THE EFFECT OF SIGNAL-TO-NOISE RATIO ON GROUND ROLL ATTENUATION USING ADAPTIVE SINGULAR VALUE DECOMPOSITION: A CASE STUDY FROM THE SOUTH WEST OF IRAN

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ABSTRACT

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Ground roll as a type of coherent noise with high amplitude, low frequency and low velocity masks the reflections in seismic data. Ground roll suppression is one of the important topics in data processing. Adaptive Singular Value Decomposition (ASVD) is a coherency based filter which decomposes data into its eigenimages and can detect horizontal events in the first eigenimages. By using the adaptive method, the ground roll is converted to a horizontal event. By zeroing the first eigenvalues which present ground roll, it can be suppressed. By increasing the number of the eigenvalues to be zeroed, ground roll is better attenuated but more reflections are damaged as well.

In this study, this filter is applied to synthetic data with various signal-to-noise ratios (SNR) and two real shot records from the South West of Iran as case studies. The first one was examined with high and low SNRs (with adding the noise). However, in the second one, extensive presence of ground roll and other noises led to an extreme decrease in SNR. Results of applying the filter to the synthetic and field data sets with various SNRs showed that the ASVD filter could attenuate the ground roll with minimum harm to signals and it was not sensitive to SNR, because the eigenvalues were sorted in a descending order in the eigenvalue spectrum. Therefore, after rotating the data, the ground roll as a horizontal and coherent event, was represented in the first eigenvalues. However, the random noise or reflections had lower energies and coherencies compared to the flattened ground roll and they were represented in the next eigenvalues. Due to this separation, the SNR has no impact on the ground roll attenuation via ASVD.

KEY WORDS: ground roll attenuation, random noise, signal-to-noise ratio (SNR),
adaptive singular value decomposition, eigenimages.

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INTRODUCTION

Source-generated noise exists in various types of coherent noise trains. Ground roll, airwaves and near surface scattered energy are the most troublesome forms of coherent noises. Ground roll is the main type of a coherent noise in land seismic surveys. Ground roll is a particular type of Rayleigh wave with high amplitudes, low frequencies (mostly under 20 Hz) and low velocities. The ground roll is dispersive, i.e., in general, the higher is the frequency, the lower the velocity. Because of these feathers of the ground roll, the shallow reflections in the near offset and deep reflections in the far offset are masked by the ground roll so that they are distributed in a fan-shaped zone. The separation of signal and noise is an important step in seismic data processing to achieve a better image and stack from the subsurface.

Up to now, many different methods have been proposed for ground roll attenuation. ASVD is a coherency-based method in separation of signal and noise which adaptively flattens the ground roll and suppresses it by zeroing the first eigenvalues. Freire and Ulrych (1988) used SVD to separate up- and down-going waves in a seismic vertical profiling (VSP) section. Jackson et al. (1991) used SVD to analyze seismic arrivals at a triaxial station and obtained estimates of the signal polarization directions and noise. Franco and Musacchio (2001) proposed that polarization analysis can be applied to extract elliptically polarized ground rolls, provided that multi-component receivers are used. Tyapkin et al. (2003) proposed to use the data alignment method of Liu (1999) to make the coherent noise horizontally aligned in one or more time sections of a common shot gather. Kendall et al. (2005) proposed an SVD-polarization filter for the ground roll attenuation on multi-component data. Lu (2006) presented an adaptive SVD filter to enhance the non-horizontal events by detection of the seismic image texture and then the horizontal alignment of the estimated dip through data rotation. Bekara and Baan (2007) proposed a local SVD approach to noise removal. Cary and Zhang (2009) stated that in order to concentrate the noise into the first eigenimages, the ground roll cone must be flattened by applying a linear move out and then by applying a trim static determined by a cross-correlation. They also designed a signal-to-noise measure that adapts to the spatial and frequency variations in the signal and the noise for choosing the number of eigenimages that represent the ground roll. Porsani et al. (2010) presented an SVD filtering method for ground roll attenuation. In their method, before the SVD computation, the normal move out (NMO) correction is applied to the data, with the purpose of flattening the reflections and constructing reflections. An inverse NMO is then applied.

In this study, the concepts of singular value decomposition and eigenimage filtering (ASVD filter) are reviewed and then the effect of signal-to-noise ratio (SNR) on the ground roll attenuation using an ASVD filter is studied over synthetic data with various SNRs and as case studies on two field data sets from the South West of Iran. The first one had a normal SNR. However, in the second one, extensive presence of the ground roll led to an extreme decrease in SNR, i.e. it contained strong ground roll and noise as well as weak signals. In addition, similar to synthetic data to examine the effect of SNR on the ground roll attenuation via ASVD filter, random noise was added to the first real data set and therefore, the SNR was decreased.

ADAPTIVE SINGULAR VALUE DECOMPOSITION

SVD is based on a theorem from linear algebra which says that a rectangular matrix **X** can be broken down into the product of three matrices - an orthogonal matrix **U**, a diagonal matrix **S** (or Σ), and the transpose of an orthogonal matrix **V**. The theorem is usually presented something like this:

$$\mathbf{X}_{mn} = \mathbf{U}_{mm}\mathbf{\Sigma}_{mn}\mathbf{V}^T_{nn} \ , \qquad (1)$$

where $\mathbf{U}^T\mathbf{U} = \mathbf{I}$; $\mathbf{V}^T\mathbf{V} = \mathbf{I}$; the columns of **U** are orthonormal eigenvectors of $\mathbf{XX}^T$, the columns of **V** are orthogonal eigenvectors of $\mathbf{X}^T\mathbf{X}$, and **Σ** (or **S**) is a diagonal matrix containing the square roots of eigenvalues from **U** or **V** in descending order (Baker, 2005). The diagonal entries σ_i of **Σ** are known as the singular values of **X**. A common convention is to list the singular values in descending order. These singular values are sorted such that $\sigma_1 > \sigma_2 > \ldots > \sigma_n$. Sacchi says "The SVD of **X** is given by (Lanczos, 1961)",

$$\mathbf{X} = \sum_{i=1}^{r} \sigma_i u_i v_i^T \ , \qquad (2)$$

Andrews and Hunt (1977) designated the outer dot product $u_i v_i^T$ as the i-th eigenimage of the matrix **X** and r is the rank of the matrix. On the other hand, in the case where all traces are equal to within a scale factor, all traces are linearly dependent; data is of rank one and may be successfully reconstructed by the first eigenimage (Sacchi, 2002). In the general case, depending on the linear dependence which exists among the traces, event may be reconstructed from only the first few eigenimages. Freire and Ulrych (1988) defined band-pass, low-pass and high-pass eigenimages in terms of the ranges of singular values used. The band-pass image is reconstructed by rejecting highly correlated as well as highly uncorrelated traces and is given by

$$\mathbf{X}_{BP} = \sum_{i=p}^{q} \sigma_i u_i v_i^T \ , \quad 1 < p \leq q < r \qquad (3)$$

where p and q are the number of eigenvalues which are used to approximate **X** and r is the rank of the matrix. The summation for the low-pass is from $i = 1$

to p−1 and for the high pass is from i = q+1 to r. These parameters may, in general, be estimated from a plot of the eigenavalues $\lambda_i = \sigma_i^2$ as a function of the index i. In certain cases, an abrupt change in the eigenvalues is easily recognized. In other cases, the change in eigenvalue magnitude is more gradual and care must be exercised in the choice of the appropriate index values (Sacchi, 2002).

