

ARTICLE

Reconstruction and quality control of non-repeatable land time-lapse seismic data

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Abstract

Onshore non-repeatable time-lapse (TL) seismic exploration is a challenging yet convenient technique for enhancing production in mature oil and gas fields. Data repeatability across two or more acquisition phases is fundamental for reliable TL analysis. However, differences in acquisition geometries – from variations in geological targets, acquisition technologies, and acquisition parameters – can cause significant inconsistencies between two data vintages. Drawing on survey design parameters, this study proposes a dual-constraint method for data reconstruction and quality control, integrating common midpoint (CMP) similarity with the sum of shot-receiver geometric distances. Unlike conventional techniques, the proposed approach simultaneously controls shot and receiver position errors through a dynamic threshold, indirectly preserving offset and azimuth consistency. Compared with typical methods, it avoids cross-domain transformations and multi-parameter adjustments, offering high applicability. Applied to conventional (2004) and high-density (2008) datasets from a Chinese onshore oilfield, the method achieved data utilization rates of 77.5% and 39.8%, respectively. The reconstructed data demonstrated higher offset distribution uniformity and improved CMP fold consistency compared with the CMP-constrained receiver deviation method. This study provides a practical reference for TL studies in onshore mature oilfields.

Keywords: Onshore seismic exploration; Non-repeatable time-lapse seismic data; Pre-stack data reconstruction

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1. Introduction

Time-lapse (TL, sometimes referred to as four-dimensional) seismic technology is a methodology for studying reservoir characteristics by analyzing differences, such as fluid changes in hydrocarbon reservoirs, and in seismic responses between two or more phases under specific conditions, including reservoir properties, fluid characteristics, and seismic data quality.^{1,2} This technology has advanced seismic exploration from static structural surveys and reservoir characterization (e.g., structural and lithological

properties) to dynamic monitoring of hydrocarbon reservoirs. Under favorable conditions, it enables effective dynamic reservoir management and enhances recovery rates.^{3,4} However, in recent years, high-precision and high-density seismic surveys have been conducted in mature exploration areas to identify complex lithological structures and subtle traps. By leveraging legacy and newly acquired data for non-repeatable TL seismic studies, reservoir development can be guided effectively without increasing acquisition costs.^{5,6} Since the 1980s,⁴ applied research on TL seismic technology has been conducted in many oilfields.^{7,8} Nguyen *et al.*⁹ reviewed prior studies and provided an in-depth introduction to recent advancements in TL seismic data processing and interpretation, focusing on four-dimensional seismic processing workflows. Sambo *et al.*¹⁰ and Emami¹¹ also provided comprehensive reviews of TL seismic studies, reaffirming its significant applications.

However, environmental factors, such as ambient noise, environmental changes, and near-surface velocity variations, along with discrepancies in field acquisition parameters (e.g., differences in geophone types and positions and source excitation methods) and divergent processing requirements (e.g., workflows, parameters, algorithms, and software), lead to poor repeatability between seismic datasets from different periods. These inconsistencies manifest as mismatches in energy, timing, phase, velocity, and frequency bandwidth, rendering legacy processing results unsuitable for direct TL seismic interpretation. Therefore, targeted data reprocessing from both periods is necessary to minimize inconsistencies and obtain the accurate TL seismic response caused by reservoir changes.¹² Seismic processing aimed at this goal is often referred to as non-repeatable TL seismic processing.^{13–16}

Given that TL seismic exploration has high requirements for the repeatability of two (or multiple) phases of non-repeatable seismic data, researchers have investigated its theoretical basis, feasibility, and practical implementation. Li and Chen¹⁷ examined the prerequisites for TL seismic by assessing its feasibility. Based on TL seismic practices, Zhang¹⁸ discussed the key conditions necessary to complete a TL project strictly, emphasizing the substantial challenges involved. Liu *et al.*¹⁹ highlighted that TL seismic exploration must be considered from the initial stage of design acquisition, underscoring the inherent difficulties of non-repeatable TL projects. Considering the challenges of conducting accurate TL seismic exploration, Zhou *et al.*²⁰ proposed the concept of pseudo-TL seismic exploration, which focuses on analyzing the response characteristics of seismic data to geological and reservoir problems rather than ensuring strict multi-phase data consistency.

Analysis shows that significant differences in wavelet characteristics—mainly energy, frequency, and phase—can arise from variations in source–receiver conditions or acquisition geometry settings, even within the same survey conducted over two (or more) periods.²¹ Therefore, applying appropriate data processing techniques to improve repeatability and reduce inconsistencies—while preserving the accurate TL seismic response caused by reservoir changes—is a core and essential task in non-repeatable TL seismic data processing.²² In general, these consistency processing steps can be grouped into three main categories:

- (i) Pre-stack data reconstruction: Initial data matching and reconstruction, including binning, midpoint alignment, fold adjustment, azimuth regularization, and signal-to-noise ratio optimization.
- (ii) Pre-stack consistency processing: Maintenance of pre-stack consistency through frequency, phase, velocity, and residual static correction adjustments.
- (iii) Post-stack equalization: Calibration of time, amplitude, frequency, energy, and phase.

Regarding the first task, Yin *et al.*²³ employed a three-dimensional Gaussian beam forward modeling method to quantitatively analyze the impact of different acquisition geometry parameters on the received energy of reservoir bins through illumination simulation. The study demonstrated that offset and azimuth are the primary factors causing inconsistencies between two-phase datasets and emphasized that bin resetting and uniform offset and azimuth distribution within bins are critical in non-repeatable TL seismic acquisition. Jin *et al.*²⁴ and Lü *et al.*²⁵ investigated bin resetting methods, proposing the composition of common midpoint (CMP) sets in pre-stack data reconstruction and introducing offset-based seismic trace extraction combined with dynamic interpolation. Implementing this approach is straightforward but may result in loss of offset and azimuth information. Yang *et al.*²⁶ addressed land-based TL seismic data processing by combining the frequency–wavenumber (FK)-domain interpolation with bin resetting, aiming to achieve acquisition geometry consistency by considering line, point, offset, azimuth, and time during the interpolation process. While valuable for onshore TL seismic studies, implementing multidomain transformation and multidimensional interpolation is challenging. Rui²⁷ designed a data reconstruction method based on source–receiver positions and consistent incidence/reflection angles to preserve offset and azimuth information in reconstructed data. However, its implementation requires numerous adjustable parameters. In 2021, Rui²⁸ proposed three core technologies—common reflection point (CRP) trace spatial extraction, FK-domain interpolation, and

r–p domain reconstruction—for acquisition geometry consistency processing, an approach largely similar to Yang's method.²⁶

For the second and third tasks, researchers such as Jin *et al.*,^{24,29,30} Guo *et al.*,^{15,31,32} Wang *et al.*,³³ Zhu *et al.*,³⁴ and Wang *et al.*³⁵ have explored key post-processing techniques for two-phase data. Liu *et al.*³⁶ performed consistency processing on data before pre-stack depth migration. Chen *et al.*³⁷ applied dual-domain near-surface Q attenuation compensation and surface-consistent Yu's wavelet deconvolution to ensure data consistency. Liu *et al.*³⁸ used matched filtering to address cross-source inconsistencies. Fomel and Jin³⁹ applied local similarity attributes to TL seismic data matching, which was further developed by Liu *et al.*⁴⁰ Chen *et al.*⁴¹ presented case studies demonstrating the application of TL seismic in offshore reservoir monitoring and a gas field. Rui *et al.*²⁸ proposed a workflow integrating well data-driven pre-stack consistency processing with pre-stack/post-stack sensitivity attribute analysis, significantly improving the applicability of non-repeatable TL seismic data and yielding promising results.

Analysis reveals that most successful TL seismic projects have been conducted in offshore environments, while onshore projects remain comparatively scarce. This is primarily due to the complexity of the onshore acquisition environment, where it is challenging to maintain consistency in acquisition geometry, source wavelet, reception conditions, and surface characteristics across surveys from different periods. Previous literature^{1–4,7–8,12,13,24,25,29–31,33–35,41–44} has focused on repeatable TL seismic exploration. Many studies^{17,19,34,41,43–45} have primarily addressed acquisition and processing technologies for offshore TL seismic data. In contrast, few publications have discussed non-repeatable TL seismic exploration,^{14–16,26,32,41} and even fewer specifically examine onshore non-repeatable TL seismic exploration.^{24,26,46} Zhou *et al.*⁴⁶ and Rui *et al.*²⁶ investigated an onshore non-repeatable TL seismic case. However, Zhou *et al.*⁴⁶ concentrated mainly on the TL geological response, while Rui *et al.*²⁸ focused on the overall processing workflow, devoting limited attention to data reconstruction strategies.

Among the three primary research tasks outlined earlier—acquisition geometry reconstruction, pre-stack data consistency processing, and post-stack consistency processing—acquisition geometry reconstruction is the most fundamental in non-repeatable TL seismic surveys. Differences in acquisition geometry are the dominant source of inconsistencies³³ and directly influence the accuracy of final interpretation results. Although previous studies^{23–27} have examined data reconstruction methods,

there remains a scarcity of literature specifically addressing algorithms for onshore non-repeatable data reconstruction (Task 1) and monitoring geometries. Furthermore, the associated technical challenges are particularly significant.^{14,16,20,26} Nonetheless, this area of research holds considerable theoretical and practical value for the exploitation and development of mature onshore oil and gas fields.^{14,26}

Building on this analysis, and considering the relationship between offset, azimuth, incident angle, and reflection angle of imaging points with the spatial arrangement of shot and receiver points, this study proposes a CMP-constrained data reconstruction method combined with quality control techniques, incorporating an additional constraint based on the sum of geometric distances of shot gathers and receiver-point sets (SumDsDr). Unlike methods relying solely on midpoint alignment, this approach controls shot-point and receiver-point positional errors using a dynamic threshold. It accounts for CMP similarity while applying dual constraints on shot-point and receiver-point deviations between two-phase datasets. In effect, it considers offset similarity and indirectly incorporates azimuth similarity. This aligns with the findings of Smit and Watt,⁴⁷ who demonstrated that trace correlation within the same bin is influenced by the combined shot–receiver distance ($\Delta S + \Delta R$); smaller $\Delta S + \Delta R$ values correspond to higher trace similarity. Compared to the methods of Yang *et al.*²⁶ and Rui *et al.*,^{27,28} the proposed approach offers a more straightforward practical implementation. Its application to onshore oilfield datasets—including conventional and high-density acquisition data—validates its effectiveness.

