Seismic Preprocessing in Terms of Wave-Field Decomposition at the Surface

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Summary

In the seismic industry there is an important trend towards multi-component data acquisition, with different source types. Such methods enable to derive more accurate and more complete information on the elastic properties of the subsurface.

In the case of land data for which stresses are applied on the surface, and particle velocities are recorded along the three coordinate axis on the free surface, the measured multi-component data are a mixture of P and S wave field. However, we want to deduce from the data the response of the medium in terms of pure upgoing P and S waves due to pure downgoing P and S wave sources.

For this we have to extract in the original data the part of the upgoing P and S waves reaching the acquisition surface. This operation will be called : " *decomposition at the receiver side* ".

As generally sources emit a mixture of P and S waves, we also have to transform the data, to make them as shot with pure P and S wave sources. This operation will be called : " *decomposition at the source side* ".

The proposed decomposition is based on the elastic wave equations for the surface layer only.

Introduction

Inversion of multi-component data can be subdivided in three main processes as described in Berkhout and Wapenaar (1988)

1. Surface related preprocessing (decomposition of the multi -component data into primary P and S wave responses).
2. Separate pre-stack migration of the primary P and S wave responses yielding the (angle-dependent) P-P, P-S, S-P and S-S reflectivity of the subsurface.
3. Target related post-processing (transformation of the reflectivity into the rock and pore parameters in the target).

This paper deals with the aspects of surface related preprocessing. It consists of two steps.

1a. Decomposition of the multi-component data (pseudo P and S wave responses) into true P and S wave responses.

1b. Elimination of the surface related multiple reflections and waves conversions. In this procedure the free surface is replaced by a reflection free surface. The effect is that we obtain " *primary* " P and S wave responses. For this step we refer to Verschuur et al. (1988).

Decomposition of multi-component data

Decomposition at the receiver side

In this first step we want to transform the recorded data expressed in terms of particle velocity components along the three coordinate axes (x, y, z), (x, y :horizontal axis, z : vertical axis pointing downward) in terms of upgoing P and S waves.

Background

In a homogeneous, isotropic, elastic region, the P waves can be expressed with a scalar potential (Φ), and the S waves with two vector potentials.(Ψ_1,Ψ_2; e.g Ψ_1 = SV, Ψ_2 = SH) The potentials are defined as follows :

$$-\rho\, \partial_t \mathbf{V} = \nabla\Phi + \nabla\times (\Psi_1 + \Psi_2), \tag{1}$$

ρ : density

$\mathbf{V}$: velocity field vector ; $\mathbf{V} = (V_x, V_y, V_z)^T$

From the elastic wave equation in a isotropic, homogeneous region it is possible to relate the velocities and the stresses to the P and S waves potential as described in Wapenaar et al (1989) :

$$\begin{pmatrix} \mathbf{V} \\ \mathbf{T_z} \end{pmatrix} = \begin{pmatrix} \underset{\sim}{L}_1^+ & \underset{\sim}{L}_1^- \\ \underset{\sim}{L}_2^+ & \underset{\sim}{L}_2^- \end{pmatrix} \begin{pmatrix} \mathbf{D}^+ \\ \mathbf{D}^- \end{pmatrix} = \underset{\sim}{L} \begin{pmatrix} \mathbf{D}^+ \\ \mathbf{D}^- \end{pmatrix}, \tag{2a}$$

$$\begin{pmatrix} \mathbf{D}^+ \\ \mathbf{D}^- \end{pmatrix} = \begin{pmatrix} \underset{\sim}{M}_1^+ & \underset{\sim}{M}_2^+ \\ \underset{\sim}{M}_1^- & \underset{\sim}{M}_2^- \end{pmatrix} \begin{pmatrix} \mathbf{V} \\ \mathbf{T_z} \end{pmatrix} = \underset{\sim}{M} \begin{pmatrix} \mathbf{V} \\ \mathbf{T_z} \end{pmatrix}, \tag{2b}$$

where

$\mathbf{D}^\pm = (\Phi^\pm, \Psi_1^\pm, \Psi_2^\pm)^T$

$\pm$: downgoing/upgoing wave.

$\underset{\sim}{L}$: composition operator.