Figs. 1a to 1d show four events with 40 Hz dominant frequency, 2 ms sampling rate and 30 traces with 10 m trace spacing. Figs. 1a and 1b show a horizontal event with an infinite SNR and SNR = 2, respectively. The SNR in this data is defined as the max amplitude in the clean signal over the max amplitude of the band-pass noise (Seismic lab MATLAB code package, 2008, Signal analysis and imaging group, University of Alberta, Canada). Figs. 1c and 1d show a linear event with a velocity of 1200 m/s with an infinite SNR and SNR = 2, respectively. Figs. 2a to 2d show the eigenvalue value spectra of Fig. 1, sequencely. Parts (a) and (b) show a sharp abrupt change which is not observed in parts (c) and (d). Eigenimages before the abrupt change represent the horizontal event (Sacchi, 2002).

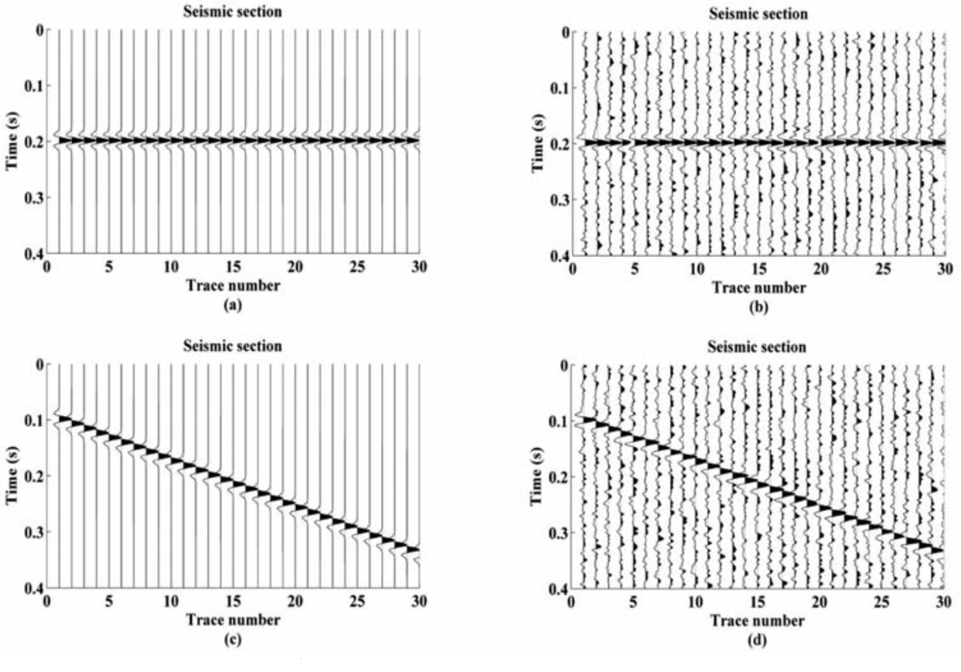

Fig. 1. Synthetic data with 2 ms sampling interval, 30 traces with 10 m trace spacing; (a) a horizontal event without random noise, (b) a horizontal event with random noise of SNR = 2, (c) a linear event with a velocity 1200 m/s and without noise, and (d) a linear event with a velocity of 1200 m/s and random noise of SNR = 2.

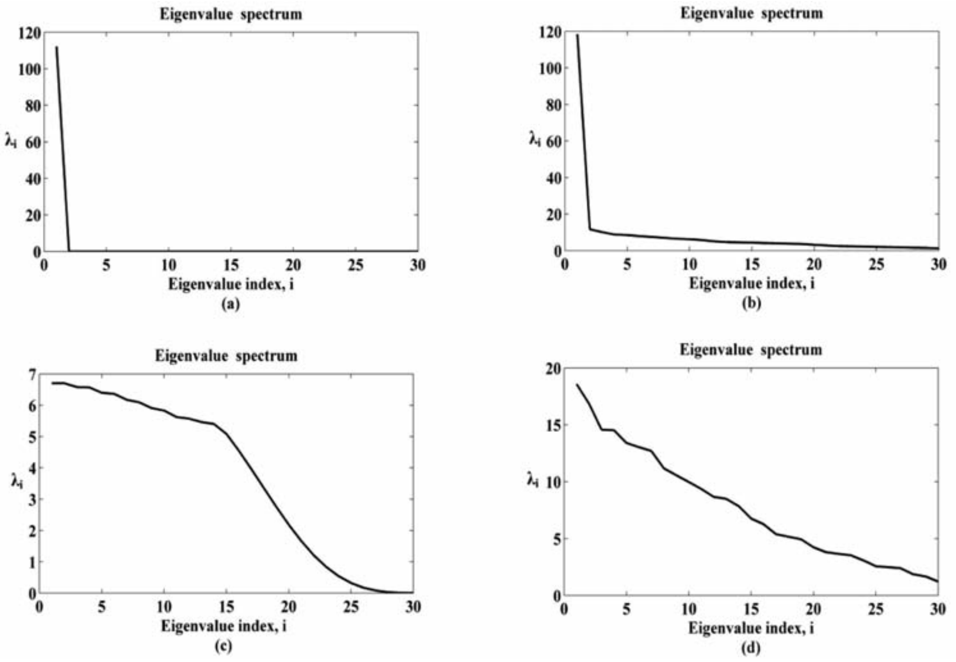

Fig. 2. Eigenvalue spectra (a) to (d) for parts (a) to (d) in Fig. 1.

Since the purpose is the ground roll attenuation with minimum damage to the signal, ASVD is only applied to the ground roll region. According to Fig. 3, since the ground roll is dispersive and there are only linear events with the same velocity in small windows both in the time and space directions, for ground roll attenuation the ground roll region must be divided into many spatial and time windows. To maintain data integrity, windows must have a 50% overlap in both directions. In each window, ground roll as a dip event is rotated to the horizontal event. As shown in Fig. 3, if a linear event such as the ground roll is flattened according to its velocity, it will be converted from a dip event to a horizontal event (Lu, 2006). The rotation defined as in Fig. 3, can be applied to any offsets but the linear move out (LMO) is rotation related to zero offset, i.e., in the case that reference offset is zero, rotation is equal to LMO. Ground roll's velocity limits are normally between 500 to 1500 m/s. Data is rotated in each window from a minimum to a maximum velocity as a loop (with a 50 m/s interval and slowness is used for sampling the velocity). According to eq. (4), in each rotation coherency index (CI) is calculated. As an adaptive method is presented, the velocity that maximizes CI is detected and it is considered as the best velocity to convert the ground roll as a horizontal event (Montagne and Vasconcelos, 2006).