For clarity, several typical methods for data reconstruction are summarized in Table 1, along with their applicable scenarios, complexity, and onshore application bottlenecks.

This paper is organized as follows: Section 2 first demonstrates the significance of repeatability in TL seismic analysis through a wavelet subtraction example. It then presents the proposed data reconstruction framework, including core algorithmic principles and technical implementation. Quality control protocols and workflow diagrams are provided, followed by a comparison with a similar method. Section 3 validates the proposed approach through field applications on two representative non-repeatable datasets from a Chinese onshore oilfield. Section 4 concludes the study by outlining the practical potential and key implementation considerations of the method.

Table 1. Typical methods for data reconstruction

Methods	Core idea	Complexity	Onshore applicability	Limitations
Yang <i>et al.</i> ²⁶	Frequency–wavenumber-domain interpolation+bin regularization	High (multidomain transformation)	Low (poor stability in complex surface conditions)	Prone to loss of offset information
Rui ²⁷	Incident angle/reflection angle constraint	Medium (complex parameter tuning)	Medium (sensitive to surface undulations)	Requires numerous adjustable parameters
This paper	Common midpoint+SumDsDr dual constraints	Low (no domain transformation)	High (dynamic threshold adapts to surface conditions)	Threshold selection depends on experience

Abbreviation: SumDsDr: Sum of geometric distances of shot gathers and receiver-point sets.

2. Data reconstruction method and quality control techniques

2.1. Importance of repeatability in TL seismic exploration

The repeatability of two-phase seismic data is the foundation of TL seismic research and a critical factor in ensuring the reliability of its results. For non-repeatable two-phase seismic data, failure to perform consistency processing prevents the differential information from accurately reflecting actual fluid changes in hydrocarbon reservoirs. As shown in the seismic data processing workflow (Figures 1 and 2), discrepancies in wavelet parameters, such as phase characteristics (including single or composite phase variations), time delays, frequency attributes, and energy distribution, may generate differential anomalies unrelated to reservoir fluid changes (Figure 2). Therefore, systematic reprocessing of both datasets is essential. Technical measures must be applied to minimize the influence of inconsistencies caused by non-hydrocarbon factors, ensuring that the TL seismic response accurately represents dynamic reservoir changes.¹²

2.2. Method

2.2.1. Related works

For two-phase non-repeatable data, it is essential to analyze the characteristics of both datasets in conjunction with the geological conditions and geophysical background of the study area. Based on this analysis, a targeted acquisition geometry reset method should be adopted to maximize the utilization of the “intersection” between the two datasets. Commonly used methods include acquisition geometry thinning, shot gather extraction, bin sorting, CRP extraction, and interpolation.^{19,24–25,42} Among these, the acquisition geometry thinning and shot gather extraction methods require the shot positions in both datasets to coincide, using the dataset with fewer shots as the extraction basis. However, differences in shot layout positions and the number of shot gathers between the two phases are common, making this a challenge. The bin sorting method has strict requirements for receiver layout.

Due to the differences in source positions between the two datasets, significant errors can occur. The CRP extraction method offers certain theoretical advantages,^{26,28} however, it involves FK-domain and τ -p-domain interpolation, which requires substantial computational resources, imposes high implementation demands, and provides insufficient accounting for offset after reconstruction. Data reconstruction methods that jointly consider offset and azimuth information, while following the principle of consistency between incident and reflection angles,²⁷ involve numerous adjustable parameters and relatively complex implementation procedures.

Previous studies have emphasized key factors for acquisition geometry resetting. Yin *et al.*²³ identified offset and azimuth as essential parameters for bin resetting. Yang *et al.*²⁶ attempted data reconstruction using five-dimensional interpolation and multidomain transformation. Rui²⁷ highlighted the importance of CRP, incidence points, reflection angles, and incident angles. Smit and Watt⁴⁷ demonstrated that, within the same bin, the smaller the sum of the shot distance and receiver distance for two seismic traces, the higher the correlation between them.

2.2.2. Data reconstruction method

Inspired by the literature and combining the composition principles of the same bin and CMP with the relationships among shot position, receiver position, shot-receiver distance, reflection angle, incident angle, and offset, this study extracted the core elements—namely, CMP points within the same bin, shot distance, and receiver distance. By operating on these core elements, the method aims to retain as much offset and azimuth information from the two phases of data as possible, without relying on multidomain transformations or neural network-based reconstruction models.

To illustrate the core concept, the method was applied to two datasets from an onshore mature oilfield in China: conventional acquisition data from 2004 and high-density acquisition data from 2008 (secondary development acquisition). The acquisition parameters of the two

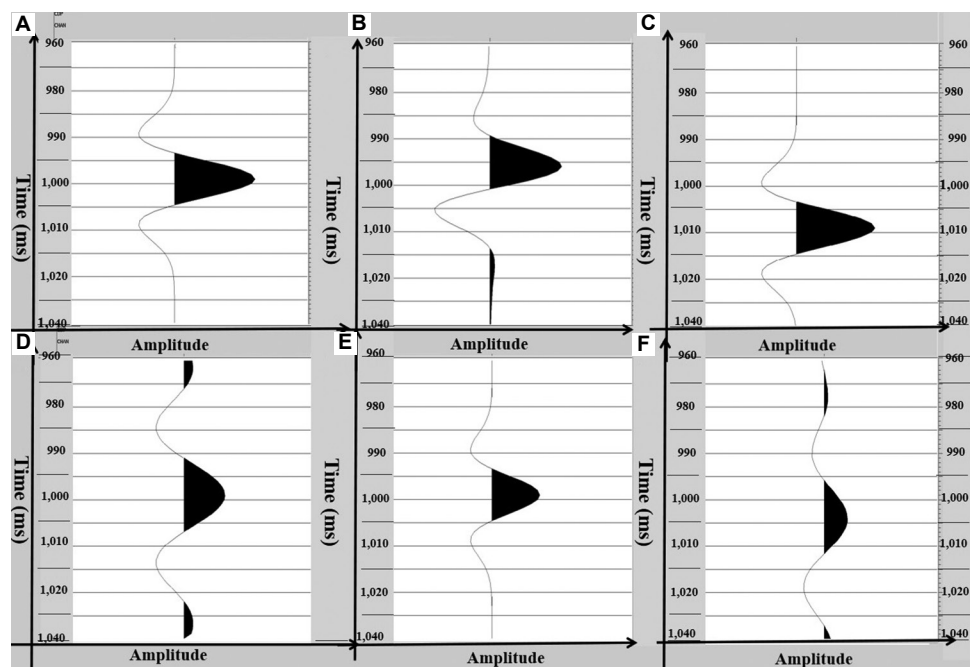


Figure 1. The original wavelet and its variations. (A) Original wavelet, (B) wavelet phase shift, (C) time shift, (D) frequency variation, (E) amplitude variation, and (F) hybrid factors. Time range: 800–1,030 ms for each plot.

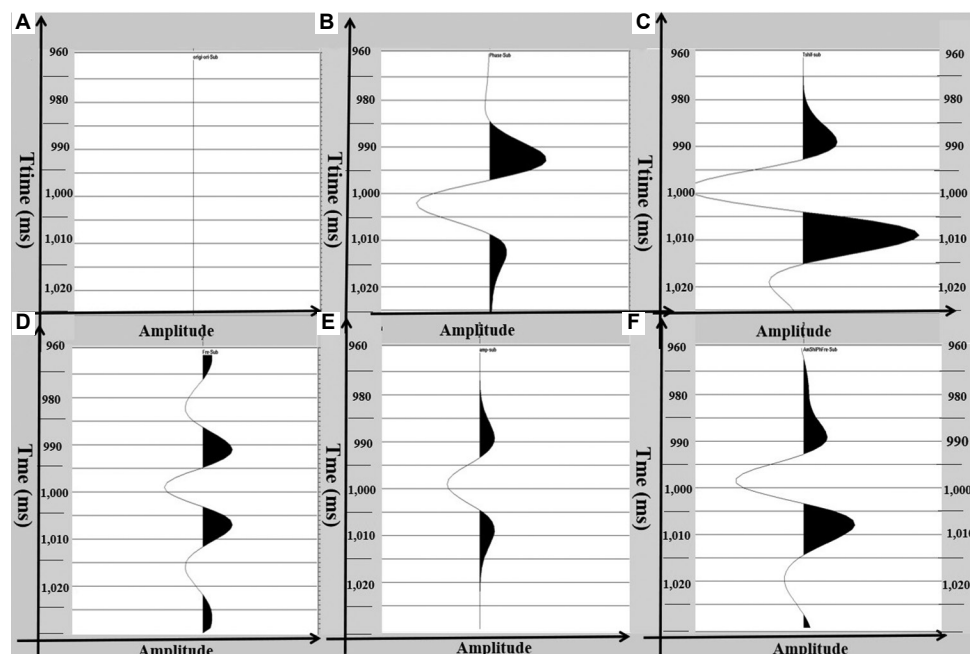


Figure 2. Subtracted results of the wavelets corresponding to Figure 1A-C. (A) Original, (B) phase shift, (C) time shift, (D) frequency variation, (E) amplitude variation, and (F) hybrid factors. Time range: 800–1,030 ms for each plot.

