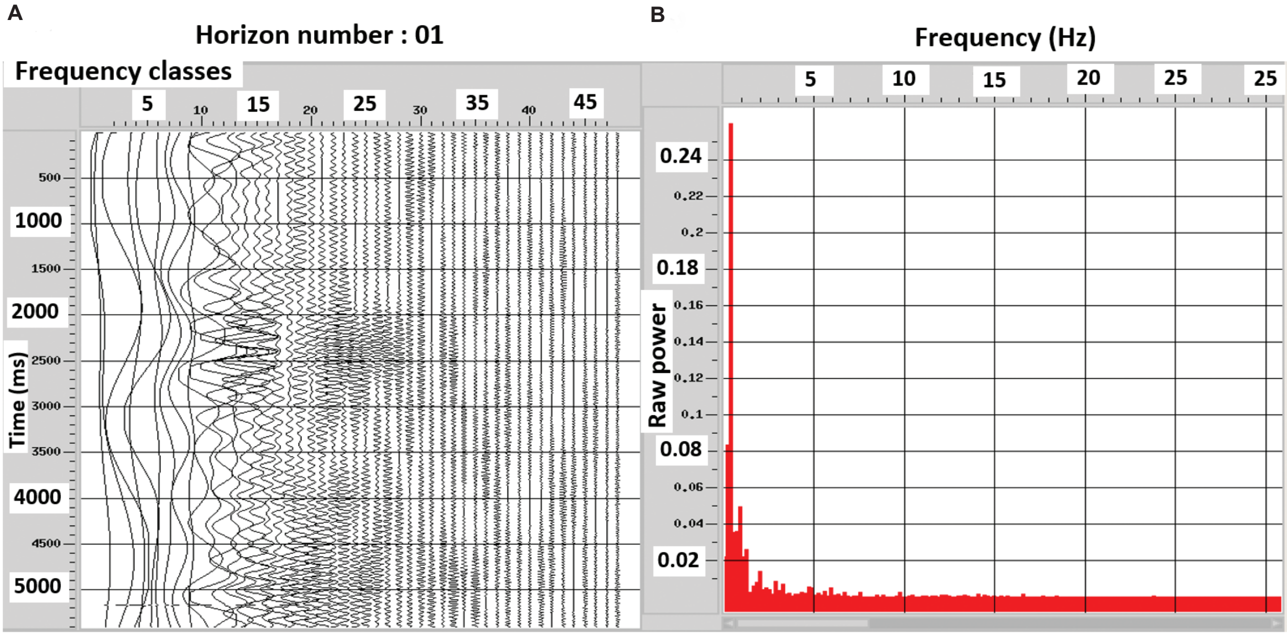

Figure 8. Horizon curve frequency decomposition and amplitude analysis. (A) Elementary frequency decomposition and (B) corresponding frequency spectrum.