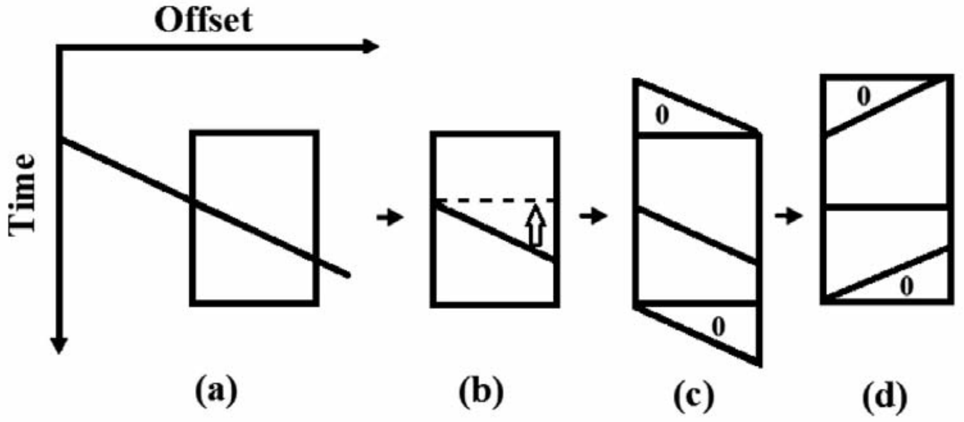

Fig. 3. An illustration of the data rotation along an angle: (a) a linear event in a shot record, (b) the input matrix before rotation, where the dipping line denotes the dipping events, (c) two parts filled with zeros are added to the top and bottom of the input matrix to form a new matrix, and (d) the output matrix after data rotation using a column shifting. Parts (b) to (d) are from Lu (2006).

$$CI = \lambda_1 / \sum_{i=1}^{r} \lambda_i \ , \tag{4}$$

where λ_i are the eigenvalues of the data and r is the rank of the data. As defined above, CI represents the relative weight of the most coherent and flattened mode in an SVD expansion. Because the first eigenvalue increases the more horizontal and coherence, the CI will be high. The ground roll becomes as horizontal as possible at a velocity equivalent to ground roll's velocity. This velocity is the optimum velocity and is calculated adaptively. It maximizes CI. The maximum CI is obtained when the ground roll is as horizontal as possible (Boustani et al., 2013). In this case, the ground roll is represented by the first eigenvalues. Since split-spread data has a ground roll with opposite slopes, to apply the filter, data must be divided into two off-end data sets. According to Fig. 3, this method is designed for events with a positive slope so the negative offset part must be folded before applying the filter. In each window, the ground roll is suppressed by zeroing the first eigenimages in the best rotation by which it is made as horizontal as possible. Manually, the ground roll is better attenuated by increasing the number of eigenvalues that are zeroed, but more signal is damaged and similarly by decreasing it, both the ground roll and the signal are retained in data. After zeroing the eigenvalues which represent the ground roll, the data must be inversely rotated by the optimum velocity because it must be replaced in its original place. Doing these steps for other windows, the ground roll would be suppressed from data.

GROUND ROLL SUPPRESSION ALGORITHM

The algorithm of the ground roll suppression via ASVD is as follows. The flowchart of the designed code is given in Fig. 4:

- Plot data record.
- Select the ground roll in a fan-shaped zone to apply the filter.
- Divide the ground roll region into many windows in the spatial and time directions.
- Apply the rotation step as in Fig. 3 in the first window for all velocities in the ground roll's velocity limits (e.g., between 500 to 1500 m/s, with a 50 m/s interval).
- Calculate CI for every velocity.
- Find the velocity which maximizes CI.
- Apply the rotation step with an optimum velocity and apply SVD again.
- Reset the first eigenvalues to zero which have higher energies and represent the ground roll and then reconstruct the data.
- Apply the inverse rotation step to replace the data in an original place.
- Apply this algorithm to the next windows.

DATA EXAMPLES

Synthetic data

Table 1 shows the earth model for generating the synthetic data. The synthetic ground roll was generated by the CPS software (Herrmann, 2006), using frequency-wavenumber method whereas reflections, refractions and random noise were generated by MATLAB. Synthetic data has 385 traces with 12.5 m trace spacing and 200 m near offset and a 4 ms sampling interval. The source was located at the depth of 14 m. Since the purpose was ground roll attenuation with minimum harm to the signals, the filter was only applied to the ground roll region. As shown in Fig. 5a, the ground roll region in the synthetic data to be filtered was selected and separated with a white line, so that the reflections out of this region were not damaged. Figs. 5b and 5c show the filtered data and the difference between (a) and (b), respectively.

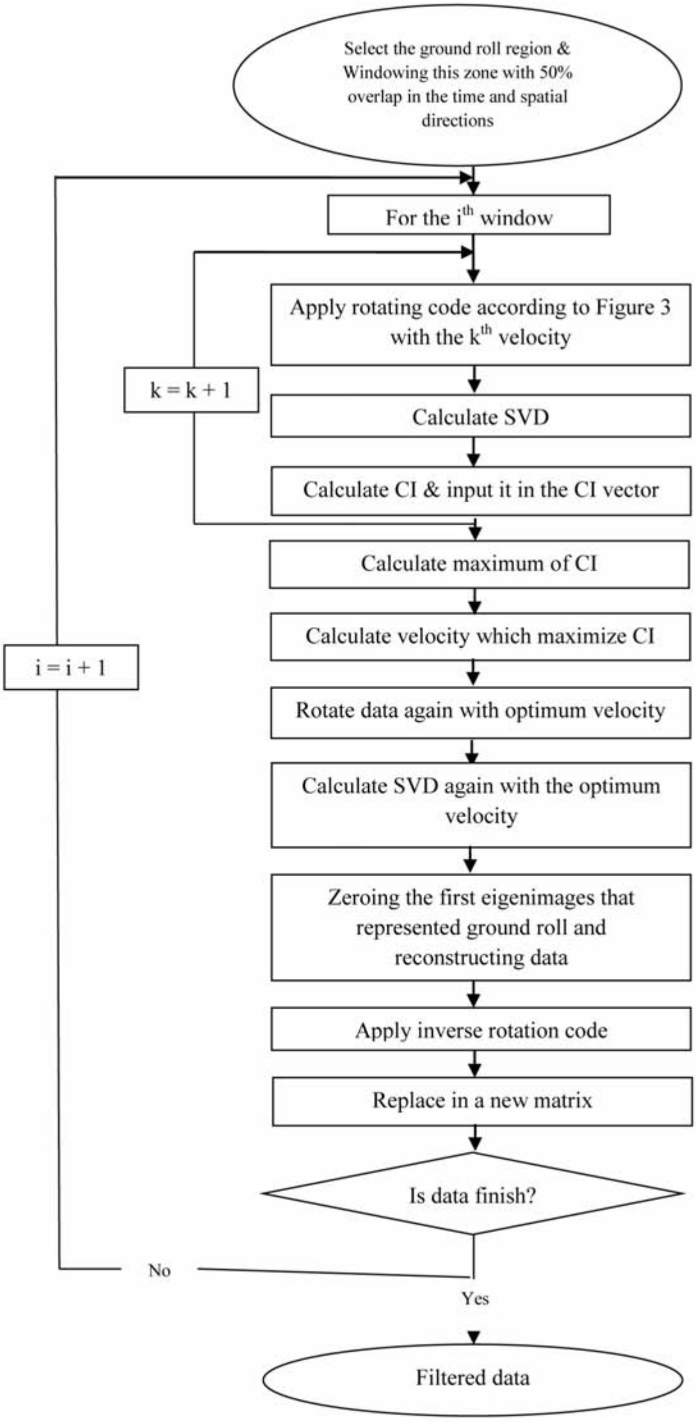

Fig. 4. The flowchart of the designed code.

Table 1. Earth model used to generate the synthetic data.