$\underset{\sim}{M}$: decomposition operator

$\mathbf{T_z}$: stress vector ; $\mathbf{T_z} = (T_{xz}, T_{yz}, T_{zz})^T$

In case of geophones placed on a traction free surface at depth z_0, $\mathbf{T_z}(z_0)=\mathbf{0}$, we find from (2b) that the upgoing waves ($\mathbf{D}^-(z_0)$) are related to the velocity field vector $\mathbf{V}(z_0)$ as follows :

$$\mathbf{D}^-(z_0) = \underset{\sim}{\mathbf{M}}_1^-(z_0)\,\mathbf{V}(z_0)\,, \quad (3a)$$

$\underset{\sim}{\mathbf{M}}_1^-(z_0)$: is the operator that enables to obtain from the velocity field, the upgoing P and S waves reaching the acquisition surface z_0.

Decomposition at the source side

Generally, seismic sources emit a mixture of P and S waves. In this second step we want to remove this effect and simulate a pure P or S wave source.
In the case of stress sources on a free surface, only downgoing waves ($\mathbf{D}^+$) are generated ($\mathbf{D}^- = \mathbf{0}$). From (2a) we find that the downgoing waves $\mathbf{D}^+$ are related to the applied stress as follows :

$$\mathbf{T}_z(z_0) = \underset{\sim}{\mathbf{L}}_2^+(z_0)\,\mathbf{D}^+(z_0)\,, \quad (3b)$$

The operator $\underset{\sim}{\mathbf{L}}_2^+(z_0)$ tells us how a P or S downgoing source wave can be simulated by a weighted distribution of stress sources T_{xz}, T_{yz} and T_{zz} on a free surface. The weighted distribution being determined by $\underset{\sim}{\mathbf{L}}_2^+(z_0)$.

$\underset{\sim}{\mathbf{L}}_2^+(z_0)$: is the operator that enables to simulate a pure downgoing P or S wave source, from several stress sources.

Decomposition both at the source and receiver side

Define $\underset{\sim}{\mathbf{Y}}(z_0)$ which represents the "admittive" response of a medium in terms of velocities recorded on a free surface at depth z_0 due to stresses sources applied on the same surface :

$$\mathbf{V}(z_0) = -\underset{\sim}{\mathbf{Y}}(z_0)\,\mathbf{T}_z(z_0)\,. \quad (4a)$$

Define $\underset{\sim}{\mathbf{X}}(z_0)$ which is the response of the medium in terms of pure upgoing P and S waves due to pure P or S downgoing source waves at the same depth :

$$\mathbf{D}^+(z_0) = \underset{\sim}{\mathbf{X}}(z_0)\,\mathbf{D}^-(z_0)\,. \quad (4b)$$

The following relation holds between $\underset{\sim}{\mathbf{X}}(z_0)$ and $\underset{\sim}{\mathbf{Y}}(z_0)$ (see fig2).

$$\underset{\sim}{\mathbf{X}}(z_0) = -\underset{\sim}{\mathbf{M}}_1^-(z_0)\,\underset{\sim}{\mathbf{Y}}(z_0)\,\underset{\sim}{\mathbf{L}}_2^+(z_0)\,. \quad (4c)$$

This is the total decomposition algorithm.
The matrix $\underset{\sim}{\mathbf{M}}_1^-(z_0)$ acts on the columns (= common shot records) of the data matrix $\underset{\sim}{\mathbf{Y}}(z_0)$. Hence, matrix $\underset{\sim}{\mathbf{M}}_1^-(z_0)$ decomposes per common shot record the received particle velocity vector into upgoing P and S wave potentials. The matrix $\underset{\sim}{\mathbf{L}}_2^+(z_0)$ acts on the rows (= common receiver records) of data matrix $\underset{\sim}{\mathbf{Y}}(z_0)$. Hence matrix $\underset{\sim}{\mathbf{L}}_2^+(z_0)$ decomposes per common receiver record the source traction vector into downgoing P and S wave potentials. The final result is the decomposed data matrix $\underset{\sim}{\mathbf{X}}(z_0)$.