datasets are listed in Table 2. Table 2 shows that, aside from the receiver channel spacing of 50 m receiver spacing and 128 channels per layout in both surveys, there are substantial differences in other acquisition parameters. These include variations in source depths, explosive

charges, non-coincident shots, and receiver positions, which result in inconsistent source wavelets between the two phases. In addition, the 2004 acquisition used a large-bin (25 m × 25 m) design with relatively uniform fold coverage, whereas the 2008 acquisition employed a small-

Table 2. Main acquisition parameters for the two datasets

Year	2004	2008
Geometry parameters		
Receiver spacing	50 m	50 m
Receiver line spacing	150 m	100 m
Number of receiver lines	8	32
Channels per line/ instrument	128	128
Number of receiver channels	1,024	4,096
Source point spacing	50 m	80 m
Source line spacing	200 m	80 m
Roll distance between arrays	600 m	800 m
Explosive charge	3 kg	1–4 kg
Non-longitudinal offset	825 m	935 m
Maximum source-to-receiver offset	4,400 m	7,200 m
Source depth	15 m, 18 m	15 m–31 m
Observation system	8L×12S×128R=1,024 3,175–25–50–25– 3,175	32L×10S×128=4,096 3,175–25–50–25– 3,175
Bin size	25 m×25 m	10 m×10 m

bin (10 m × 10 m) design. The bin sizes of the two datasets are not integer multiples of each other, making direct bin matching infeasible. These differences significantly increase the complexity of data reconstruction and subsequent processing. Methods such as acquisition geometry thinning or bin sorting could reduce reconstruction accuracy under these conditions, highlighting the need for a more robust approach.

Acquisition discrepancies between the two seismic datasets are inherent and unavoidable. To address this, the algorithm proposed in this study aims to maximize the utilization of both datasets (e.g., shot gathers) within a defined error tolerance, while ensuring that the reconstructed non-repeatable seismic data maintain consistency in azimuth, offset, fold, and other key attributes.

The specific workflow of the algorithm is illustrated in Figure 3. First, a unified bin grid was established. Within each bin, the 2004 dataset (DATA1) was used as the reference. Based on the spatial distribution of central points in conventional three-dimensional surveys, a threshold for the SumDsDr was applied as the screening criterion. From the 2008 dataset (DATA2), data whose central points are identical or spatially proximate to those in DATA1 were selected, and redundant fold data in DATA2 were discarded. If, within the threshold range,

particular shot gathers in DATA1 cannot be matched with corresponding data in DATA2, those unmatched shot gathers in DATA1 were excluded. This matching process automatically ensured central point correspondence and maintained fold, offset, and azimuth consistency.

The main steps of the workflow are as follows:

- (i) Define a unified bin grid for datasets and set a pre-controlled distance threshold.
- (ii) Within each bin, use the 2004 dataset (DATA1) as the reference to extract seismic traces from the 2008 dataset (DATA2) that match the midpoint positions in DATA1.
- (iii) Handle unmatched data: Discard redundant fold data in DATA2 that exceeds the threshold; if particular shot gathers in DATA1 have no matching data in DATA2 within the threshold, discard those unmatched shot gathers from DATA1.
- (iv) Automatic alignment: The algorithm ensures midpoint position correspondence and consistency in fold, offset, and azimuth.

Algorithm 1: Data reconstruction algorithm

Given distance threshold SumDsDr and bin size (e.g., 25 m × 25 m)

For each bin *i* in the survey area:

- 1 Extract shots and receivers of DATA1 (2004) and DATA2 (2008) within bin *i*
- 2 **For** each shot *j* in DATA1 within bin *i*:
- 3 Calculate DS (distance between shot *j* and DATA2 shots)
- 4 Calculate DR (distance between receivers of shot *j* and DATA2 receivers)
- 5 **If** DS + DR < SumDsDr:
- 6 Retain matched shots (*j* in DATA1) and corresponding DATA2 data
- 7 **Else:**
- 8 Discard unmatched data in DATA1
- 9 Discard redundant DATA2 data exceeding the threshold

Output reconstructed DATA1 and DATA2

2.2.3. Parameter setting

In the algorithm, DS denotes the shot-point distance, DR denotes the receiver-point distance, and DS + DR represents the sum of the two. SumDsDr is the threshold for reconstructed data in TL seismic processing; its value determines the allowable adjacent distance between the two datasets during reconstruction.

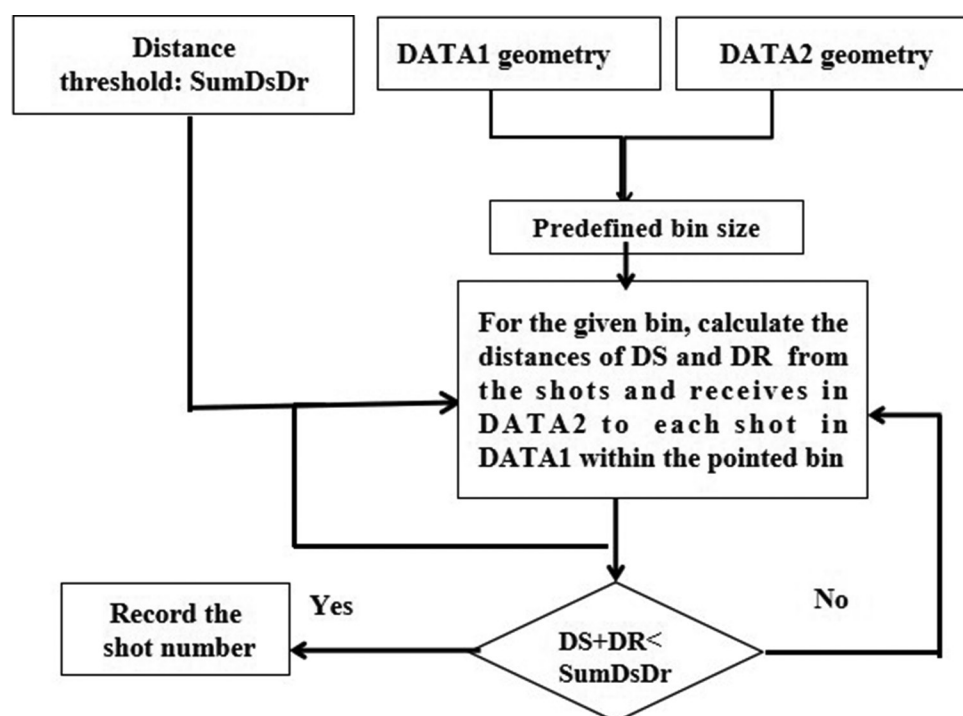


Figure 3. Flowchart of non-repeatable time-lapse reconstruction algorithm for two-phase data

Abbreviations: DS: Distance of shot gathers; DR: Distance of receiver-point sets; SumDsDr: Sum of geometric distances of shot gathers and receiver-point sets.

According to Smit and Watt,⁴⁷ smaller DS + DR values correspond to higher trace correlation similarity. Therefore, variations in DS, DR, and SumDsDr will affect the size and accuracy of the matched data between DATA1 and DATA2, ultimately impacting the fold, offset, and azimuth of the reconstructed data. As illustrated in Figure 4, when using parameter Set 1 (DS < 150 m, DR < 150 m, SumDsDr = 150 m), more original 2008 data were retained (i.e., fewer shots are discarded) compared with parameter Set 2. Consequently, the CMP fold of the 2008 data reconstructed with parameter Set 1 was slightly higher than that obtained using parameter Set 2 (Figure 4, where DS = 0, DR = 150 m, and SumDsDr = 150 m). However, the fold of the reconstructed 2008 data using parameter Set 2 was overall more uniform.

In practice, the value of SumDsDr must be determined experimentally for each dataset. Tests indicate that 150 m serves as a reasonable upper limit for both DS and DR. When SumDsDr exceeded 150 m, no additional improvement in reconstructed data consistency was observed (Figure 5). Therefore, 150 m was adopted as the experimental parameter in all subsequent examples in this study.

For the 2004 and 2008 seismic datasets, considering both their characteristics and the precision requirements of TL seismic processing, DS and DR were each set to

150 m. The statistical characteristics of the sorting and reconstruction results for the two datasets are shown in Figure 5. In the figure, the X-axis represents the preset error threshold, and the Y-axis represents the percentage of sorted gathers relative to the total original gathers under the corresponding error conditions.

Figure 5 shows that the sum of the shot-point and receiver-point errors for the two datasets is mainly distributed in the 40–120 m range. Due to inherent differences in the acquisition geometries, such as shot line spacing, shot-point spacing, receiver line spacing, and receiver-point spacing, the proportion of post-sorting receiver-point errors in the range of 10–30 m was nearly 50%, while those in the range of 40–60 m accounted for about 40%. Shot-point errors were concentrated in the range of 10–100 m. The effective utilization rate of the 2004 dataset reached 77.5%, while that of the 2008 dataset was 39.8%. It should be noted that 39.8% refers to the utilization rate of the number of shots in the 2008 dataset, calculated based on Equation I:

$$\text{Data utilization rate (\%)} = (\text{Number of shots retained after reconstruction} / \text{Total number of shots}) \times 100\% \quad (\text{I})$$

The 2008 dataset represents high-density acquisition, with each shot containing more channels than the 2004 dataset.