Layers	Thickness (km)	Density (g/cc)	S-wave velocity (km/s)	P-wave velocity (km/s)
1st layer (weathered)	0.01	1.8	0.3	0.9
1st layer	0.9	2	1.2	2.2
2nd layer	0.6	2.2	1.4	2.4
3rd layer	0.5	2.4	1.5	2.7
4th layer	0.7	2.5	1.6	2.9
Half space	Infinite	2.7	2	3.4

In this synthetic data, SNR was 10, to examine the effect of SNR on the ground roll attenuation via ASVD filter, random noises were added (SNRs of 2 and 1) to this synthetic data. Synthetic data with SNR = 2 is shown in Fig. 6a. The data after filtering and the difference between (a) and (b) are shown in Figs. 6b and 6c, respectively. Fig. 7a shows data with SNR = 1. The data after filtering and difference between (a) and (b) are shown in Figs. 7b and 7c, respectively. Considering Figs. 6 and 7 it can be concluded that, SNR has no considerable effect on the ground roll attenuation by ASVD.

Field data

Of the case studies, the ASVD filter was applied on two field data sets from the South West of Iran, the first one had a normal SNR, but in the second one, extensive presence of the ground roll led to an extreme decrease in SNR, i.e., it had strong ground roll and weak signals. In addition, to examine the effect of SNR on the ground roll attenuation via ASVD filter, random noise was added to the first real data set. Fig. 8a shows the first split spread shot record consisting of 350 traces with 30 m trace spacing, 4 ms sampling interval, and 2 s total recorded data. True amplitude recovery and statics corrections were applied to this data. The suitable ground roll region is selected for applying the filter as shown in Fig. 8a with a white line. Fig. 8b shows the data after filtering and Fig. 8c shows the difference between Figs. 8a and 8b. To evaluate

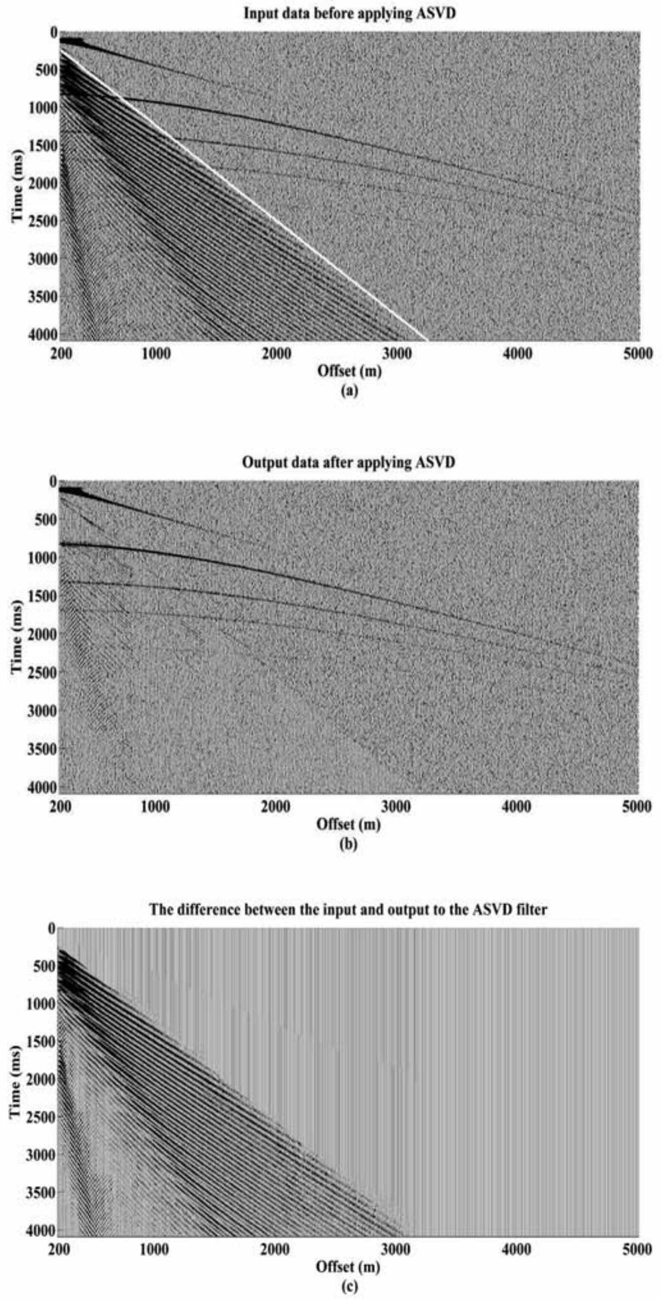

Fig. 5. The ground roll attenuation: (a) synthetic data for an earth model which the 1st layer is weathered (Table 1) with the sampling interval of 4 ms, near offset 200 m, receiver offset 12.5 m with 385 traces and SNR = 10, (b) the output data after applying ASVD, and (c) the difference between (a) and (b). The synthetic ground roll was generated by the CPS software (Herrmann, 2006) using frequency-wavenumber method whereas reflections, refractions and random noise were generated by MATLAB.

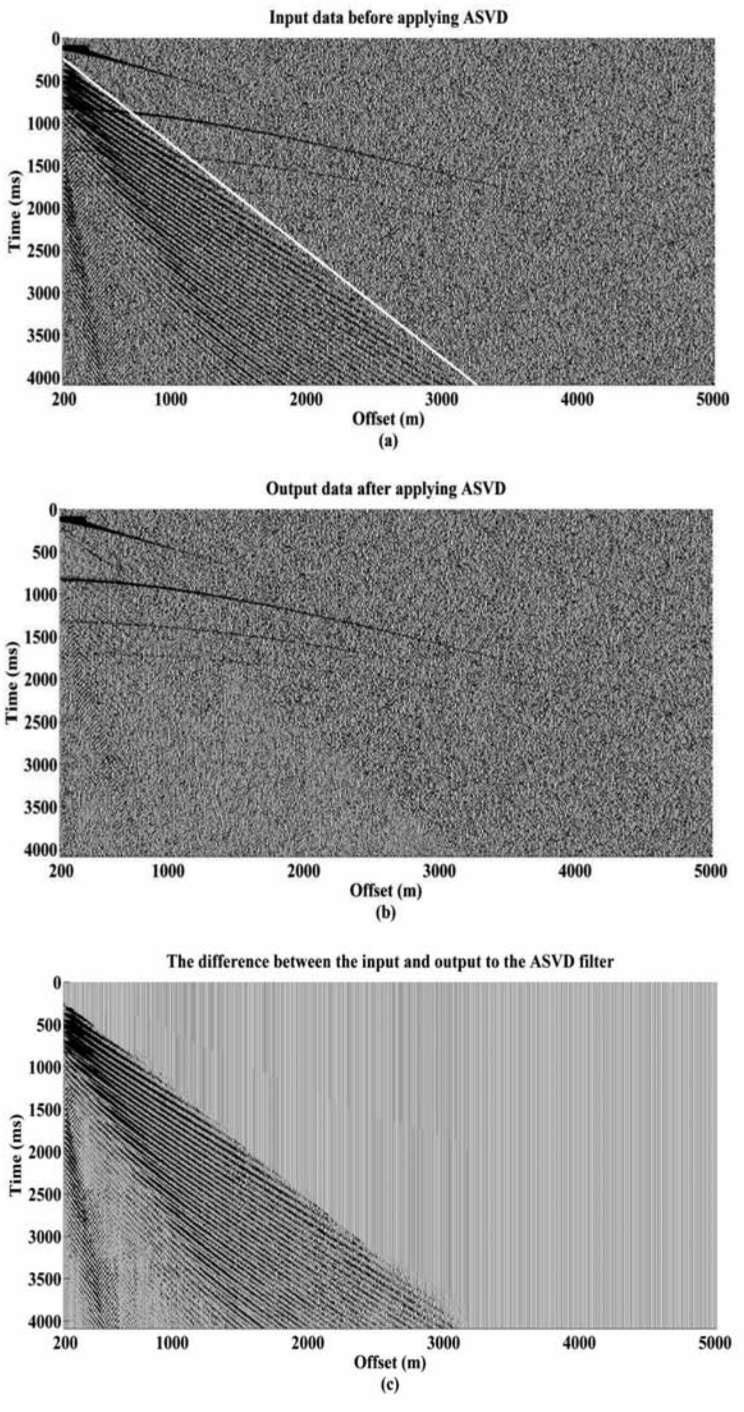

Fig. 6. The effect of SNR evaluation: (a) synthetic data with SNR = 2, (b) the output data after applying ASVD, and (c) the difference between (a) and (b).

