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An Engineering-consistent Inversion of Time-lapse Seismic Data

S. Tian* (Heriot-Watt University), C. MacBeth (Heriot-Watt University) & A. Shams (Heriot-Watt University)

SUMMARY

Engineering-consistent (EC) concept is built into a “coupled” 4D inversion workflow to represent the reservoir changes. The inversion, with geology and reservoir engineering constraints, is performed on a consistent reservoir grid. The result takes time shift into consideration and shows less non-uniqueness according to the production activities. We applied the method to a West Africa field and updated the reservoir model by improving its dynamic behavior and the consequent match between the synthetic and observed 4D seismic data.

Introduction

3D and 4D seismic inversion serve as tools in the procedure of reservoir model building. In particular, inversion of 4D seismic data is aimed at delivering robust quantitative estimates of reservoir changes. Unlike 3D inversion, 4D inversion workflows face the unique uncertainties associated with data repeatability. However, as the reservoir engineering activities are recognized as the driving force for 4D signals, the integration and consistency between the reservoir domain and seismic domain is a critical controlling factor. Here, we use the predictions from the fluid-flow simulation as a constraint to invert for changes of impedance, in a coupled inversion scheme, defined on the reservoir model grid. These results are engineering-consistent (EC), in the sense that they are found by jointly satisfying both simulation model predictions and seismic data. The benefits delivered by being EC, make our inversion workflow less non-unique, and more suitable for simulation model updating. We apply the workflow to data from a West Africa field.

An EC workflow to invert 4D seismic data

A consistent reservoir model grid has proven to be important for EC-4D inversion (Thore and Hubans, 2011), and we also design our workflow with such a platform. Our EC inversion can be divided into three stages: petro-elastic model (PEM) calibration, simulator to seismic (sim2seis) modelling (Amini et al., 2011) and the inversion process (Figure 1). The simulator firstly gives a prediction of the fluid and pressure fields, and the PEM is then calibrated against available pre-production well log data. After this, it is possible to run sim2seis to transfer the dynamic simulation output into elastic properties at different calendar times. We then define distributions of the cell-based model properties according to the known facies classification. These provide a geological constraint for the baseline seismic inversion part of this workflow, which yields the desired seismic properties defined on the corresponding reservoir model grid. These results are now used as an initial guess for the inversion of the 4D seismic difference. This coupled scheme is more stable than the “uncoupled” approach as it handles the uncertainties of the PEM and optimization algorithm only once (Anno and Routh, 2007). Here, fluid flow predictions are used as a constraint to define the available solution space, and a search is carried out over all active cells

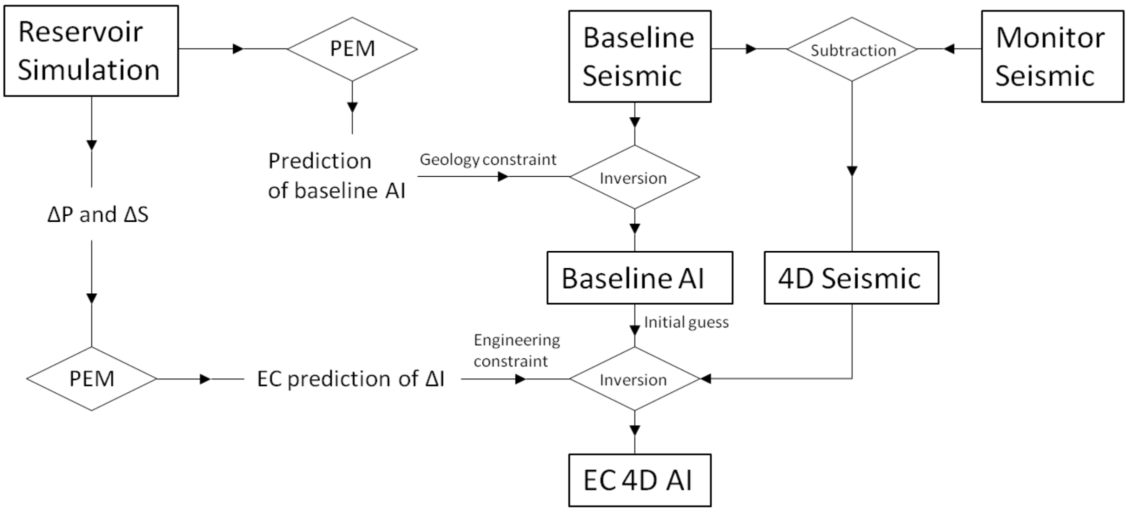

Figure 1 *Workflow of EC-4D Inversion. Geological constraints are used in the baseline inversion. EC constraints are developed in the model domain, which guide the perturbation for the 4D inversion solution.*