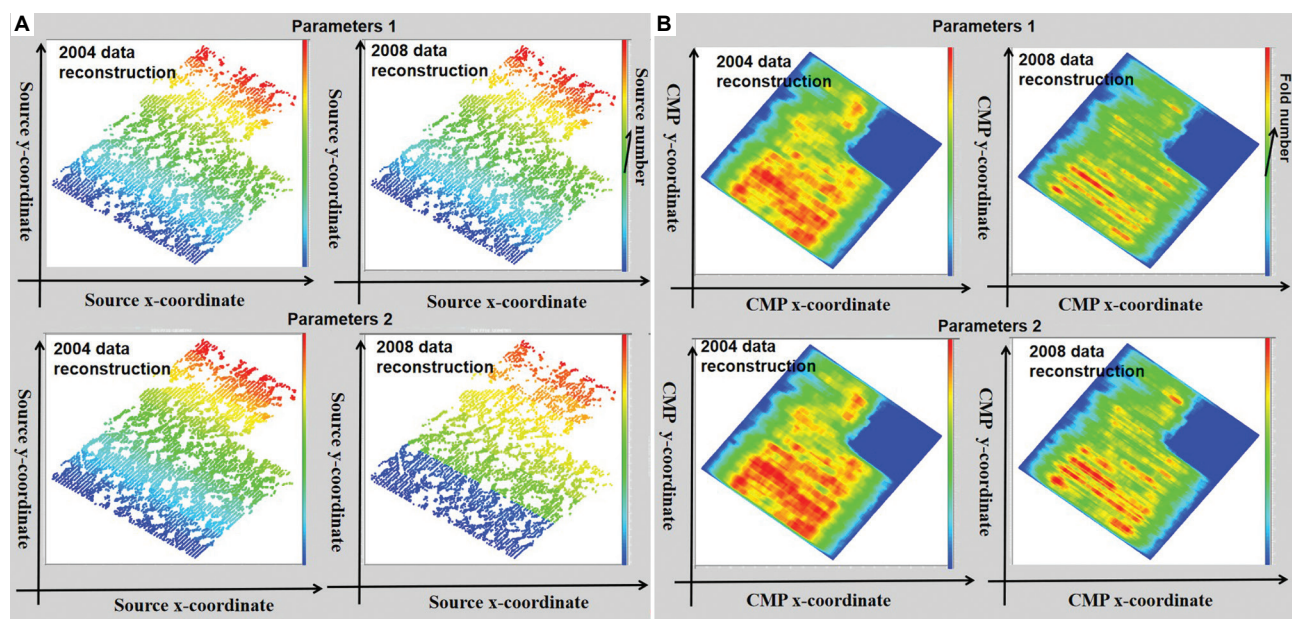


Figure 4. Shot-point distribution (A) and CMP fold (B) after data reconstruction with different DS, DR, and SumDsDr thresholds for the two datasets. Abbreviations: CMP: Common midpoint; DS: Distance of shot gathers; DR: Distance of receiver-point sets; SumDsDr: Sum of geometric distances of shot gathers and receiver-point sets.

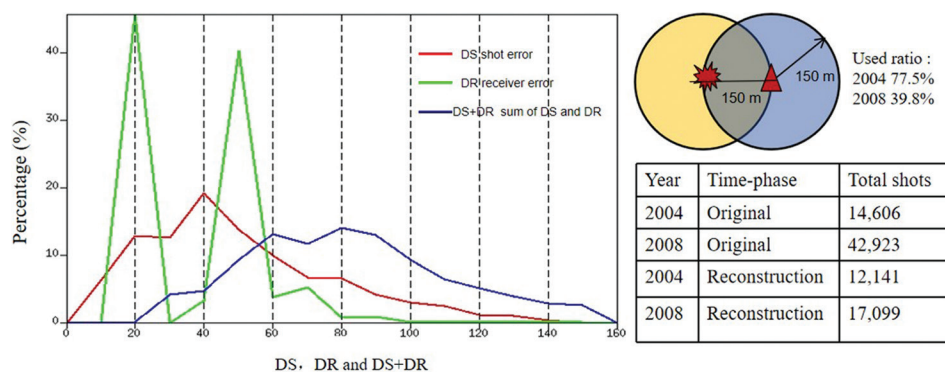


Figure 5. Utilization statistics of the original data in the reconstructed datasets. DS = DR = 150 m, showing the retained ratio for both datasets. Abbreviations: DS: Distance of shot gathers; DR: Distance of receiver-point sets.

During data reconstruction, maximizing original data retention must be balanced with maintaining consistency in key information such as offset and azimuth (as supported by the theory in Yin *et al.*²³). Therefore, using DS + DR as the upper error limit for reconstructed data meets the precision requirements for acquisition geometry resetting in TL seismic exploration, ensuring an optimal balance between data volume and reconstruction quality. This is further illustrated in the following subsection.

2.3. Quality control study during the data reconstruction

As data reconstruction fundamentally depends on the acquisition geometries of both surveys, key quality control

metrics include correspondence of source–receiver pairs before and after reconstruction, shot position proximity, consistency in offset and azimuth distributions, fold consistency within individual bins, overall fold distribution after reconstruction, and comparative analysis of initial migration sections.

Figure 6 compares the acquisition geometries, spatial coverage, and key characteristics of the two surveys. The 2008 survey employed high-density acquisition with smaller bins and multiple receiver spreads, whereas the 2004 survey used a sparser shot distribution with fewer receiver spreads. Differences in acquisition parameters, such as shot line spacing, shot-point spacing, and receiver line spacing, resulted in low repeatability of shot and

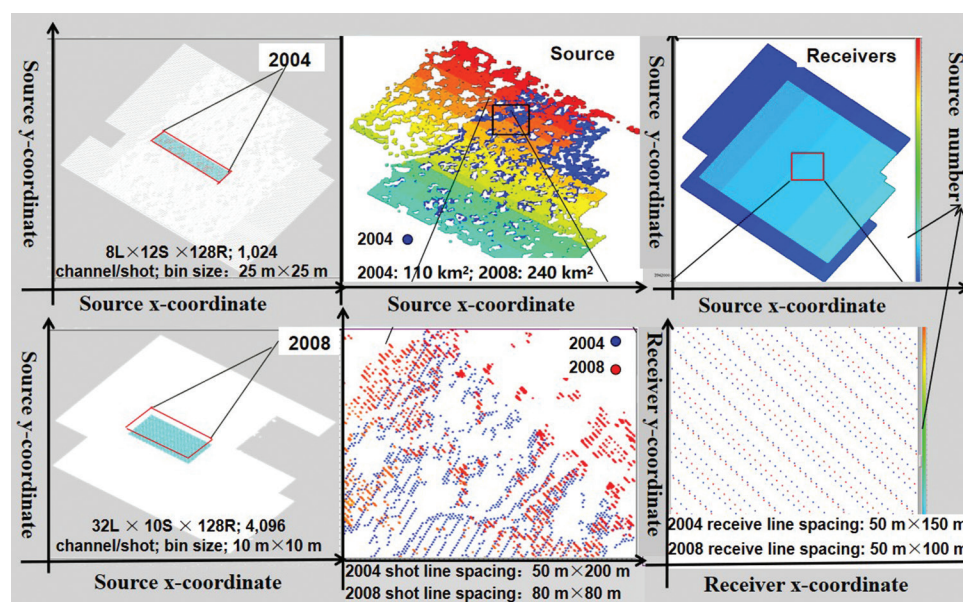


Figure 6. Comparison of shot and receiver geometries before data reconstruction for the two datasets

receiver positions between the datasets. Although the 2008 dataset covers a larger area, the 2004 data extends further in the upper-right corner. These acquisition disparities significantly increased the complexity of TL data reconstruction during the preliminary research phase.

Figure 7A shows zoomed-in views of shot-point distributions before and after matching, while Figure 7B shows zoomed-in receiver-point distributions for the same area. The figures indicate that the repeatability of shot-point distributions between the surveys is extremely low due to differences in receiver line spacing, shot-point spacing, and shot line spacing. The 2004 shot points are more regularly distributed, while overlaps in receiver points occur only occasionally; most positions differ between the datasets. Based on the preset threshold, the sorting process removed mismatched shot points from both datasets, retaining only shot and receiver points that meet the error requirements within the same bin.

Figure 8 compares CMP distributions before and after reconstruction, using the 2004 bin size standard (25 m × 25 m). Differences in the initial bin design rules for the two acquisition periods mean that resetting the bins alone could not resolve the uneven fold distribution in the 2008 data (Figure 8B). The fold maps obtained after bin resetting with the proposed reconstruction scheme (Figures 8C and D) showed substantial improvement in uniformity among adjacent bins. As illustrated in Figure 9, the fold values of the two datasets within the same area were largely consistent, and spatial uniformity was significantly enhanced in the post-reconstruction sections.

It should be noted that the scales of Figure 8A (25 m × 25 m grid) and Figure 8B (10 m × 10 m grid) are different, although the grid sizes may appear similar visually. After binning with the same bin size, however, the scales of Figure 8C and D were highly comparable. Figure 9 presents the CMP fold maps of the two-phase data before and after reconstruction. Figure 9A and B represent the entire survey areas, while Figure 9C and D show the matched portions of the reconstructed datasets. To more clearly highlight the reconstruction effect, Figure 9C and D are presented after simple normalization of the reconstructed two-phase data.

Figures 10 and 11 show the azimuth and offset distributions before and after data reconstruction. These plots demonstrate that the reconstructed datasets exhibited improved alignment in azimuth and offset ranges, resulting in significantly better consistency of maximum and minimum offset distributions.