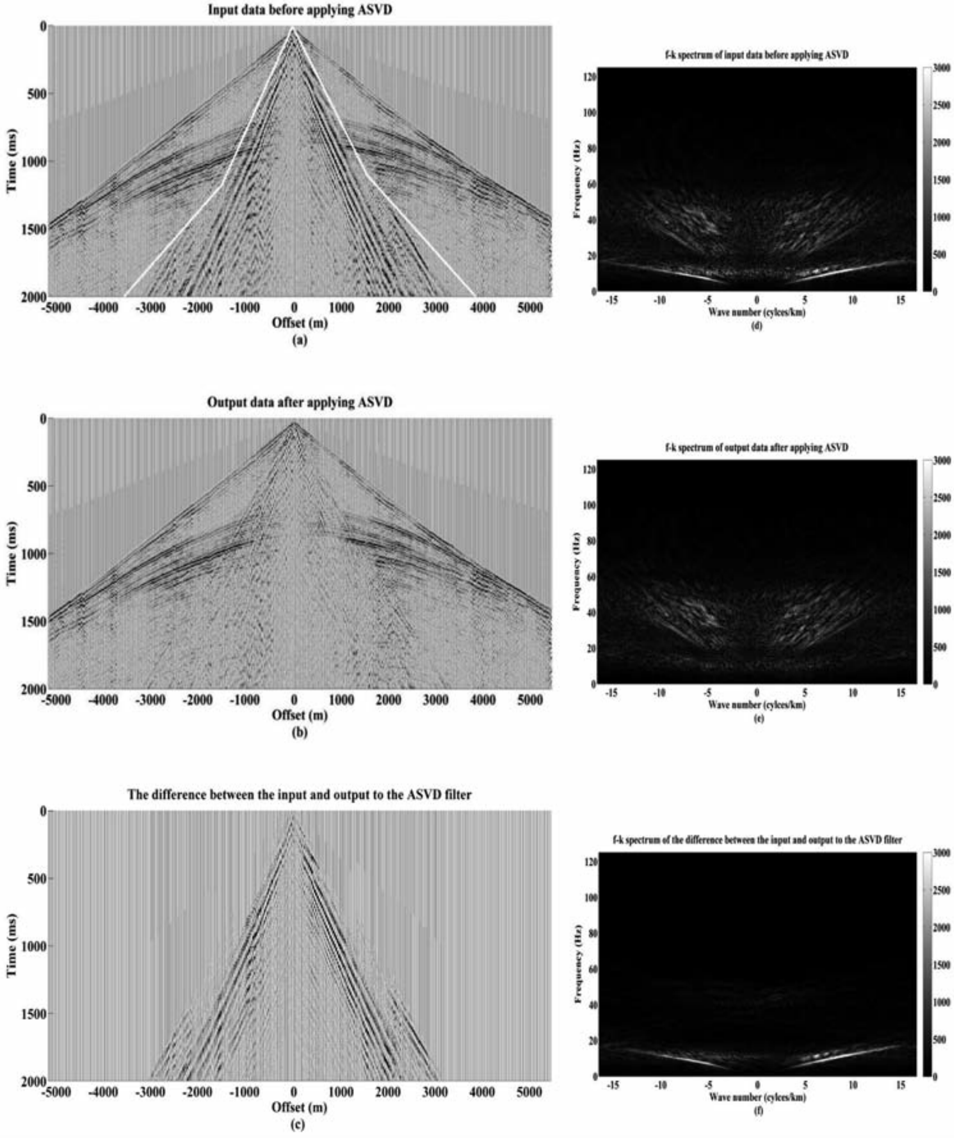

Fig. 7. The effect of SNR evaluation: (a) synthetic data with SNR = 1, (b) the output data after applying ASVD, and (c) the difference between (a) and (b).

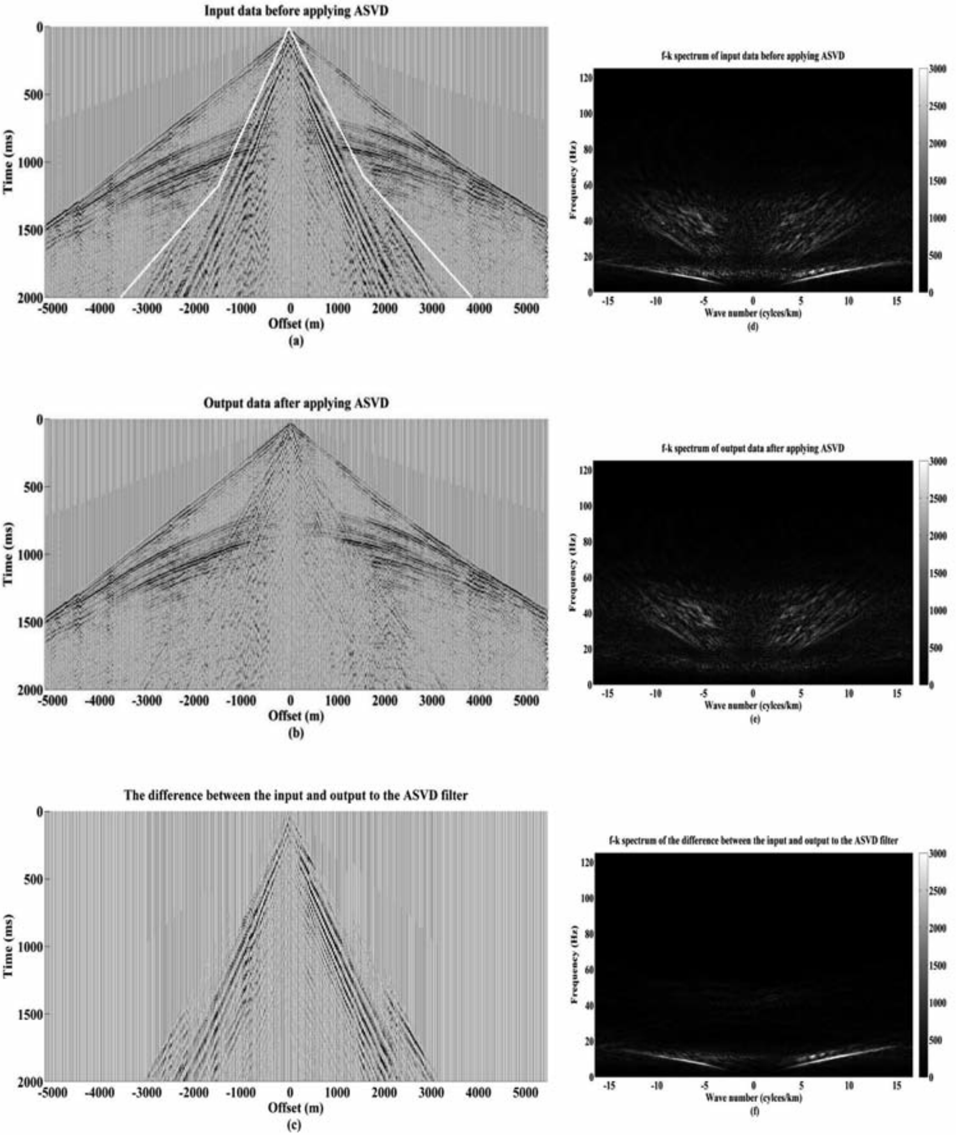

Fig. 8. The ground roll attenuation in a shot record with acceptable SNR: (a) a shot record from the South West of Iran, with the sampling interval of 4 ms and a 30 m trace interval for 350 traces, (b) the output data after applying ASVD, (c) the difference between (a) and (b), (d) f-k spectrum of the data input data, (e) f-k spectrum of the output data after applying ASVD, and (f) f-k spectrum of (c).