Application to the West Africa field – 2D example

The 4D seismic data were acquired in 1999 and 2002, during which time gas injection was initiated in order to maintain the reservoir pressure. The initial simulation model has captured the geometry of turbidite channels, and the production history has also been matched. The biggest challenge for the

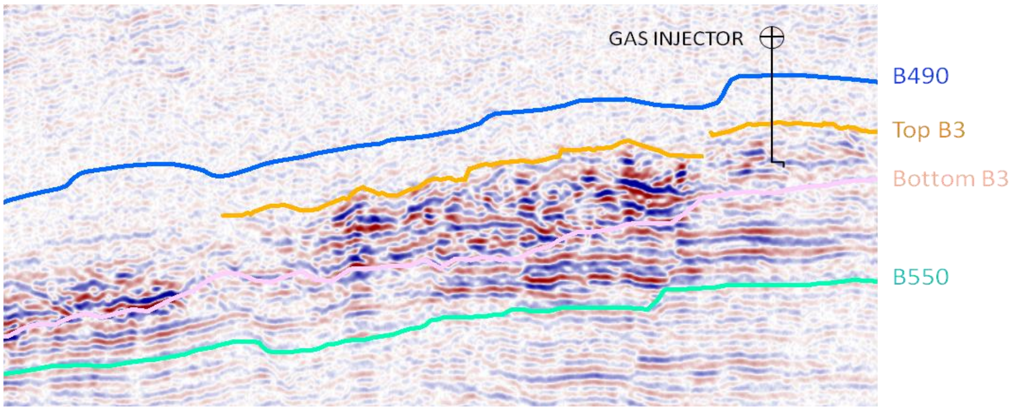

Figure 2 *Observed 4D seismic section through a turbidite channel. The difference of amplitude is calculated from the baseline and monitor seismic vintages, for which top reservoir is aligned. There are observed cumulative time shifts, these creating a base reservoir signal which can also be used in the inversion.*

model is the reservoir connectivity between channels and faults, therefore the possible paths for fluid flow. We have validated our method with observed 4D seismic data as shown in Figure 2. Baseline seismic data is inverted into P-wave velocities and densities, with constraints from well log calibration and static predictions from sim2seis modelling as an initial solution. Dynamic changes are also predicted and they define the solution spaces for the search of possible ΔI changes. Baseline and monitor seismic have been aligned at the top reservoir before subtraction. The 4D signal below top reservoir is a combination of amplitude changes from the reservoir production, and artefacts caused by time shifts. The inversion results are shown in Figure 3, and they are compared with the sim2seis prediction. After EC-4D inversion, a layer of impedance decrease (softening) is identified, this being interpreted here as a gas cap. This solution makes engineering sense as it is consistent with the activity of the gas injector situated nearby. In addition, EC-4D inversion has the benefit of taking care of the time shift related amplitude changes because EC constraints will locate the cells where the actual reservoir changes are taking place. The inverted results do not show a change in the bottom part of reservoir where the time shifts exist. Conventional inversion could interpret this base reservoir response as possible impedance changes as one possible scenario. The difference between the sim2seis and inversion is visible mainly in the gas cap.

Application to the West Africa field – reservoir model updating

From the RMS map of the 4D seismic (Figure 4), the production-affected reservoir is illuminated. By looking into the production activities, the dominant source of the 4D signal is interpreted as a change in gas saturation. Except for a local area which is dominated by the water injector, the distinctive 4D signals can be directly correlated to impedance softening caused by the presence of gas. In the north, injected gas is dominant, whilst in the south the gas is exsolved due to pressure depletion prior to the start of injection. By inverting the 4D seismic into ΔI the inversion results show good agreement with the observed seismic data and are directly comparable with the simulation predictions. In this case, an inconsistency is noticed between the observed 4D seismic and simulation predictions (red circled regions) where the model missed the injected gas (Figure 5). The correct reservoir scenario appears not to have been included as a possible solution in applying the EC-4D constraints. However, no satisfactory solution is found for the 4D seismic in this area, and the reservoir model disagrees with the observed data. We therefore conducted an EC-4D inversion with looser constraints to obtain a more 4D seismic-consistent solution (Figure 4) in order to reduce the earlier inconsistencies. We updated the transmissibility multipliers in the region to redistribute the gas flow. By updating the multipliers rather than transmissibility themselves, we then change the fluid flow barriers while keeping the model geology sensible. After several trials of different cut-offs and multiplier values, a suitable set is found, and the updated model shows a consistent signal pattern with the observed 4D seismic. This therefore yields a more interpretable constraint for EC-4D inversion, while staying matched with the production history.