Synthetic example

To illustrate the whole procedure, we apply the processing step by step on a synthetic example. We start with the 2D layered model depicted in fig 2. After ground roll elimination the Vx, Vz velocities recorded at the free surface due to Txz, Tzz sources at the same surface are schown in fig 3a-d. After decomposition at the receiver side, we obtain the response of the medium in terms of upgoing P and S waves due to Txz, Tzz sources, see fig 4a-d. From those four panels we process the decomposition at the source side to obtain the response of the medium in terms of upgoing P and S waves due to pure P and S wave sources, see fig 5a-d. After elimination of surface related multiples and wave conversions in the P-P, S-P, P-S and S-S panels, we obtain the result in fig 6a-d. More realistic results will be presented during the presentation.

Conclusion

When we compare the four panels in fig 6a-d obtained after the surface related preprocessing with the original data in fig 3a-d, we see how the interpretation of the data has been improved. These data can now be further processed independently, using standard acoustic migration software. With the decomposition scheme (4c), 2D as well as 3D problems can be handeld. Also lateral velocity variations along the acquisition surface z_0 can be accomodated.

Acknowledgments

The investigations were supported by the sponsors of the DELPHI consortium project at the laboratory of Seismics and Acoustics of the Delft University, The Netherlands.

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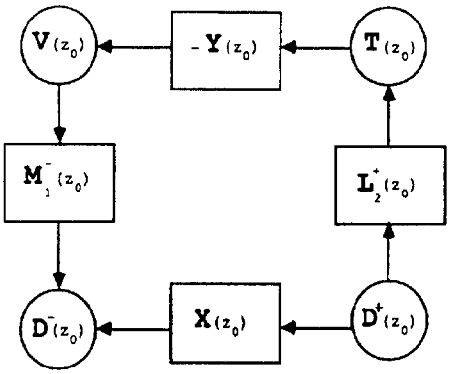

FIG. 1. Relation between $\underline{Y}(z_0)$ and $\underline{X}(z_0)$ impulse responses.

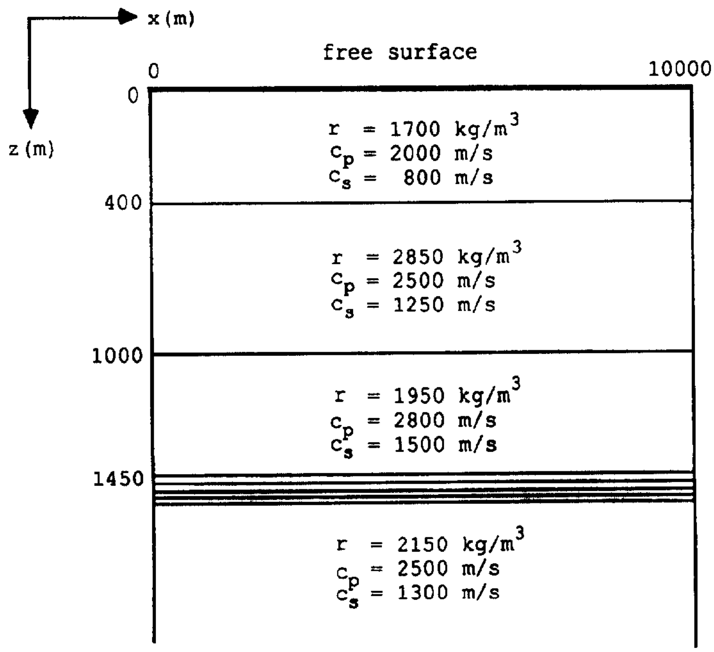

FIG. 2. Subsurface model used for elastic modeling.

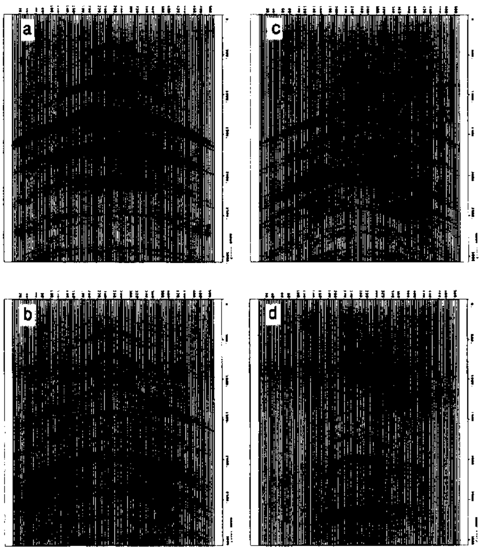

FIG. 3. (a) S: $\mathbf{T_{zz}}$, D:$\mathbf{V_z}$; (b) S: $\mathbf{T_{zz}}$, D: $\mathbf{V_x}$; (c) S: $\mathbf{T_{xz}}$, D: $\mathbf{V_z}$; and (d) S: $\mathbf{T_{xz}}$, D: $\mathbf{V_x}$.

