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3D Seismic-gravity Simultaneous Joint Inversion for Near Surface Velocity Estimation

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SUMMARY

A novel 3D simultaneous joint inversion scheme for gravity and seismic travel time data is developed to solve for near-surface complex velocity distributions. The method incorporates industry-standard gravity and travel time inversion techniques while the joint inversion problem is solved by the introduction of various regularization functions about the model such as a-priori parameter distribution information, solution-space bounds, structural similarity via cross-gradient constraints and rock physics relations. The effectiveness of our joint inversion is demonstrated against a synthetic model representing a complex pattern of near-surface anomalies incorporating low and high velocity and density bodies. Results demonstrate the superiority of our approach where the shallow anomalies are better reconstructed by the joint inversion rather than that obtained by the single-domain inversions. The developed algorithm is tested with real data from Saudi Arabia acquired over a wadi structure. The results show a significant uplift of the time stack using the seismic-gravity joint inversion velocity model. The developed methodology is part of a multi-geophysics platform for near-surface velocity model building in complex geology scenarios.

Introduction

Complex near-surface conditions typically occur when high velocity bodies are brought close to the surface such as in thrust belts or in layered geology when, for example, high velocity carbonates are outcropping or are close to the surface. In desert environments, geomorphological features such as dunes, wadis and sabkhas (salt plains) and the presence of dissolution cavities in shallow limestone and evaporitic rocks (i.e., karsting) further complicate the velocity distribution near the surface and offer a challenging problem that is difficult to solve with conventional velocity analysis methods.

Seismic travel time tomography is a very efficient and practical method for solving shallow velocity reconstructions but it is generally insufficient when velocity inversions occur. In such conditions, the first arrival travel time picks are low quality due to the vanishing of first arrival phases at increasing offsets (hidden layer effect). In addition to this, the kinematics of the refracted waves (i.e., head, diving and transmitted waves) makes them more sensitive to high velocity than to low velocity features. As a result, localized low velocity anomalies are undersampled and cannot be properly reconstructed by tomographic inversion. The inclusion of gravity data for joint inversion of seismic travel time and gravity residuals is an appealing and practical approach because gravity inversion resolves density variations in the shallow subsurface and density correlates consistently with P-wave velocity in most rocks. Simultaneous joint inversion of such multi-geophysical data could provide more accurate imaging than interactive approaches. In fact, by simultaneously satisfying multiple geophysical observations, the inversion is likely to converge more steadily to the global minimum of the solution space. There are several published approaches for performing joint inversions. Zhang and Morgan (1997) developed joint seismic travel time and DC resistivity tomography for imaging underground caves. In their approach, the normalized model curvatures of seismic slowness and resistivity are calculated to constrain each other during the inversion without assuming any direct velocity and resistivity relationships. Each property variation suggests possible geological interfaces to the other in terms of model variances, without constraining its true values. Colombo and De Stefano (2007) performed 2D simultaneous inversion of seismic, gravity, and magnetotelluric data. Their joint inversion approach imposes structural similarity by a cross-gradient function and by rock physics relations, and minimizes an objective function with respect to the multi-parameter model vector.

In this paper, we describe a novel joint seismic and gravity inversion approach that extends the simultaneous reconstruction of density and velocities to 3D by using various regularization schemes such as structural constraints provided by cross gradient products, rock physics relations (e.g., Gardner et al., 1974) and prior reference model information. By doing this, we aim to establish a robust joint inversion workflow to make the integration of geophysical data part of an extended toolbox for near-surface velocity model building.