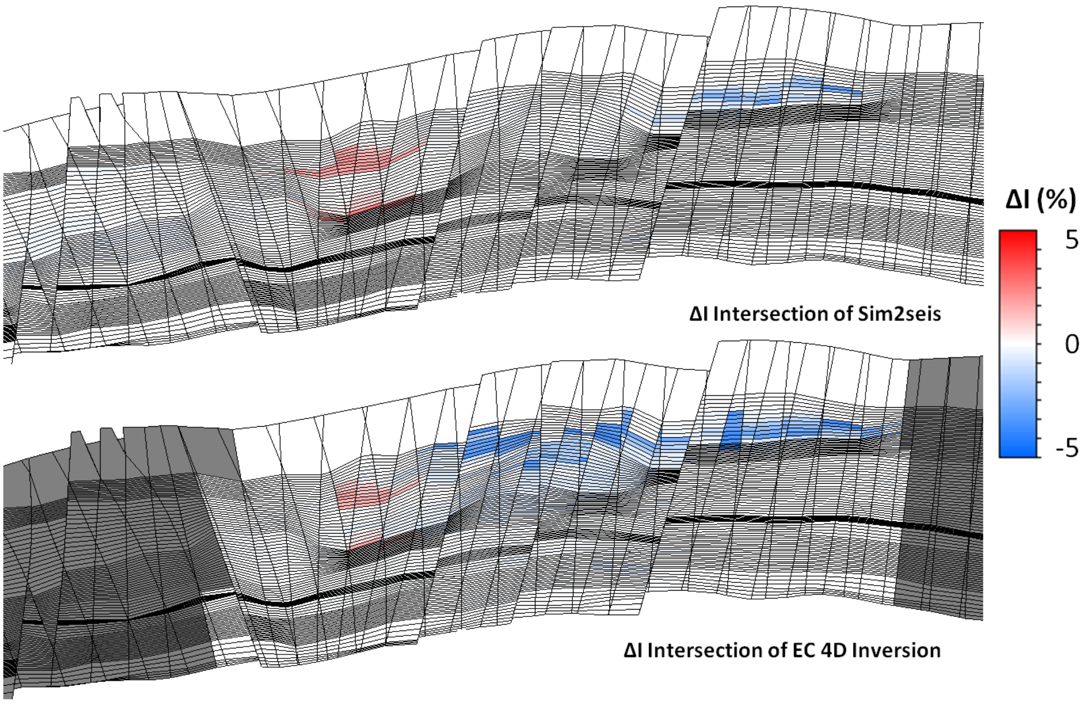

Figure 3 *Sim2seis prediction of ΔI (top) and EC-4D Inversion ΔI (bottom) results through the same vertical section as in Figure 2.*

Conclusions

The EC-4D inversion has proven its potential in direct model updating. The non-unique problem of seismic inversion is reduced using engineering constraints. Inversion with a reservoir model grid benefits the algorithm in terms of static and dynamic stability as the constraints are calculated from smooth pressure and saturation changes defined cell by cell. In addition, the results are in a convenient form to assess the consistency of the predictions and observations, and therefore to examine possible updates to the model.