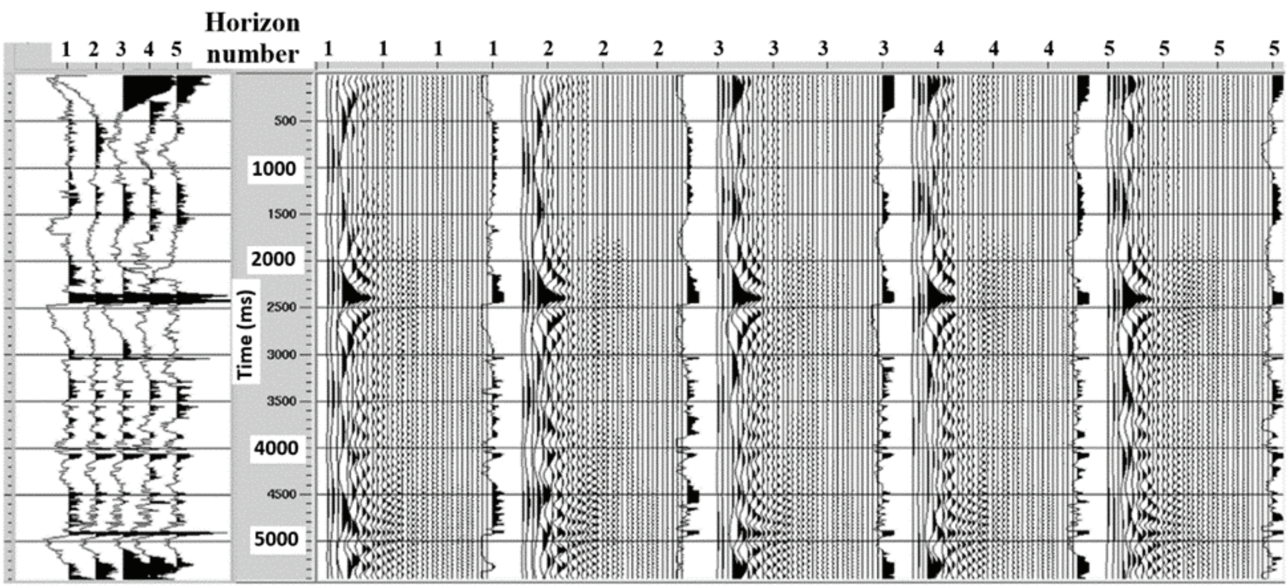

Figure 9. Elementary frequency decomposition of the selected seismic horizons using the short-time Fourier transform.

data to correct regional trends, the suggested method eliminates the need for such calibration. This improved accuracy enhances continuity, coherence, resolution, and the representation of geological structures, making this approach highly efficient for seismic data processing.

A comparison of the results showed that this method provided more accurate static corrections, significantly reducing errors and enhancing the quality of seismic horizons in terms of continuity, energy, resolution, and signal-to-noise ratio across the entire seismic section (Figures 16 and 17).

4. Discussion

In this study, we proposed an innovative method for calculating static corrections by analyzing horizons in the near-trace section, thereby eliminating the need for prior modeling of the near-surface layers.

The impact of heterogeneity and discontinuous

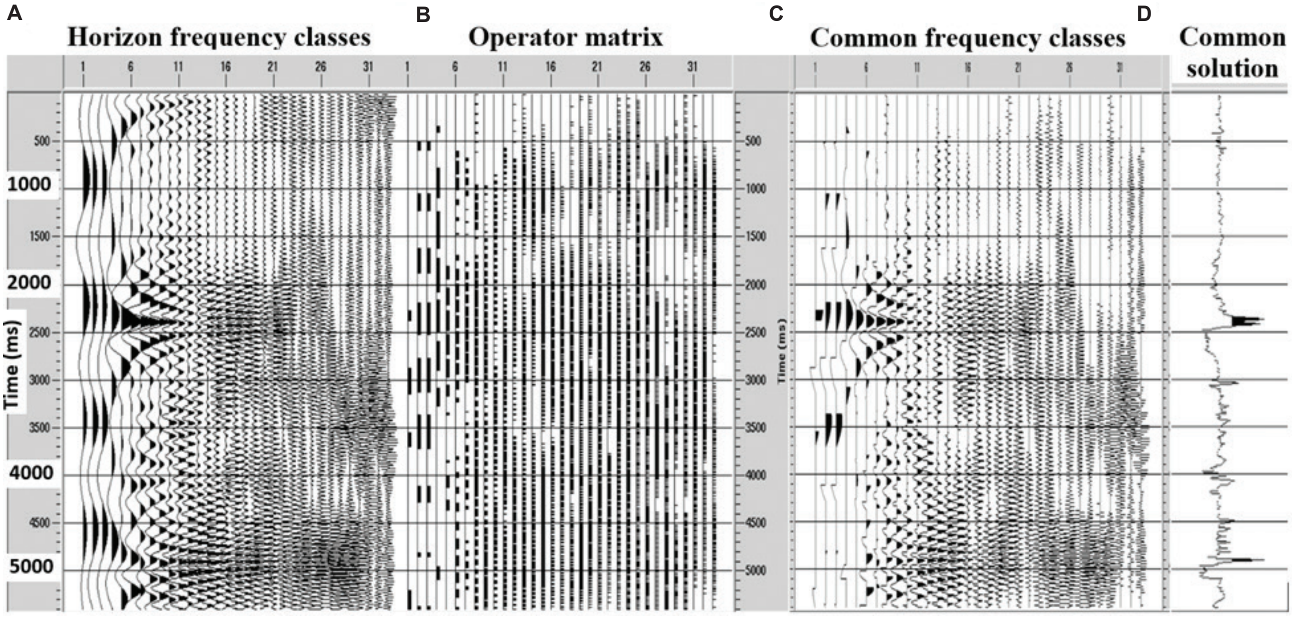

Figure 10. Decomposed horizons matrix, the separation operator matrix, and the common solution pre-stack matrix and post-stack curve. (A) Decomposed horizons. (B) Separation operator. (C) Pre-stack common solution. (D) Common solution curve.