Method

We start from industry standard solutions for 3D gravity and seismic travel time inversions based on adaptive finite-difference model representations. The 3D gravity inversion algorithm is formulated as a constrained least squares problem solved by minimizing a global objective function composed of model regularization function, data misfit (Li and Oldenburg, 1998) and a logarithmic barrier term to constrain the solution to lie within given physical bounds (Li and Oldenburg, 2003). The algorithm can incorporate *a-priori* information into the model objective function by using one or more appropriate weighting functions. The seismic first-arrival travel time inversion is based on a standard formulation of the objective data misfit function with Laplacian smoothness regularization (Zhang and Toksöz, 1998). The joint seismic-gravity inversion is formulated as a constrained least squares problem and solved using Lagrange multipliers and a preconditioned conjugate gradient iterative algorithm to minimize an objective function of the form:

$$\phi_t(\boldsymbol{m}) = \phi_m(\boldsymbol{m}) + \frac{1}{\lambda_1}[\phi_d(\boldsymbol{m}) - \phi_d^*] + \frac{1}{\lambda_2}\phi_b(\boldsymbol{m}) + \frac{1}{\lambda_3}\phi_x(\boldsymbol{m}) + \frac{1}{\lambda_4}\phi_{rp}(\boldsymbol{m}) \quad (1)$$

where $\lambda_i, i = 1, \ldots 4$ are different Lagrange multipliers. The model regularization function $\phi_m(\boldsymbol{m})$ is defined as:

$$\phi_m(\boldsymbol{m}) = (\boldsymbol{m} - \boldsymbol{m_0})^T \boldsymbol{W_m^T} \boldsymbol{W_m} (\boldsymbol{m} - \boldsymbol{m_0}) = \|\boldsymbol{W_m}(\boldsymbol{m} - \boldsymbol{m_0})\|_{L_2}^2 \tag{2}$$

where $\boldsymbol{m}$ and $\boldsymbol{m_0}$ are, respectively, the unknown and the prior models, including M_s slowness and M_ρ density parameters; $\boldsymbol{W_m}$ is a model weighting (or covariance) matrix including spatially dependent weighting functions, a depth weighting function (used to counteract the decay of the gravity kernel with depth), a model smoothing operator and prior information on the model. The data misfit is defined as:

$$\phi_d(\boldsymbol{m}) = (\boldsymbol{Jm} - \boldsymbol{d_{obs}})^T \boldsymbol{W_d^T} \boldsymbol{W_d} (\boldsymbol{Jm} - \boldsymbol{d_{obs}}) = \|\boldsymbol{W_d}(\boldsymbol{Jm} - \boldsymbol{d_{obs}})\|_{L_2}^2 \tag{3}$$

where $\boldsymbol{d_{obs}}$ is the vector of the observed data (including N_t travel times and N_g gravity observations); $\boldsymbol{J}$ is the Jacobian or the sensitivity matrix; and $\boldsymbol{W_d}$ is a data weighting (or covariance) matrix taking into account the relative importance of the observations and the effect of the noise in the data. A logarithmic barrier term (Li and Oldenburg, 2003) can be defined as:

$$\phi_b(\boldsymbol{m}) = -\sum_{i=1}^{M} \left[ln\left(\frac{m_i - m_{Li}}{m_{Hi} - m_{Li}}\right) + ln\left(\frac{m_{Hi} - m_i}{m_{Hi} - m_{Li}}\right) \right] \tag{4}$$

where H=high and L=low bounds; so that if $m_i \to m_{Li}$ or $m_i \to m_{Hi}$, then $\phi_b \to +\infty$. M is the model space cardinality and corresponds to $M_s + M_\rho$, for slowness and density parameters, respectively. The two remaining terms, $\phi_x(\boldsymbol{m})$ and $\phi_{rp}(\boldsymbol{m})$, representing cross gradient and rock physics misfit, are defined on a common grid for both the slowness and density models. We therefore introduce the model subsets $\boldsymbol{s} \in \boldsymbol{m}$ and $\boldsymbol{\rho} \in \boldsymbol{m}$ of the slowness and density parameters associated to the same grid location. We can define the cross-gradient $\boldsymbol{x}_k$ of slowness and density at the *k-th* grid location as:

$$\boldsymbol{x}_k = \boldsymbol{\nabla} s_k \times \boldsymbol{\nabla} \rho_k = \begin{vmatrix} \boldsymbol{i} & \boldsymbol{j} & \boldsymbol{k} \\ \dfrac{\partial s_k}{\partial x} & \dfrac{\partial s_k}{\partial y} & \dfrac{\partial s_k}{\partial z} \\ \dfrac{\partial \rho_k}{\partial x} & \dfrac{\partial \rho_k}{\partial y} & \dfrac{\partial \rho_k}{\partial z} \end{vmatrix} \tag{5}$$