the performance of the filter, f-k spectra of the input data, filtered data and the difference of them are shown in Figs. 8d, 8e and 8f, respectively. Similar to the synthetic data, to examine the effect of SNR on the ground roll attenuation via ASVD filter, random noise was added to the first real data set and therefore, the SNR was decreased. The new data with lower SNR is shown in Fig. 9a. The ground roll region for applying the filter and the other effective parameters such as the number of windows in the time and spatial directions in this data was considered similar to Fig. 8. Fig. 9b shows the data after filtering and Fig. 9c shows the difference between (a) and (b). To evaluate the performance of the filter, f-k spectra of the input data, filtered data and their differences are shown in Figs. 9d, 9e and 9f, respectively. The second shot record is split-spread and consists of 680 traces with 25 m trace spacing, 4 ms sampling interval, and 5.2 s total recorded data. This data contained strong ground roll and other noises as well as weak signals (i.e., very poor SNR). Similar to the first data set true amplitude recovery and statics corrections were applied to it. Only, the ground roll zone was filtered. Fig. 10a shows the input data. Figs. 10b and 10c show data after filtering and the difference between the input and output, respectively. Again to evaluate the performance of the filter, f-k spectra of the input data, filtered data and the difference between (a) and (b) are shown in Figs. 10d, 10e and 10f, respectively. Considering the results once more it can be concluded that, SNR has no considerable effect on the ground roll attenuation by ASVD.

DISCUSSION

Based on the above, after dividing the ground roll region to many windows in time and spatial directions and converting the ground roll to the horizontal event, ASVD can detect it in the first eigenimages, so the ground roll must be suppressed. There are optimum number of considering windows in time and spatial directions in ground roll region for synthetic data and two field data sets in Table 2.

Table 2. The optimum numbers of considering windows in the time and spatial directions in the ground roll region for the synthetic data and two field data sets.

	Synthetic data	The first field data (Figs. 8 and 9)	The second field data (Fig. 10)
Number of windows in the time direction	5	2	10
Number of windows in the spatial direction	8	14	12

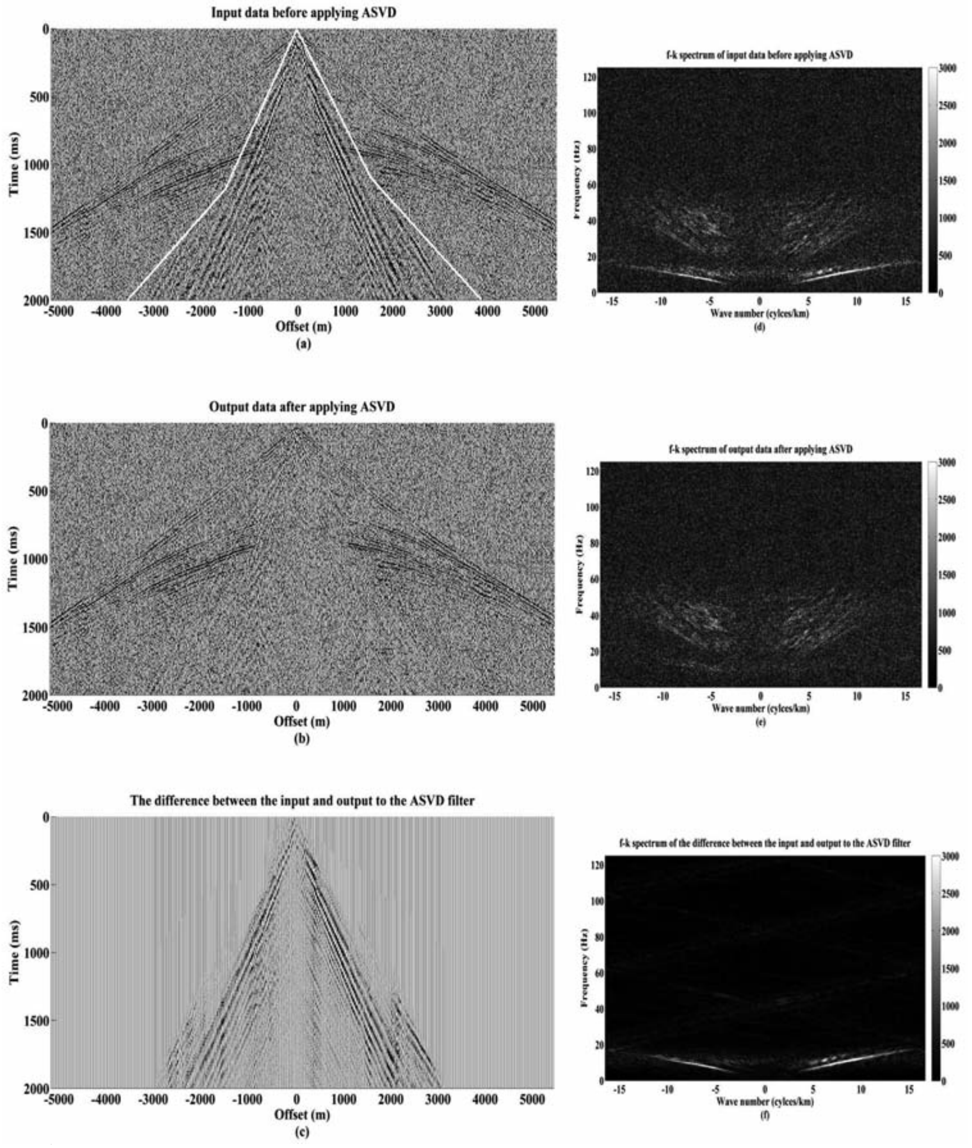

Fig. 9. The ground roll attenuation in a shot record with lower SNR compared with Fig. 8 (SNR = 2): (a) a shot record from the South West of Iran with added noise, and the sampling interval of 4 ms and a 30 m trace interval for 350 traces, (b) the output data after applying ASVD, (c) the difference between (a) and (b), (d) f-k spectrum of the data input data, (e) f-k spectrum of the output data after applying ASVD, and (f) f-k spectrum of (c).