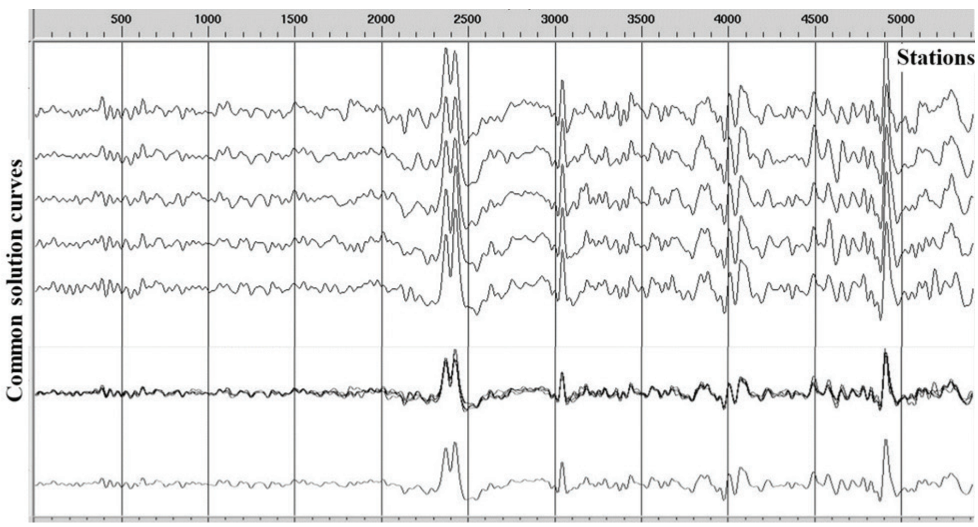

Figure 11. All common solution curves obtained from each reflector (top). Middle: Superposed all common curves. Bottom: Average stack of the common curves (Total static solution).

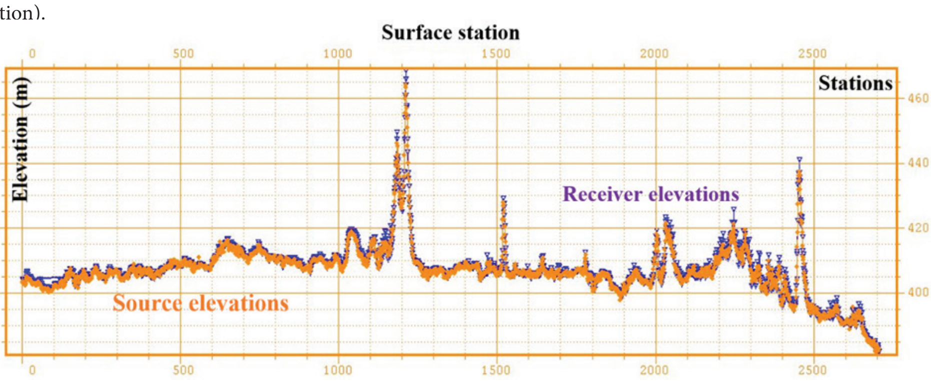

Figure 12. Source elevations (orange) and receiver elevations (blue) along the acquisition line.

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structures near the surface on seismic wave velocity is evident in the variations observed in the travel times of reflected seismic waves. The method is based on accurately identifying these horizons in a zero-offset section (before applying static corrections). The total static correction is derived by extracting the common deformation curve shared among the horizons. However, regardless of the complexity of the near-surface structures, if the seismic horizons cannot be clearly identified after advanced processing and filtering, the method will not be applicable and will be considered a limitation.[34,35] The application of the proposed methodology to simulated data demonstrated its effectiveness, showing excellent agreement with theoretical models and thereby validating the robustness of the technique. This robust performance on simulated datasets provided a solid foundation for its application to real-world seismic data. However, while the results obtained from the real data offered valuable insights, they also revealed certain limitations, particularly under challenging conditions. These observations raise important considerations regarding the method's reliability in less-than-ideal acquisition or geological contexts.

The results obtained from both simulated and real seismic data demonstrated that the proposed approach significantly outperformed traditional methods, particularly refraction statics, in terms of both accuracy and efficiency. When applied to real data, it yielded a notable enhancement in seismic image quality by effectively mitigating regional anomalies typically observed with calibrated static corrections. This improvement is critical for ensuring the continuity and consistency of seismic horizons, which are fundamental for reliable geological interpretation. Compared to calibrated refraction statics, the method produced substantial gains in image clarity, including enhanced structural continuity and resolution. Moreover, eliminating the need for borehole calibration streamlines the processing workflow while delivering clearer and more coherent seismic sections than conventional techniques.