2.4. Comparison with other methods

As reviewed in the literature, similar reconstruction methods often suffer from high implementation complexity or poor reproducibility. For example, the method by Yang *et al.*²⁶ requires data extraction and FK-domain transformation for reconstruction. In contrast, the method by Rui²⁷ necessitates the extraction of incident angles, reflection angles, and azimuths at CRP points. Some approaches also have limited applicability and are restricted to marine data or repeatable TL datasets. This study compares the proposed method only with the “common CMP point + DR constraint” method

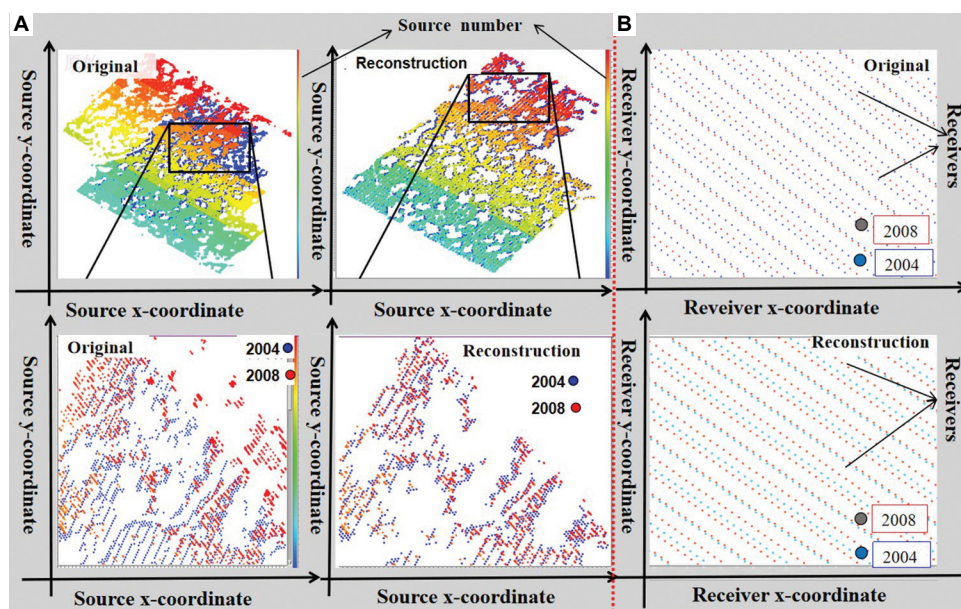


Figure 7. Shot (A) and receiver (B) point distributions before and after data reconstruction

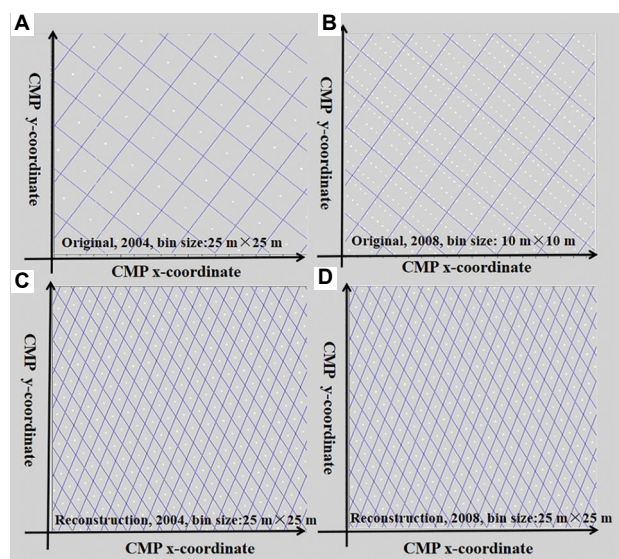


Figure 8. Common midpoint (CMP) bin. (A and B) Before and (C and D) after bin regularization.

(abbreviated as the DR method). In the DR method, reconstruction is performed under the constraint that the receiver-point error $DR \leq V$ (where V is a given value, 150 m in this study).

The experimental results are presented in Figure 12. Compared with the CMP + DR method, the DS + DR dual-constraint method proposed in this paper produced reconstructed datasets with more uniform offset distribution, higher CMP fold for both datasets, and higher utilization rate of original data. The DR

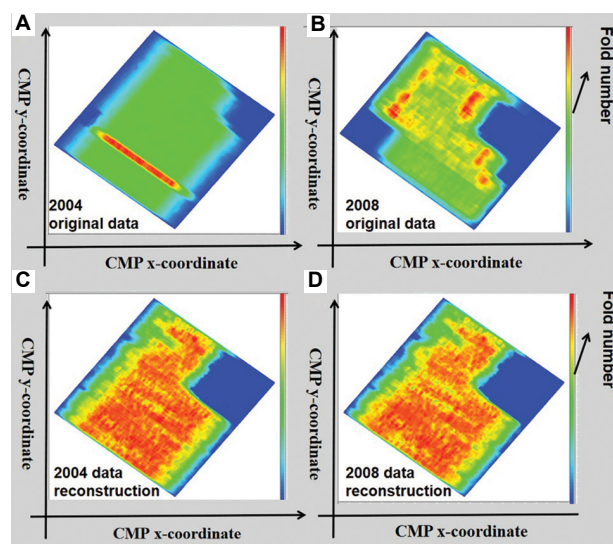


Figure 9. Common midpoint (CMP) fold maps before (A and B) and after (C and D) data reconstruction showing the matched parts of the two-phase datasets

method yielded utilization rates of 70.4% for the 2004 dataset and 38% for the 2008 dataset, which are lower than the 77.5% and 39.8%, respectively. Consequently, the consistency between the reconstructed 2004 and 2008 datasets improved, consistent with the trends shown in Figure 5.

In summary, for onshore oilfield acquisition data with significant differences in acquisition geometries between survey periods, the TL seismic data reconstruction method presented here balances data utilization and matching

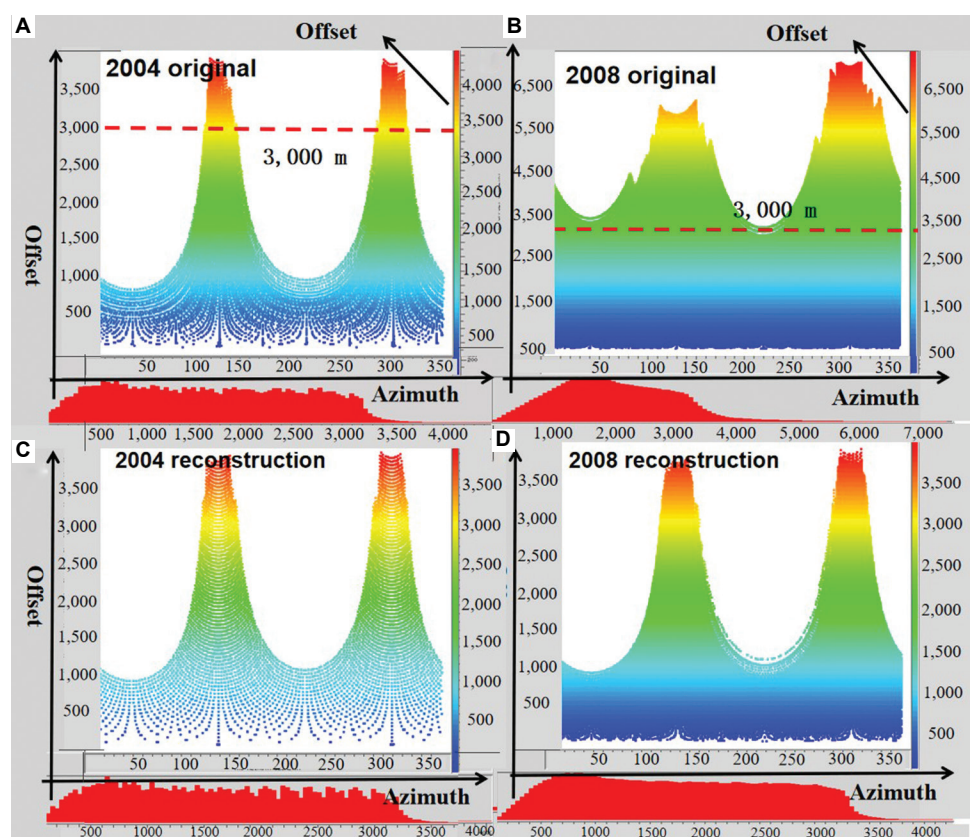


Figure 10. Azimuth distributions before and after data reconstruction for dual-phase datasets. (A) 2024 original: maximum offset: 4,400 m; minimum offset: 50 m; focus: 100–3,300 m. (B) 2024 original: maximum offset: 7,200 m; minimum offset: 25 m; focus: 100–4,200 m. (C) 2024 reconstruction: maximum offset: 4,300 m; minimum offset: 50 m; focus: 100–3,300 m. (D) 2024 reconstruction: maximum offset: 4,300 m; minimum offset: 50 m; focus: 100–3,300 m.