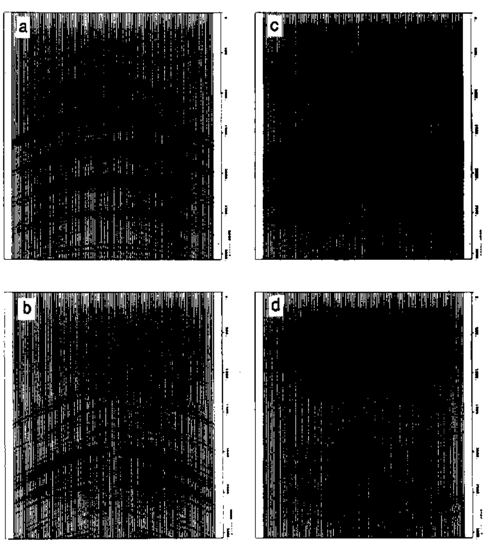

FIG. 4. (a) S: $\mathbf{T_{zz}}$, D: $\mathbf{P}^-$; (b) S: $\mathbf{T_{xz}}$, D: $\mathbf{P}^-$; (c) S: $\mathbf{T_{zz}}$, D: $\mathbf{S}^-$; and (d) S: $\mathbf{T_{xz}}$;, D: $\mathbf{S}^-$.

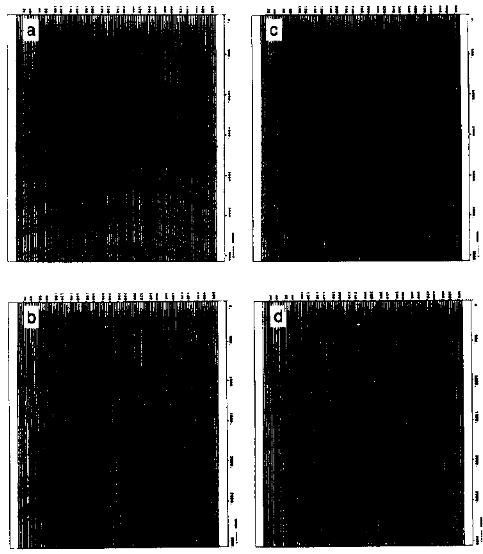

FIG. 5. (a) S: $\mathbf{P}^+$, D: $\mathbf{P}^-$; (b) S: $\mathbf{P}^+$, D: $\mathbf{S}^-$; (c) S: $\mathbf{S}^+$, D:$\mathbf{P}^-$; and (d) S: $\mathbf{S}^+$, D: $\mathbf{S}^-$.

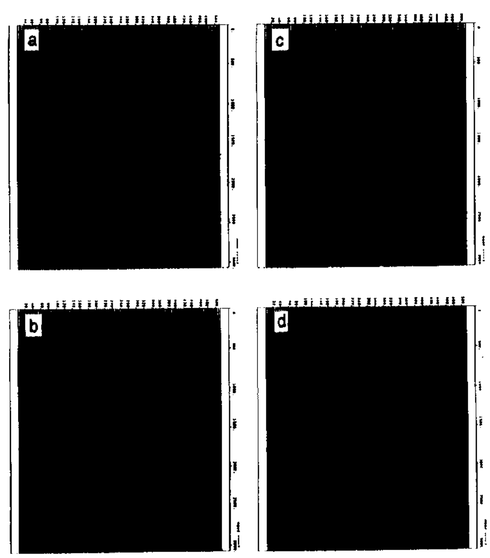

FIG. 6. (a) **PP** data; (b) **SP** data; (c) **PS** data; and (d) **SS** data.