Marchenko imaging below complex overburdens in the Middle East

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Summary

Recently, a novel methodology was presented to retrieve the up- and downgoing parts of the Green's function in an unknown medium by iterative substitution of the coupled Marchenko equations. This methodology requires as input single-sided reflection data (recorded at the Earth's surface) and a macro velocity model of the subsurface. By cross-correlating the retrieved upgoing Green's function with the direct downgoing field and evaluating the result at zero time-lag (imaging condition), a seismic image can be generated that is free of artefacts from internal multiples. We investigate the effectiveness of this approach for seismic imaging below complex overburdens in the Middle East, using a 1D synthetic model that is inspired by an onshore oilfield in Saudi Arabia. It is demonstrated that artefacts from internal multiples are removed effectively in the image domain. Despite the 1D character of this initial test, the Marchenko methodology can also be applied in 2D or 3D.

Introduction

Seismic imaging below complex overburdens in the Middle East is a significant problem. Strong heterogeneities in the shallow subsurface result in severe multiple scattering, posing limitations to conventional imaging algorithms that are typically based on a single-scattering assumption. Although a multitude of methods has been proposed to remove internal multiples from seismic data (Weglein et al., 1997, Berkhout and Verschuur, 2005), the problem remains very persistent. An iterative scheme that is based on the coupled Marchenko equations, as recently presented by Wapenaar et al. (2014), might provide an alternative solution.

Theory

It has been derived how Green's functions can be retrieved in an unknown medium by iterative substitution of the coupled Marchenko equations (Wapenaar et al., 2014). By expressing the retrieval of the upgoing Green's function as a series and applying the imaging condition to each term in the series individually, we can write for the resulting image at location (x, y, z):

$$i(x, y, z) = i_0(x, y, z) + \sum_{n=1}^{N} i_n(x, y, z). \qquad (1)$$

Here, each term on the right-hand side represents the image of an individual update of the Marchenko scheme. The first term in this series i_0 can be interpreted as a conventional Kirchhoff depth image. While primary reflections are positioned correctly in this image, it is prone to artefacts from internal multiples. The role of later terms in the series is to eliminate these artefacts. We point out that retrieved internal multiples can also be imaged. This requires to replace the cross-correlation imaging condition that we used in equation 1 by multidimensional deconvolution of the upgoing part of the Green's function with the downgoing part of the Green's function at each depth level (Wapenaar et al., 2014).

Complex Overburdens in the Middle East

In the Middle East, seismic imaging is often hampered by strong internal multiples, stemming from the complex shallow subsurface. Due to the clear separation of physical primary reflections and the artefacts caused by the multiples, the Marchenko methodology might be an effective tool to improve seismic imaging in this environment. To investigate the feasibility of this idea, we test Marchenko imaging on a 1D model that is inspired by the subsurface conditions in Saudi Arabia (Alexandrov et al., 2012). We simulate a dataset with internal multiples and an equivalent dataset without internal multiples for comparison. Both datasets have frequencies up till 240Hz (peak at 120Hz). In Figure 1a, we show initial (Kirchhoff) images i_0 of both datasets. A significant difference is observed, emphasizing the importance of internal multiples in this environment. In Figure 1b, we show the sum of all predicted updates $-\sum_{n=1}^{N} i_n$ after 50 iterations. We have multiplied this sum with -1, such that the result can be directly interpreted as the artefacts in the initial image i_0, caused by the internal multiples. We subtract these artefacts from the initial image i_0 and compare the result with the image of the data without internal multiples, see Figure 1c. We observe that most artefacts have indeed been successfully removed.

Resolution

To remove all artefacts from the image, we know that our maximal frequency should be high enough with respect to the layered structure. If the maximal frequency is too low, we are not able to handle internal multiples from the very thin layers correctly, being a fundamental limitation of the methodology (Slob et al., 2014). To investigate the relevance of this problem for the model from Saudi Arabia, we repeat the experiment with frequencies up till 120Hz (peak at 60Hz) and up till 60Hz (peak at 30Hz) - see Figures 1d and 1e. Although we observe a slight mismatch in the amplitudes of some arrivals in the latter case, the results are still of remarkable quality and the processing scheme appears to be robust in these frequency ranges.

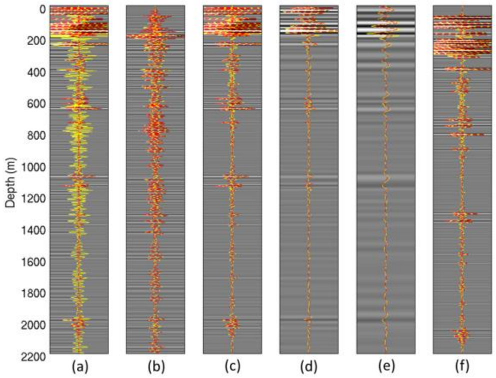

Figure 1: (a) Initial image $\boldsymbol{i_0}$ of data with internal multiples (solid yellow + left half of grey-scale image) versus an image of data without internal multiples (dashed red + right half of grey-scale image). (b) Predicted artefacts by the Marchenko scheme $-\sum_{n=1}^{N} \boldsymbol{i_n}$ (solid yellow + left half of grey-scale image) versus the difference of the images with and without internal multiples (dashed red + right half of grey-scale image). (c) Image $\boldsymbol{i}$ after the predicted artefacts have been subtracted from $\boldsymbol{i_0}$ (solid yellow + left half of grey-scale image) versus the image of data without internal multiples (dashed red + right half of grey-scale image). (d) Same as (c) for data up till 120Hz (peak at 60Hz). (e) Same as (c) for data up till 60Hz (peak at 30Hz). (f) Same as (c) imaged in a constant velocity model.

Model Independence

In the Marchenko methodology, the Green's functions are retrieved in time, while the only role of the velocity model is to convert time to depth. Hence, even if the velocity model is incorrect, the subtraction process remains intact (Slob et al., 2014). To demonstrate this, we repeated the process on the same data, using a constant velocity model to generate the images, see Figure 1f. Although the reflections are positioned at erroneous locations due to the velocity errors, the artefacts are still removed. The situation is slightly different in 2D and 3D media, where move-out knowledge is required to ensure successful Green’s function retrieval (Wapenaar et al., 2014). However, as demonstrated by Broggini et al. (2014), stable results can still be obtained in these type of media, even with significant errors in the velocity model.

Adaptive Subtraction?

At last, we observe that the structure of equation 1 is ideally suited for adaptive subtraction. Since all physical contributions to the image are embedded in i_0, the remaining terms might be subtracted adaptively with a minimum-energy criterion imposed on final image i. Although care is required with respect to overlapping arrivals, it is clear that the image from the data without internal multiples in Figure 1a has significantly less energy than the image from the data with internal multiples (the NRMS-ratio of both images is 0.54 in this example), which could be exploited in the future. An adaptive strategy may be key to apply the Marchenko methodology to field data, which is an important focus of our current research.

Conclusion

We demonstrated the potential of Marchenko redatuming for seismic imaging below complex overburdens in the Middle East. Despite the limitations that are posed by the finite frequency band of the input data, satisfying results could still be obtained at relatively low frequencies. Since the Green's functions that are used for the images are constructed in time rather than in depth, the method is relatively insensitive for errors in the velocity model. Although our initial test was carried out in 1D, the methodology can equally be applied in 2D or 3D, relying on some encouraging results that have been presented in several recent publications on this topic.

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