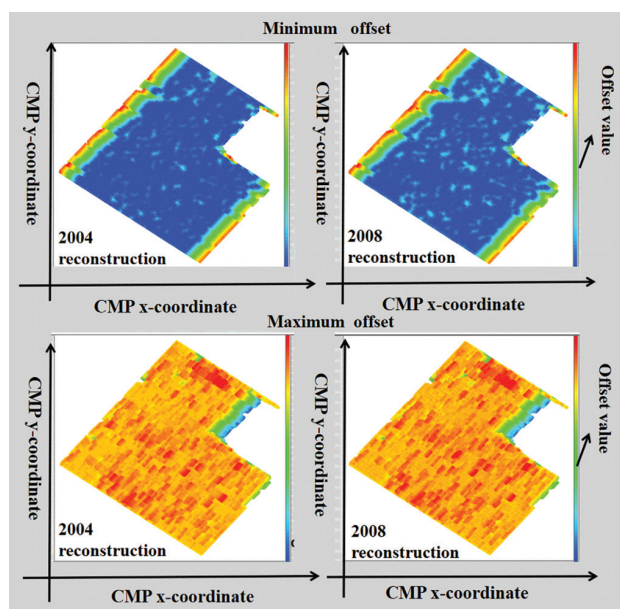


Figure 11. Offset distributions before and after data reconstruction for dual-phase datasets

Abbreviation: CMP: Common midpoint.

accuracy by adjusting thresholds. Indirectly incorporating the consistency of offset and azimuth distributions into the reconstruction process accounted more comprehensively for the impact of offset distribution differences on TL analysis than traditional methods. Our method yielded higher-quality reconstructed data compared to reconstruction approaches that consider only DR. It is also more practical for applications than other popular but complex methods, such as neural networks, compressed sensing theory, or interpolation-based reconstruction in various domains. For reconstructed two-phase datasets meeting specific conditions, shot-point distribution, receiver-point distribution, fold, azimuth, offset, and their distributions within the acquisition geometry served as key indicators for measuring repeatability. The figures presented in this study can be used as visual monitoring tools and for exporting monitoring metrics. It should be emphasized that the reconstruction algorithm provides only the foundational basis for the dataset. Even after reconstruction, the two-phase data may still exhibit inconsistencies in time, energy, waveform, frequency,

and phase. To fully meet the requirements for subsequent TL seismic interpretation, pre-stack consistency processing and post-stack mutual equalization techniques must be applied.

3. Application effects

To evaluate the practical efficacy of the proposed algorithm, the stacked profiles of the two datasets before

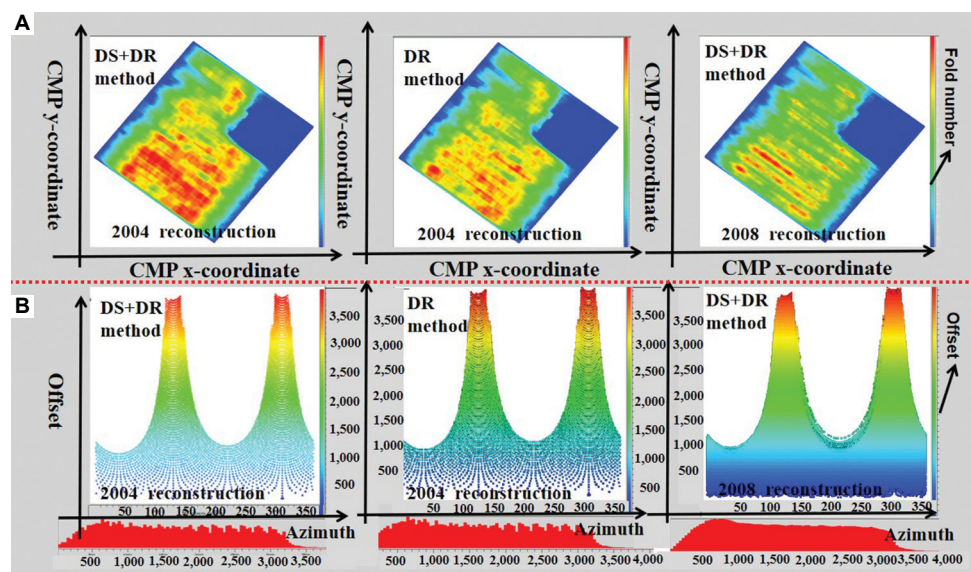


Figure 12. Comparison of DS + DR and DR methods. Common depth point fold (A) and azimuth versus offset (B). Abbreviations: DS: Distance of shot gathers; DR: Distance of receiver-point sets.

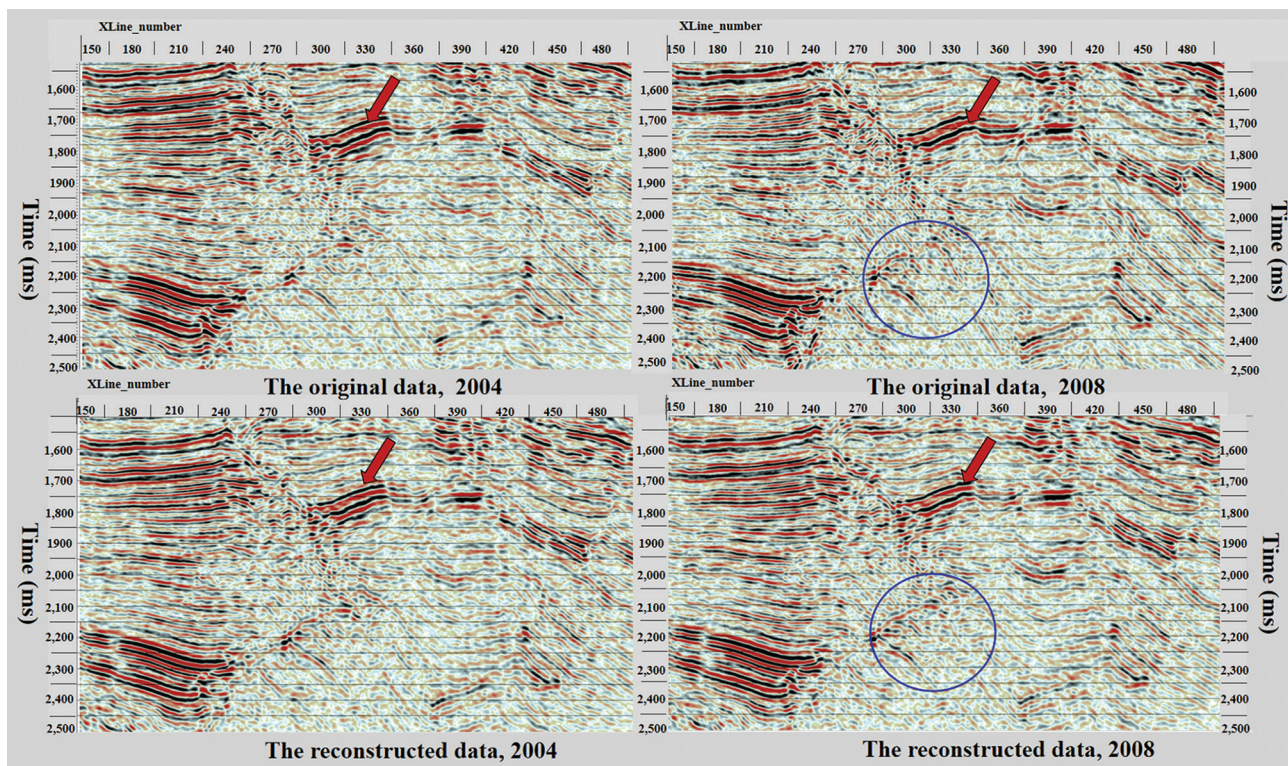


Figure 13. Stacked sections before and after data reconstruction. Blue circles and red arrows indicate areas used to assess reconstruction effectiveness.

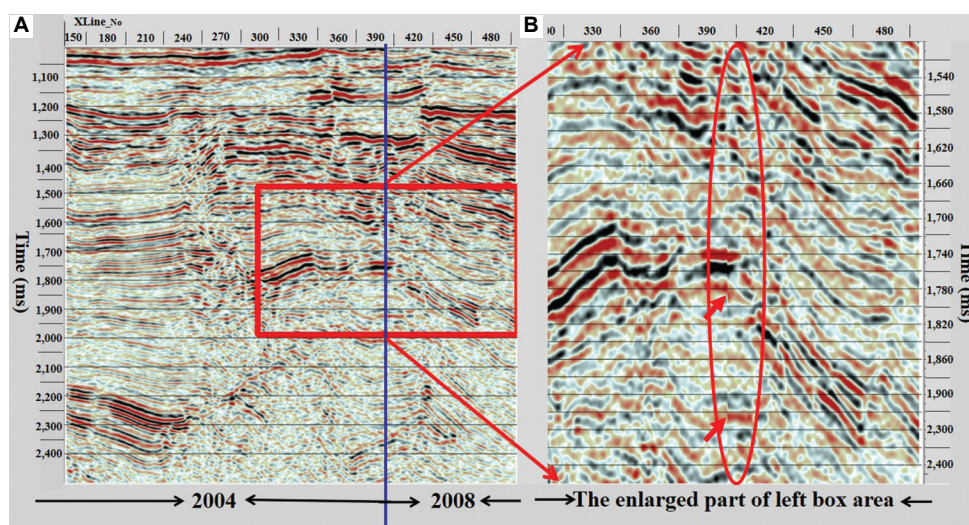


Figure 14. Merged, reconstructed, and stacked sections of dual-phase data. (A) Original. (B) Enlarged view. The blue line marks the boundary between the 2004 and 2008 datasets.