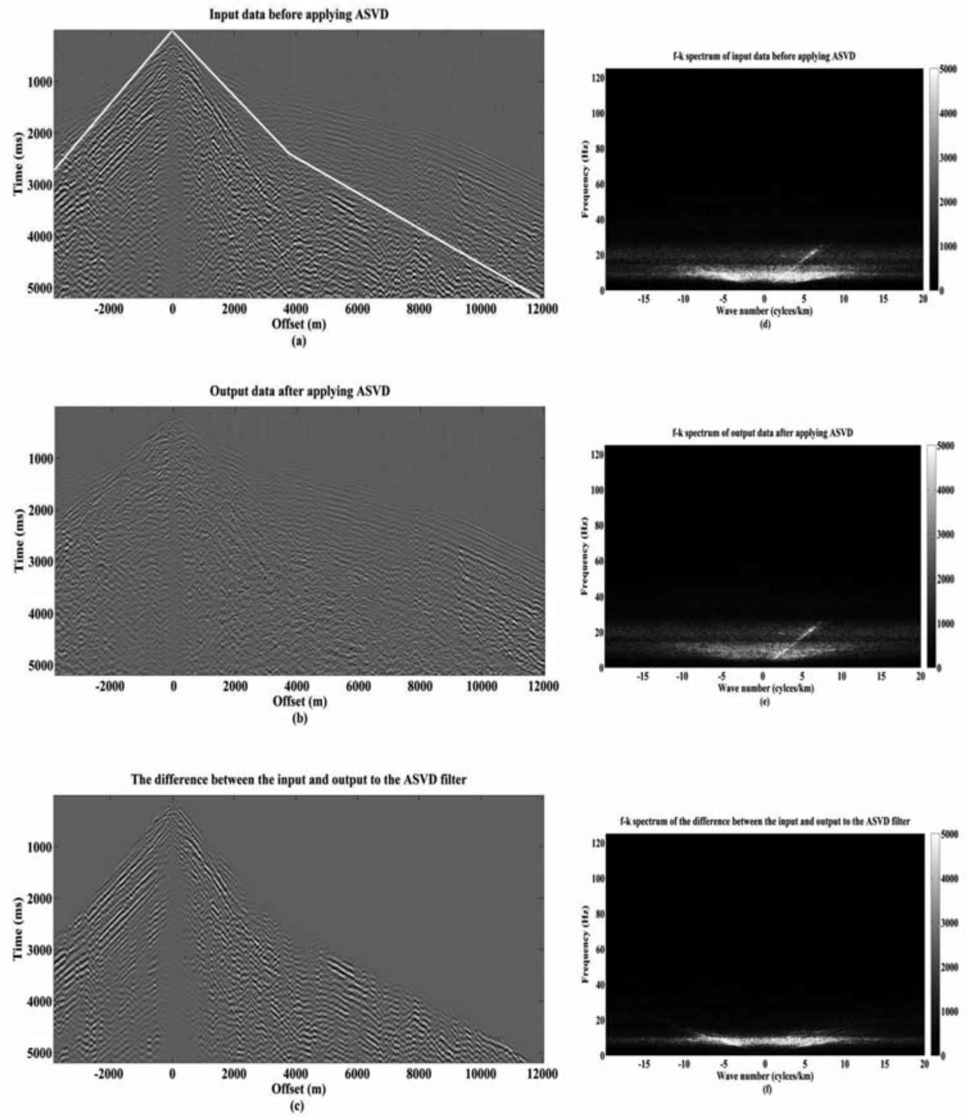

Fig. 10. The ground roll attenuation in a shot record with very poor SNR: (a) the second shot record from the South West of Iran, with the sampling interval of 4 ms and a 25 m trace interval for 680 traces, (b) the output data after applying ASVD, (c) the difference between (a) and (b), (d) f-k spectrum of the data input data, (e) f-k spectrum of the output data after applying ASVD, and (f) f-k spectrum of (c).

To evaluate the effect of SNR in ASVD performance, the filter was applied to a synthetic data with various SNRs and two real shot records. The first field data set was examined by high and low SNRs (with adding the random noise). In the second one extensive presence of the ground roll and other noises led to an extreme decrease in SNR. Since the purpose was ground roll suppression with reflection preservation, in all shot records the ground roll zone was separated and the filter was only applied to the region contaminated by the ground roll.

Figs. 5 to 7 show the synthetic data with SNR = 10, SNR = 2 and SNR = 1, respectively. As shown in these figures, ASVD attenuated the ground roll in all cases and it is not sensitive to SNR. It can suppress the ground roll successfully, even with a high random noise ratio. To have quantitative assessment of the effect of SNR on ASVD filter, three methods were used as follows:

- The difference between sections with SNR = 1 & 2 after applying the filter is shown in Fig. 11a. Similarly, the difference between sections with SNR = 1 & 10 and 2 & 10 after applying filter is shown in Figs. 11b and 11c. Also the f-k spectra of parts (a), (b) and (c) are shown in parts (d) to (f), respectively. As it is clear from Fig. 11, the difference sections and their f-k spectra show random noise and there are no any reflections and ground roll. Therefore, the SNR has no significant effect on the ground roll suppression.

- The primary reflection strength is a known variable during the construction of the synthetic for each SNR. Since ASVD is applied to ground roll region, in after-filter sections, just the first 10 traces between 800 to 900 ms are stacked. Stacking causes random noise cancel out largely. The results of stacking at the different noise levels are shown in Fig. 12. Similar to the synthetic data, stacking of the first field data (with higher (Fig. 8) and lower SNR (Fig. 9)) after applying the filter between offset of −660 to −900 and time interval of 900 to 1000 ms is shown in Fig. 13. These results provide an insight into the amplitude preserving abilities of ASVD and further highlight claims about the impact of SNR on the results.

- The values of the attenuated energies in ground roll region in three cases are calculated according to eq. (5).

$$\text{dB} = 10 * \log[(\text{energy after applying filter})/(\text{energy before applying filter}) \ . \qquad (5)$$

For SNR = 10, 2 and 1, these values are −10.45, −7.29 and −4.58, respectively. Because in SNR = 1, there is more random noise before and after filtering compared to SNR = 2 & 10. Presence of this noise causes a less value for the attenuated energy. Similarly SNR = 2 has a less value compared to SNR = 10. To evaluate the filter performance on the field data with various