with $\boldsymbol{i}$, $\boldsymbol{j}$ and $\boldsymbol{k}$, the Cartesian coordinate axes unit vectors. Perfect structural similarity between slowness and density models is achieved when $\boldsymbol{\nabla} s_k$ and $\boldsymbol{\nabla} \rho_k$ share the same direction and $\boldsymbol{x}_k = \boldsymbol{0}$. We encourage structural similarity between the models by minimizing the cross product of the model gradients defined as:

$$\phi_x(\boldsymbol{m}) = \sum_{k=1}^{K} \|\boldsymbol{x}_k\|_{L_2}^2 \tag{6}$$

with K representing the grid cell numbers (Gallardo and Meju, 2004). Empirical or physical relations mapping different geophysical domains can be derived through rock physics (Carcione et al., 2007) such as Gardner's rule (Gardner et al., 1974). The rock physics misfit term is added to the objective function by:

$$\phi_{rp}(\boldsymbol{m}) = \sum_{k=1}^{K} \left\| \rho_k - f_{rp}(s_k) \right\|_{L_2}^2 \tag{7}$$

The method proposed here is a generalized simultaneous joint inversion scheme that can be easily extended to multiple domains and different properties (e.g., seismic-EM-gravity).

Synthetic model and field data example

We test the joint inversion algorithm on a synthetic model representing idealized complex near-surface conditions, where the overall flat-layered geology is perturbed by sharp lateral variations of velocity (Figure 1d) and density (Figure 1a). Source and receiver points are regularly distributed every 100 m with the whole receiver spread live for each shot. This provides a maximum source-receiver offset of ~8.3 km for a total of ~13 million travel times. The gravity stations are simulated every 100 m to generate a total of 1,681 gravity observations that occupy the central portion of the seismic spread. The inversion procedure is started from seismic travel times using a 1D velocity of 1,800 m/s at the surface with a depth gradient of 0.4 m/s. We obtain the initial density distribution by applying Gardner's relation to transform velocity into density. The simultaneous joint inversion, however, is performed using the cross-gradient product as the only cross-domain regularization term. The inversion procedure is completed in 10 iterations obtaining the minimization of both the data residual for gravity and seismic travel times, as well as the minimization of the cross-gradient values. Results are shown in Figure 1 where the synthetic models of density and velocity are compared to the single domain stand-alone inversion (Figures 1e and 1b) and to the multi domain joint inversion results (Figures 1f and 1c). It can be noticed that the travel time single domain inversion (Figure 1e) does not recover the low velocity anomaly as it recovers the high velocity feature. This happens regardless of the large number and optimal coverage of the data. The single domain gravity inversion (Figure 1b), on the other hand, performs well in recovering both the low-density and high-density features laterally but with a lack of resolution in depth. Finally, the joint inversion of travel time and gravity residuals subject to the cross-gradient constraint recovers both the low-velocity and high-velocity features in the model, providing the desired velocity reconstruction (Figures 1f and 1c).