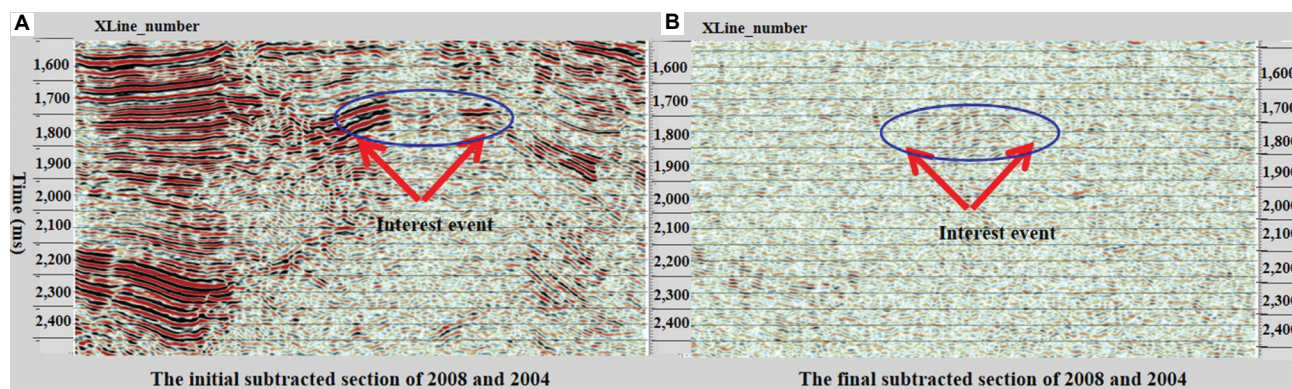


Figure 15. Subtracted seismic section. (A) Initial and (B) final.

and after reconstruction were compared. To ensure objectivity, pre-reconstruction and post-reconstruction data were processed using an identical pre-stack workflow, and results from the same longitudinal survey line were selected for analysis (Figures 13-15).

Figure 13 presents the initial stacked sections of the two datasets before and after reconstruction, while Figure 14 displays the spliced comparison of stacked profiles from the two reconstructed datasets at the same CMP location, along with the differential results obtained by directly subtracting the reconstructed data (Figure 15A). As shown in Figure 13, the reconstructed datasets exhibited substantial consistency in the positions of major structural events, overall frequency content, and wave group characteristics. Compared to the pre-reconstruction state, the proposed algorithm effectively removed shot gathers that compromised inter-dataset consistency. Although slight energy attenuation was observed for certain events in

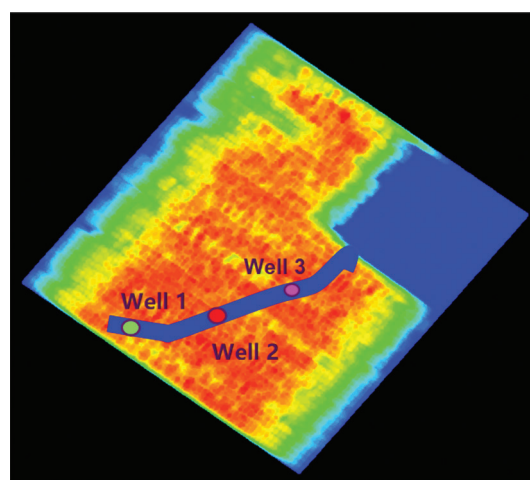


Figure 16. Seismic line crossing wells 1-3

the reconstructed section, the overall consistency between the two datasets was significantly enhanced.

From the spliced comparison and local magnifications of the two datasets (Figures 14A and B), minor time shifts remain, but they were negligible in magnitude. The subtraction results in Figure 15A reveal residual inconsistencies, including occasional false structures and non-seismic artifacts, indicating that the proposed method effectively mitigated significant inconsistencies between the datasets. Building on this, further pre-stack and post-stack consistency processing is recommended to suppress interference from non-reservoir fluid factors. This ensures that the differential results reflect actual TL changes in reservoir fluids, providing a solid foundation for residual oil interpretation and prediction. Figure 15 illustrates this, where the initial subtraction section (Figure 15A) and the final result after further processing (Figure 15B) can be used for TL interpretation, as noted in Figure 16.

To further illustrate the study results, a seismic survey line passing through production oil and gas wells 1–3 within the study area was selected (Figure 16). The consistency between the two-phase reconstructed data, their subtraction section (for fluid monitoring), and the production well data is shown in Figure 17.

Figure 17 shows that after processing, the subtraction section exhibited high correspondence with the production wells along the survey line. Strong seismic response events in the subtraction section aligned well with the lithological change depths in the three production wells.

This correspondence reliably reflects the monitored fluid response, providing valuable data support for oil and gas production decision-making.

4. Discussion

Research on onshore non-repeatable TL seismic is highly challenging yet holds significant practical importance for developing and producing mature oil and gas fields. However, the proposed method depends on the manual selection of the SumDsDr threshold. In regions with pronounced surface undulations, the utilization rate may decline further due to significant deviations in shot or receiver positions, underscoring the need to develop an adaptive threshold algorithm in future work.

The dual-constraint reconstruction method presented in this study effectively balances data utilization and consistency in onshore oilfields with substantial differences in acquisition geometries, providing a valuable reference for preprocessing non-repeatable TL seismic data. Nevertheless, its applicability requires further verification under varying surface conditions.

An important direction for subsequent research is to objectively quantify consistency evaluation indicators for reconstructed data. Potential metrics include offset distribution indices, azimuth distribution ranges, fold uniformity, and correlation coefficients between the datasets before and after reconstruction. Establishing such

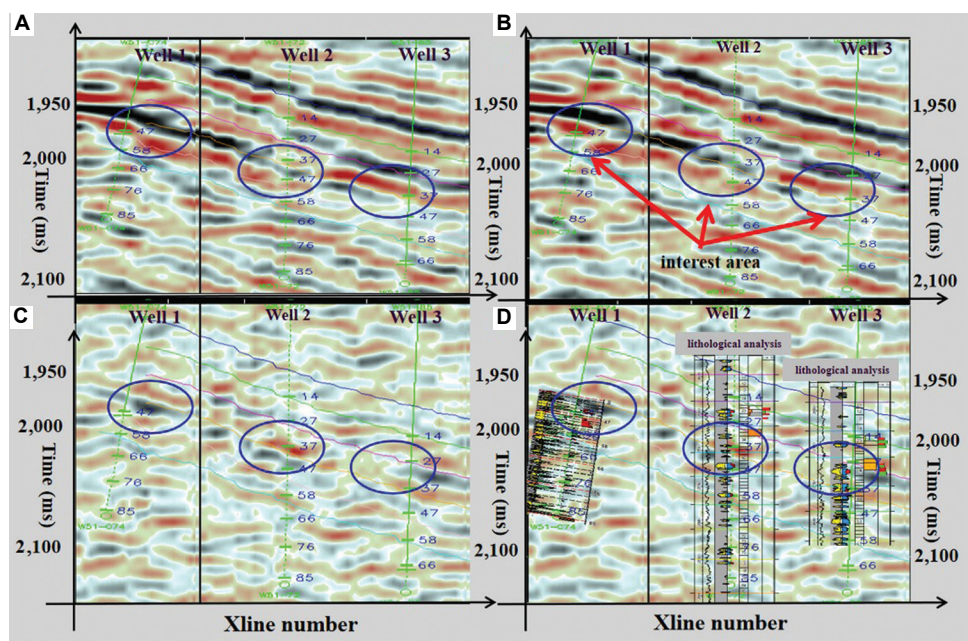


Figure 17. Seismic stack section crossing wells 1–3, corresponding to Figure 15. Green line: well logging curves and stratigraphic divisions; blue circles: areas of interest. (A) Reconstructed data of 2004; (B) reconstructed data of 2008; (C) subtraction section of 2008 and 2004; and (D) subtraction section with lithological analysis.

quantitative measures would enhance the reliability and comparability of reconstruction results.

5. Conclusion

The dual-constraint method for data reconstruction in this study can significantly reduce the inconsistency between the two onshore non-repeatable datasets. It can be used as the first step in fulfilling essential work for TL seismic exploration. The easy-to-execute yet straightforward strategy provides a practical reference for TL studies in onshore mature oilfields.

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Conflict of interest

The authors declare that they have no competing interests.

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Availability of data

The data can be obtained from the Exploration and Development Research Institute of Henan Oilfield through a request (subject to approval), and the original algorithms and codes can be obtained on request to BGP, CNPC.

References

1. Wang Z. Feasibility of time-lapse seismic reservoir monitoring: The physical basis. *Leading Edge*. 1997;16(9):1327-1329.
doi: 10.1190/1.1437796
2. Guerin G, He W, Anderson RN, *et al*. 4D seismic: The fourth dimension in reservoir management Part 5-Reservoir simulation as a tool to validate and constrain 4-D seismic analysis. *World Oil*. 1997;218(9):75-79.
3. Nur A, Tosaya C, Thanh DV. Seismic Monitoring of Thermal Enhanced oil Recovery Processes. In: *Expanded Abstracts of the 54th Annual International SEG Meeting*. SEG; 1984. p. 337-340.
doi: 10.1190/1.1894015
4. Greaves RJ, Fulp TJ. Three-dimensional seismic monitoring of an enhanced oil recovery process. *Geophysics*. 1987;52(9):1175-1187.
doi: 10.1190/1.1442381
5. Efnik MS, Taib SH, Islami N. Using time-lapse 4D seismic to monitor saturation changes in carbonate reservoirs. *J Pet Explor Prod Technol*. 2016;88(6):736-742.
doi: 10.1007/s12594-016-0541-3
6. Xin KL. Application of 4D seismic technology in SAGD steam chamber monitoring. *Pet Geophys Prospect*. 2019;54(4):882-890.
doi: 10.13810/j.cnki.issn.1000-7210.2019.04.020
7. Lumley DE. Time-lapse seismic reservoir monitoring. *Geophysics*. 2001;66(1):50-53.
doi: 10.1190/1.1444921
8. Jenkins SD, Waite MW, Bee MF. Time-lapse monitoring of the Duri steamflood: A pilot and case study. *Leading Edge*. 1997;16(9):1267-1273.
doi: 10.1190/1.1437778
9. Nguyen PKT, Nam MJ, Park C, Park C. A review on time-lapse seismic data processing and interpretation. *Geosci J*. 2015;19(2):375-392.
doi: 10.1007/s12303-014-0054-2
10. Sambo C, Iferobia CC, Babasafari AA, Rezaei S, Akanni OA. The role of time lapse (4D) seismic technology as reservoir monitoring and surveillance tool: A comprehensive review. *J Nat Gas Sci Eng*. 2020;80:103312.
doi: 10.1016/j.jngse.2020.103312
11. Emami Niri M. 3D and 4D seismic data integration in static and dynamic reservoir modeling: A review. *J Pet Sci Eng*. 2018;167:514-529.
doi: 10.22078/jpst.2017.2320.1407
12. Zhuang H, Xu Y. 4D seismic data processing and its key