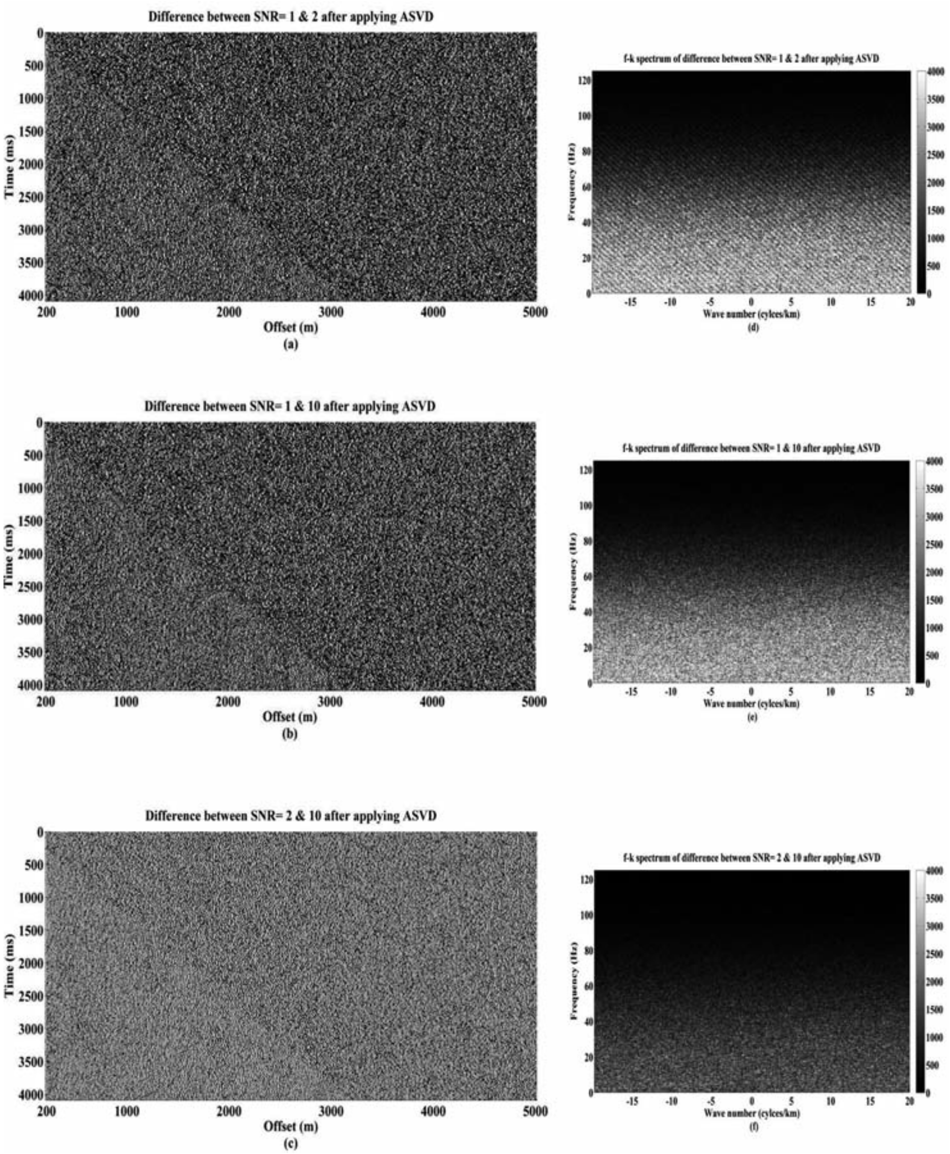

Fig. 11. Quantitative assessment of SNR on ASVD filter: (a) the difference between sections with SNR = 1 & 2 after applying filter, (b) the difference between sections with SNR = 1 & 10 after applying filter, (c) the difference between sections with SNR = 2 & 10 after applying filter, (d), (e), and (f) are f-k spectra of (a), (b), and (c), respectively.

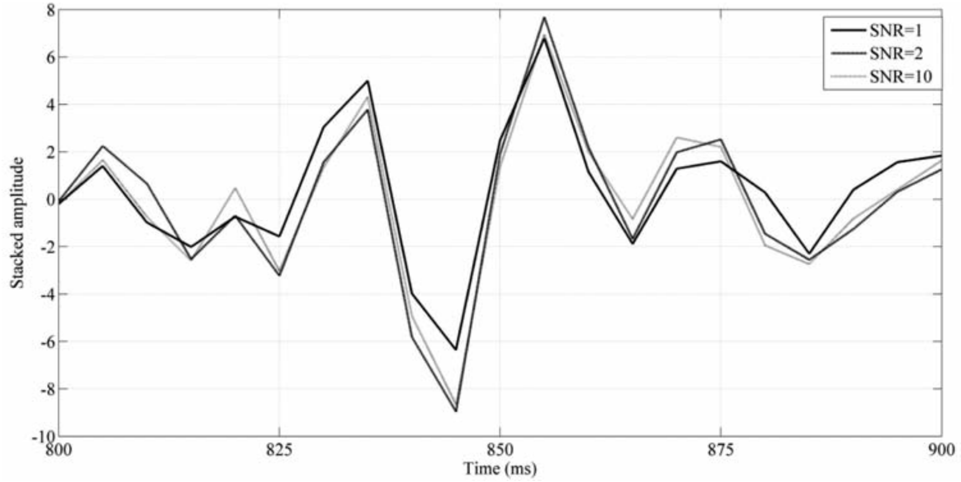

Fig. 12. Amplitude preservation abilities of ASVD for the first reflection after applying filter for different SNR levels in the synthetic data.

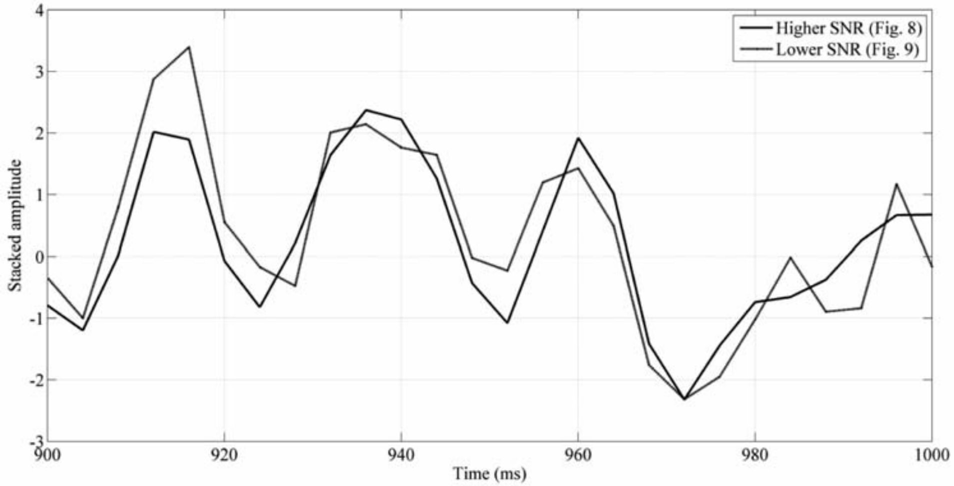

Fig. 13. Amplitude preservation abilities of ASVD between the offset of −660 to −900 and the time interval of 900 to 1000 ms after applying filter for different SNR levels in the first field data.

SNR levels, f-k spectra of the input, output and their differences are shown parallel of their sections in Figs. 8, 9 and 10, respectively.

ASVD is a coherency-based filter. As the results of a synthetic data set with various SNRs, two field data sets (the first field data set with high and low SNRs, the second field data set with very poor SNR, caused by the presence of undesired events such as ground roll and the other noises) and their f-k spectra show, ASVD has successfully attenuated the ground roll in the suitable selected zone with various SNR levels. Because the eigenvalues are sorted in a descending order, after rotating the data, the ground roll is represented in the first eigenvalues as a horizontal and coherent event. However, the random noise or reflections have lower energies and coherencies compared to the flattened ground roll and they are represented in the next eigenvalues. Due to this separation, the SNR had no impact on the ground roll attenuation via ASVD.

CONCLUSIONS

ASVD is a coherency-based filter for suppressing the ground roll. To evaluate the effect of SNR on the performance of ASVD filter, the filter was applied to synthetic data with various SNRs and two field data sets from the South West of Iran as case studies (the first one with lower and higher SNRs). According to the results filter attenuated the ground roll successfully with a minimum damage to reflections in all cases. The SNR had no significant effect on the performance of this filter, i.e., ASVD filter is not sensitive to SNR. Because the eigenvalues are sorted in a descending order in the eigenvalue spectrum therefore, after flattening the ground roll, the ground roll as a horizontal and coherent event is represented in the first eigenvalues. However the other events such as random noise or reflections have lower energy and coherency compared to flattened ground roll and they are represented in the next eigenvalues. Due to this separation, the SNR had no impact on the ground roll attenuation via ASVD.

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