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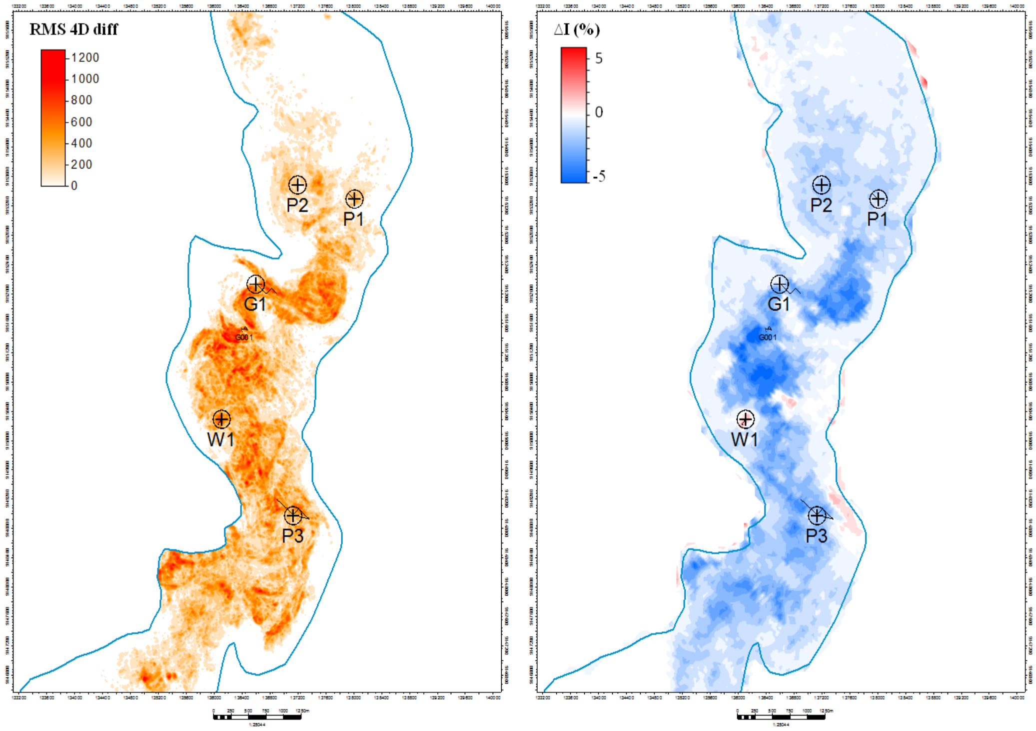
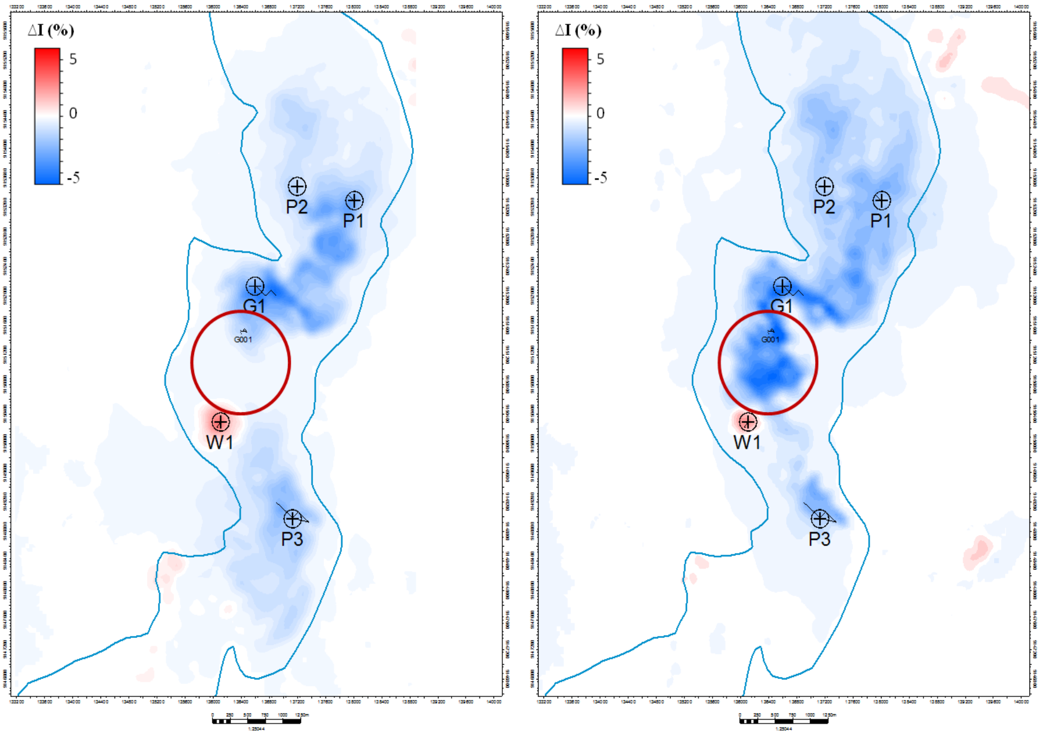


RMS map of observed 4D seismic difference
B3 Sequence (2002 – 1999)

Average map of inverted ΔI difference
B3 sequence (2002 - 1999)

Figure 4 *RMS map of observed 4D seismic (left) over the B3 sequence, orange shows the major seismic changes. EC-4D inversion (right) results are in good agreement with the observed 4D pattern, but disagree with the simulated prediction between the two injectors.*



Average map of sim2seis ΔI difference
B3 sequence before update

Average map of sim2seis ΔI difference
B3 sequence after update

Figure 5 *Sim2seis 4D impedance prediction from the original model (left) and the updated model (right). After updating, gas is able to flow into the circled area, and the model is more consistent with the observed 4D seismic as well as the inverted impedance shown in Figure 4.*