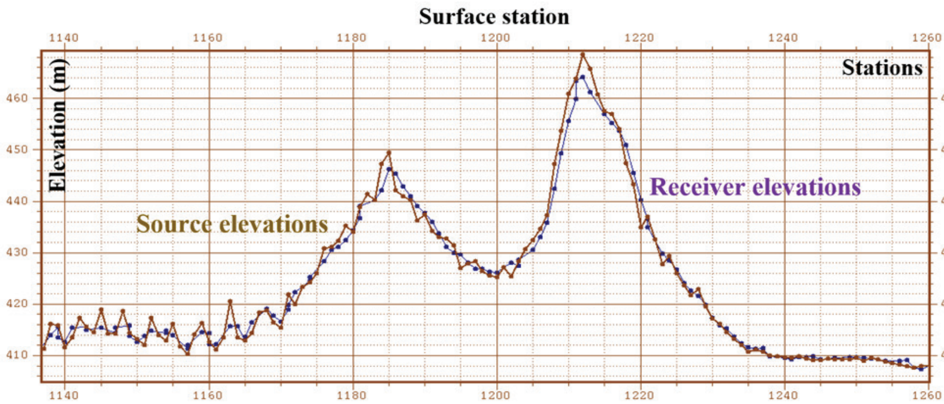

Figure 13. Zoomed-in view of source (brown) and receiver (blue) elevation curves, highlighting elevation variations along the seismic profile.

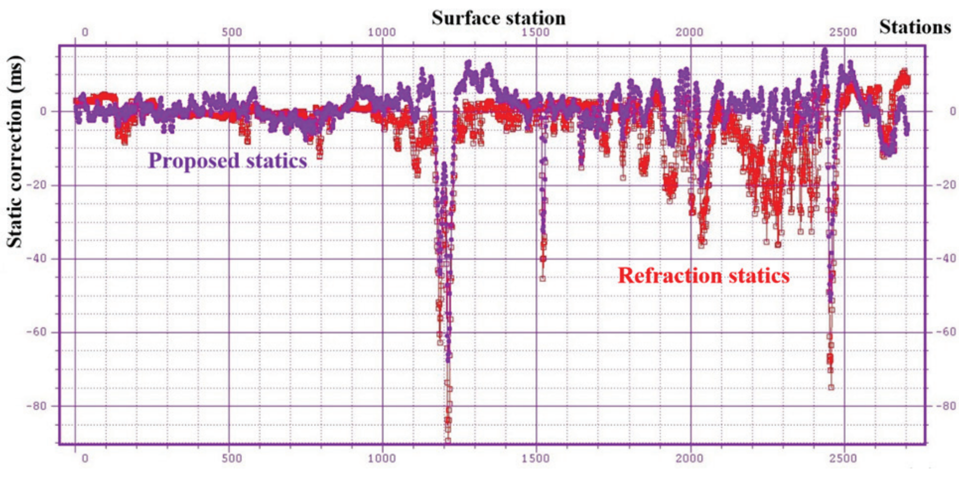

Figure 14. Comparison of static correction curves obtained using the proposed method (purple) and the refraction method (red).

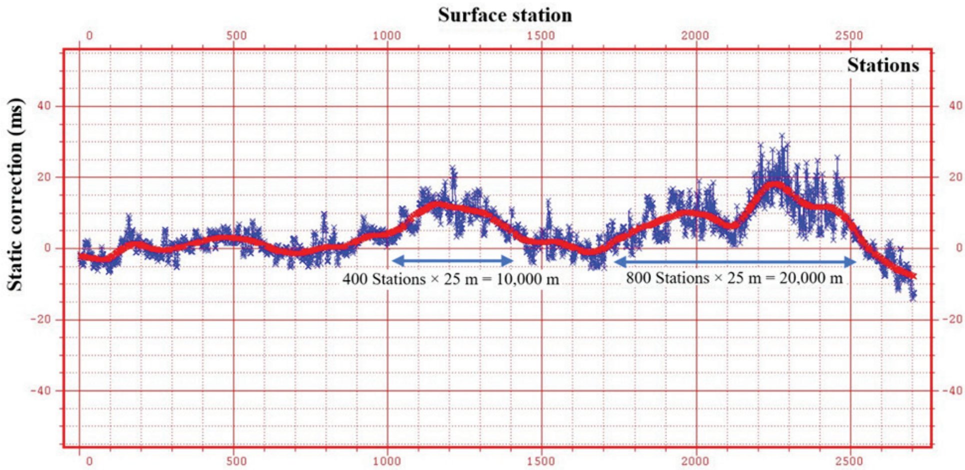

Figure 15. The difference between the static curves obtained from the proposed method and the refraction method, presented with smoothing (red) and without smoothing (blue).