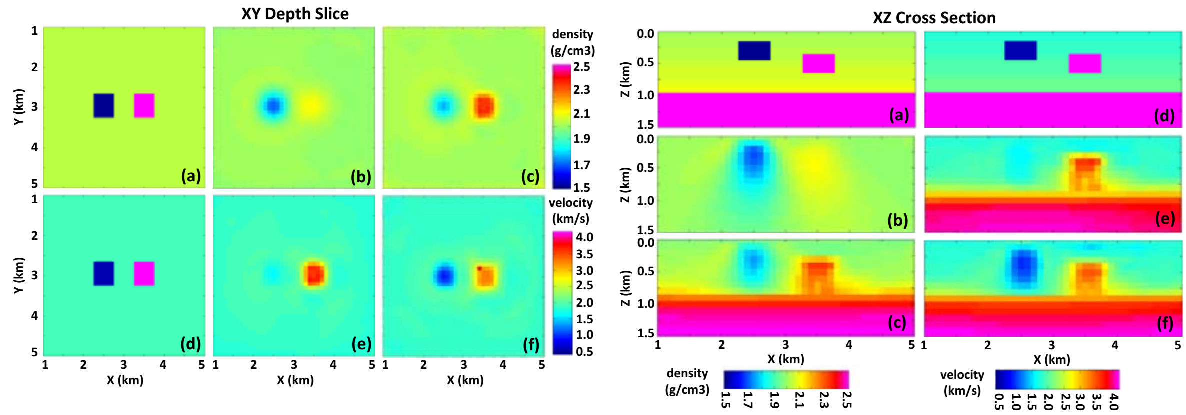

***Figure 1**: Comparison of density and velocity models along an XY depth slice at 400 m and an XZ cross section through the center of the model. The results as single domain inversions and as multi domain joint inversion are shown in (a) synthetic density model, (b) density from single domain inversion, (c) density from joint inversion, (d) synthetic velocity model, (e) velocity from travel time inversion and (f) velocity reconstruction from joint inversion.*

To validate the new joint inversion algorithm on field data, we use a dataset from a wadi area in Saudi Arabia where detailed gravity measurements are available (Colombo et al., 2012). Figure 2 compares the stack obtained with the joint inversion velocity model followed by wave equation redatuming (WED) vs. the stack with elevation statics only. The joint inversion result provides a noticeable improvement in the lateral continuity and flatness of the reflected events through the wadi confirming the robustness of the developed methodology. Similar field data validation tests are being carried out in various locations in Saudi Arabia where 3D seismic and gravity data are available.

Conclusions

We developed an efficient and robust workflow to perform simultaneous joint inversion of seismic and gravity data for near-surface velocity reconstruction. The joint inversion is successfully demonstrated with a synthetic model comprising both low and high density/velocity anomalies in the near surface. The procedure was able to recover the low velocity feature otherwise poorly reconstructed by the stand-alone travel time inversion. The field data example shows that the joint inversion algorithm can improve seismic imaging where the gravity data (and electromagnetic data in the future) become part of a multi-geophysics toolbox for velocity model building in areas of complex near-surface geology.

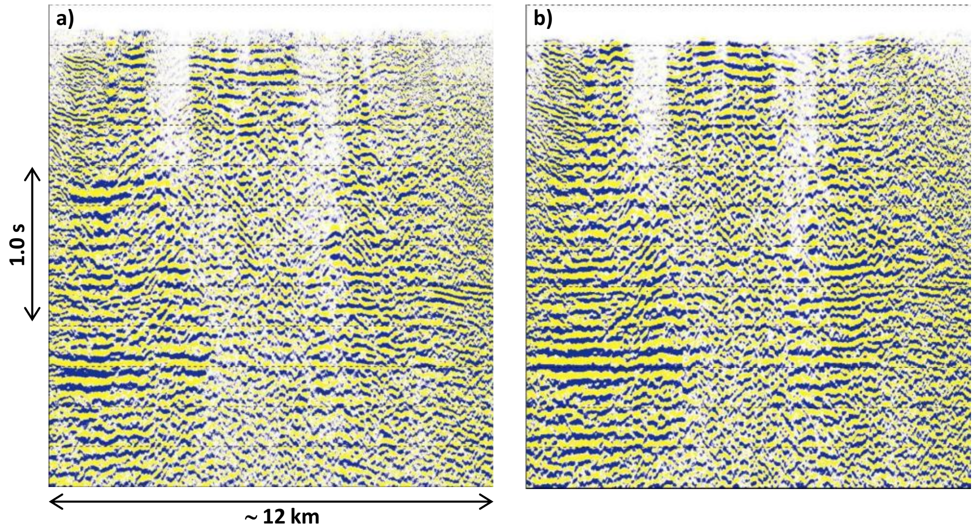

***Figure 2**: Stack with (a) elevation statics correction; and (b) wave-equation datuming using the near-surface velocity model derived from the joint inversion of seismic and gravity data.*

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