- techniques. *Prog Geophys*. 1999;14(2):33-43.
13. Yang Q, Zhong W. 4D seismic technique in oil and gas field development. *Geophys Prospect Pet*. 1999;38(3):50-57.
 14. Wu D, Li Z, Jiang B, Huang X, Li F, Chen X. The problems for land non-repeated time-lapse seismic data processing and its countermeasures. *Pet Geophys Prospect*. 2015;54(4):427-434.
doi: 10.3969/j.issn.1000-1441.2015.04.009
 15. Guo N, Shang X, Liu X, Wang S. Key techniques for non-repeated time-lapse seismic data processing technology. *Pet Geophys Prospect*. 2011;46(4):581-592.
doi: 10.1007/s12182-011-0118-0
 16. Ling Y, Huang X, Gao J, Lin J, Sun D. Case study of non-repeatable acquisition in time-lapse seismic exploration. *Geophys Prospect Pet*. 2007;46(3):231-248.
doi: 10.3969/j.issn.1000-1441.2007.03.003
 17. Li J, Chen X. Feasibility analysis and evaluation technology of time-lapse seismic reservoir monitoring. *Geophys Prospect Pet*. 2012;51(2):125-132.
doi: 10.3969/j.issn.1000-1441.2012.02.003
 18. Zhang A. Research on key techniques of time-lapse seismic feasibility demonstration. *Petrochem Technol*. 2024;31(2):204-206.
doi: 10.3969/j.issn.1006-0235.2024.02.070
 19. Liu W, Deng H, Zhang L, Huang F, Li F, Chen X. Feasibility study of time-lapse seismic acquisition timing: A case study in the L gas field. *Geophys Prospect Pet*. 2022;61(3):490-498.
doi: 10.3969/j.issn.1000-1441.2022.03.011
 20. Zhou X, Xia T, Zhang Z, Liu X. Application of pseudo-time-lapse seismic to residual oil analysis in the middle and late stages of oilfield development. *Geophys Prospect Pet*. 2024;63(2):449-458.
doi: 10.12431/issn.1000-1441.2024.63.02.016
 21. Yang W. 3D Processing and Interpretation Integration Group. Study on analysis and monitoring methods of 3D seismic data. *Pet Geophys Prospect*. 2002;(5):433-440.
doi: 10.3321/j.issn:1000-7210.2002.05.001
 22. Rosa DR, Schiozer DJ, Davolio A. Evaluating the impact of 4D seismic data artefacts in data assimilation. *Pet Geosci*. 2023;29(3):603-614.
doi: 10.1144/petgeo2022-069
 23. Yin C, Ge ZJ, Rui Y, Zhao S, Cui Q. Feasibility study on time-lapse seismic reservoir monitoring with non-uniform acquisition. *J Southwest Pet Univ Nat Sci Ed*. 2014;36(1):170-180.
doi: 10.11885/j.issn.1674-5086.2013.10.28.01
 24. Jin L, Chen X, Liu Q. Quality control method of time-lapse seismic cross-equalization processing with correlation parameters. *Nat Gas Ind*. 2005;25(11):33.
doi: 10.3321/j.issn:1000-0976.2005.11.011
 25. Lü X, Chen X, Diao S. An approach to time-lapse seismic rebinning and its realization. *Prog Explor Geophys*. 2004;27(3):117-181.
 26. Yang H, Li D, Zhang H, Yang J, Ma N. Key Technology of Time-Lapse Processing on Land. In: *Proceedings of the 2020 International Field Exploration and Development Conference*. Chengdu China; 2020. p. 7.
doi: 10.26914/c.cnkihy.2020.042217
 27. Rui YJ. Key techniques for time-lapse seismic processing with non-uniform onshore acquisition. *Geophys Geochem Explor*. 2016;40(4):778-782.
doi: 10.11720/wtyht.2016.4.22
 28. Rui YJ, Shang XM. Exploration and practice of non-uniform time-lapse seismic key technology in Shengli Oilfield. *Geophys Geochem Explor*. 2021;45(6):1439-1447.
doi: 10.11720/wtyht.2021.1219
 29. Jin L, Chen X. Hybrid factor processing method of cross-equalization for time-lapse seismic. *Pet Geophys Prospect*. 2005;40(4):400-406.
doi: 10.3321/j.issn:1000-7210.2005.04.011
 30. Jin L, Chen X. Effects of time-lapse seismic non-repeatability and verification of cross-equalization processing. *Prog Explor Geophys*. 2003;26(1):45-48.
 31. Guo N, Meng Y, Yang W, Li H. Repeatability measurement and consistency analysis methods for time-lapse seismic data. *Comput Techn Geophys Geochem Explor*. 2012;34(2):186-192.
doi: 10.3969/j.issn.1001-1749.2012.02.014
 32. Guo N, Wu G, Shang X. Application of cross-equalization method in non-repeatable time-lapse seismic data processing. *Pet Geophys Prospect*. 2011;50(6):600-606.
doi: 10.3969/j.issn.1000-1441.2011.06.010
 33. Wang Y, Shen G, Xu H, Fu J, Shan L. Key Technology Applications of Non-Uniform Time-Lapse Seismic. In: *Proceedings of the SPG/SEG Beijing 2016 International Geophysical Conference*. Beijing China; 2016. p. 382-385. Available from: <https://d.wanfangdata.com.cn/conference/ChtDb25mZXJlbnNIbmV3UzIwMjU4MjAxMDQxNTUSBzk1NjY3ODYyYCDU4bGw1dmFq> [Last accessed on 30 May 2025].
 34. Zhu Z, Wang X, He Y, Sang S, Li L, Liu Z, et al. Research and application of key marine time-lapse seismic technologies. *China Offshore Oil and Gas*. 2018;30(4):76-85.
doi: 10.11935/j.issn.1673-1506.2018.04.009
 35. Wang D, Liu J, Qiu B, Yan H. Quality control technology of ocean time-lapse seismic data processing. *Chin J Eng Geophys*. 2018;15(3):253-260.
 36. Liu W, Lei X, Sui B, Li Y, Chen F, Liu Z, et al. Research on

- non-repeatable time-lapse seismic matching processing based on OBC and streamer data. *Prog Geophys*. 2025;1-13.
37. Chen CQ, Dai HT, Gao Q, Chen J, Luo W, Wang Z. A processing method for seismic data consistency under complex surface conditions and its applications. *Geophys Geochem Explor*. 2023;47(4):954-964.
doi: 10.11720/wtyht.2023.1162
 38. Liu L, Chen S, Wang YL, Xiao Y, Yue H. Research on the application of mixed source data matching processing technology in 3D seismic exploration of coal field. *Prog Geophys*. 2024;39(5):1951-1962.
doi: 10.6038/pg2024HH0498
 39. Fomel S, Jin L. Time-lapse image registration using the local similarity attribute. *Geophysics*. 2009;74(2):A7-A11.
doi: 10.1190/1.2793090
 40. Liu X, Chen X, Bai M, Chen Y. Time-lapse image registration by high-resolution time-shift scan. *Geophysics*. 2021;86(3):M49-M58.
doi: 10.1190/geo2020-0459.1
 41. Chen X, Yang X, Xiao P, Lv W, Zhang X, Duan R. Application of time-lapse seismic technology in deepwater turbidite reservoir monitoring: A case study of the deep water fan a oilfield in West Africa. *Geophys Prospect Pet*. 2023;62(3):538-547.
doi: 10.12431/issn.1000-1441.2023.62.03.015
 42. Dong FS, Fu LY, Quan HY, Dong K. Matched multi-trace geometry repeatability for time lapse seismic. *Chin J Geophys*. 2016;59(8):3056-3067.
doi: 10.6038/cjg20160828
 43. Wu Y, Ling Y, Zhang Y, Guo X. Case study of towed streamer time-lapse seismic acquisition design in offshore areas. *Pet Geophys Prospect*. 2016;51(1):1-12.
doi: 10.13810/j.cnki.issn.1000-7210.2016.01.001
 44. Li X, Hu G, Fan T, et al. The application conditions and prospects of time-lapse seismic technology in offshore oilfield. *China Offshore Oil Gas*. 2015;27(6):48-52.
doi: 10.11935/j.issn.1673-1506.2015.06.008
 45. Zhou J, Xie Y, Chen Z, Wang S. Application of time-lapse seismic in offshore gas fields in China. *Prog Explor Geophys*. 2011;46(2):285-292.
 46. Zhou J, Zhang L, Liu W, Hu L, Wang Q. Application of time-lapse seismic gas reservoir monitoring in the Yacheng 13-1 gas field. *Geophys Prospect Pet*. 2020;59(4):637-646.
doi: 10.3969/j.issn.1000-1441.2020.04.014
 47. Smit JA, Brain J, Watt K. Repeatability Monitoring During Marine 4D Streamer Acquisition. In: *Extended Abstracts of the 67th EAGE Conference and Exhibition*. EAGE; 2005. p. C015.
doi: 10.3997/2214-4609-pdb.1.C015