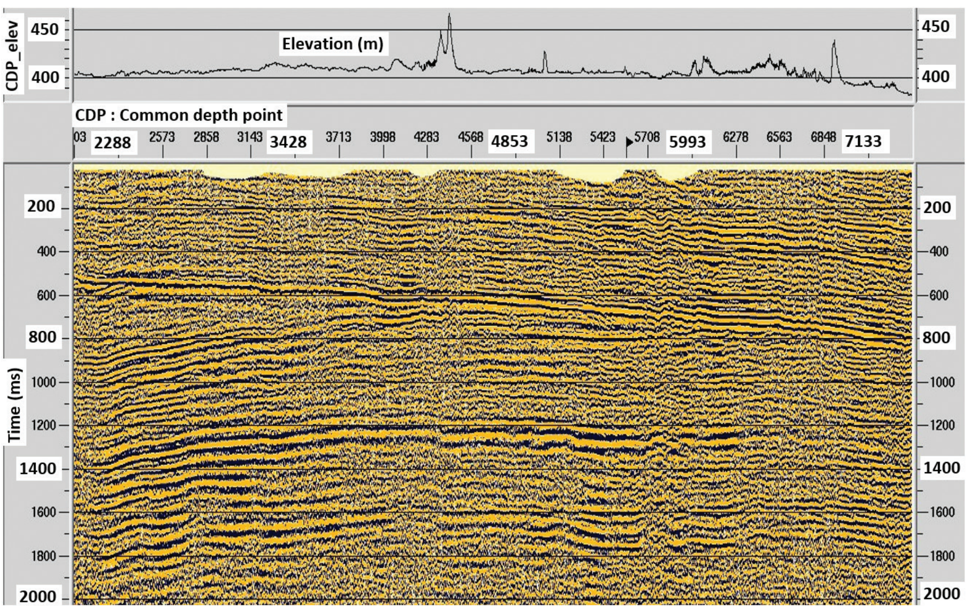

Figure 16. Seismic section processed using refraction static corrections. CDP_elev refers to CDP elevation.
Abbreviation: CDP: Common depth point.

Although the results are promising, it is essential to acknowledge certain limitations of the study. One of the main sources of error lies in the data quality, particularly when the data presents a low signal-to-noise ratio. In such cases, powerful filtering is required to clarify reflected seismic horizons, complicating their analysis and shape tracking.

In summary, this method demonstrated that the proposed method offers an efficient and reliable solution for calculating static corrections in seismic exploration. By simplifying the process and improving the quality of seismic images, it addresses one of the main challenges in seismic exploration: the modeling of complex and heterogeneous near-surface layers. Traditional methods, such as refraction statics, heavily rely on the quality of first arrivals, which can be problematic in challenging geological environments.[10,11,36] The proposed method circumvents the need for first arrival picking and near-surface layers modeling, which are both time-consuming and prone to human error.

Although this study has demonstrated the applicability of our methodology, it is essential to continue refining this approach to maximize the impact of the results in the field. It would be relevant to develop this method to integrate the

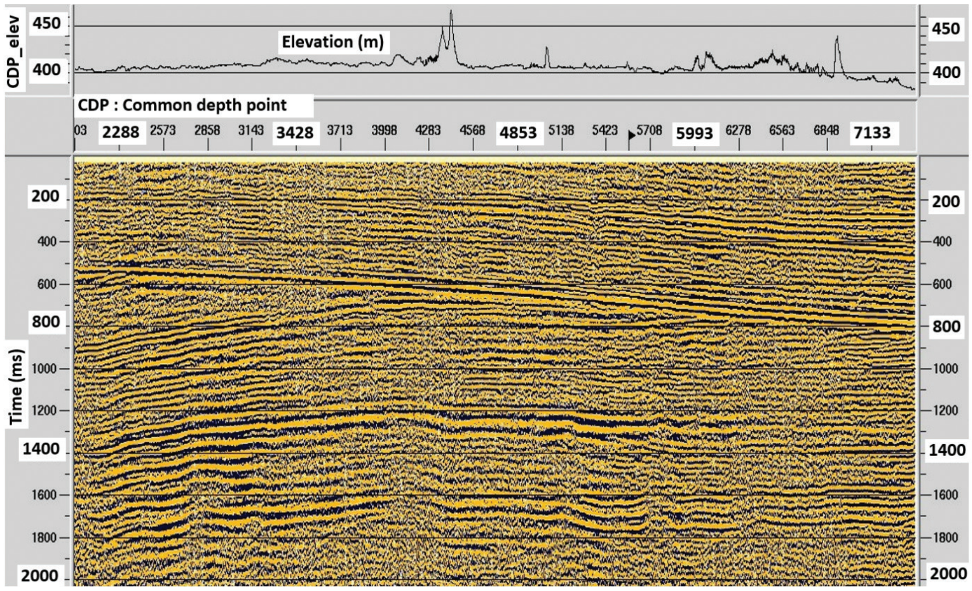

Figure 17. Seismic section processed using the proposed static corrections. CDP_elev refers to CDP elevation.
Abbreviation: CDP: Common depth point.

study and analysis of discontinuous and segmented seismic horizons in the case of sedimentary basins with complex and rugged geology. Furthermore, it is essential to further develop this method to be suitable for three-dimensional studies. These complementary avenues of research could strengthen the robustness of the method and broaden its scope of application.

5. Conclusion

The innovative method developed for calculating static corrections represents a significant advancement in seismic exploration methodologies. Based on the reality of geological structures, this approach utilized images of seismic horizons to directly estimate total static corrections without relying on prior information from the WZ model. This independence streamlined the correction process and enhanced the reliability of seismic interpretations.

The technique analyzes time seismic horizons (reflectors) selected from the near-trace section. By correcting for variations in surface elevation, the velocities of near-surface layers, and the bedrock (replacement velocity), the method effectively addresses the regional components of static corrections. This analysis prevents the introduction of fictitious structures, ensuring the final seismic images remain true to geological reality.

A comparison of the results showed that this method provides more accurate static corrections, and improves the seismic imaging and the quality of seismic horizons in terms of continuity, coherence, energy, resolution, signal-to-noise ratio, while respecting the reality of geological structures over the entire seismic section, making this approach efficient for seismic data interpretation (Figures 16 and 17).

In addition, utilizing the near-trace section for horizon selection reduces the effort required for first arrival picking. This expedites the process and minimizes human error, resulting in faster execution than conventional methods. This advancement is achieved without needing borehole data surveys, increasing efficiency and accessibility, particularly in challenging terrains.

Overall, the results highlight the advantages of this method in improving seismic imaging and its impact on data interpretation. The proposed static corrections are more reliable than traditional techniques, particularly in complex geological settings.

The methodological advances introduced in this study encompass several key innovations and offer a robust and efficient alternative for computing static corrections in seismic exploration. It overcomes key limitations of traditional techniques. First, directly calculating static corrections eliminates the need for prior knowledge of the WZ model. In addition, the study removes the necessity for picking first arrivals and avoids calibration with borehole data, which reduces human error, simplifies the process, and lowers costs. The method is also independent of complex near-surface structures, effectively addressing discontinuity, heterogeneity, and anisotropy challenges in the near-surface layers. Moreover, it demonstrates efficiency in execution, achieving faster processing times through near-trace sections. Finally, the quality and reliability of seismic images are enhanced by adhering to the structural geological reality.

Furthermore, this innovative method represents a substantial advancement in seismic exploration, contributing to more reliable and efficient geological assessments.

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Conflicts of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Youcef LADJADJ
Formal analysis: Youcef LADJADJ
Investigation: Youcef LADJADJ
Methodology: Youcef LADJADJ
Supervision: Mohamed Cherif BERGUIG, Said GACI
Validation: Youcef LADJADJ, Mohamed Cherif BERGUIG, Said GACI
Visualization: Youcef LADJADJ
Writing–original draft: Youcef LADJADJ
Writing–review & editing: Youcef LADJADJ, Mohamed Cherif BERGUIG, Said GACI

Availability of data

All data analyzed have been presented in the paper.

Further disclosure

Part of the findings has been presented in the:

(i) 9th International Symposium on Hydrocarbons and Chemistry (ISHC9) on Jun 25 and 26, 2024, at Boumerdès (Algeria), under the title, "Seismic Reflection Data for Accurate Statics Correction Determination: A Novel Approach."

(ii) Near Surface Modeling and Imaging Workshop (SEG) in Muscat, Oman, from September 27–29, 2022, under the title, "A New Approach for Estimating Accurate Statics Correction."

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