Indirect Monitoring of Hydrocarbon Reservoir Deformations by Measuring Ground Surface Movements

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ABSTRACT

Subsurface pressure changes generated during hydrocarbon production, waste/water reinjection will induce surface movements. It is important to predict these induced surface deformations. On the other hand, surface deformation monitoring can be applied to indirectly monitor subsurface deformations. Two numerical models were developed in this study based on the unidirectional deformation technique: 1) direct model: predicts induced surface deformations due to reservoir volumetric changes; 2) inverse model: simulates subsurface volume changes using surface deformation measurements. In order to solve the inverse ill-posed problem, a regularization technique was developed in this study. A detailed sensitivity analysis was also performed to determine the most suitable surface deformation measurement resulting in the best inverse simulation. Tilt measurements we found to be better input than vertical displacements for modeling subsurface deformations.

RÉSUMÉ

Les variations de pression du sous-sol générés pendant la production d'hydrocarbures, déchets/réinjection d'eau va entraîner les mouvements de surface. Il est important de pouvoir prédire les déformations induites de surface. D'autre part, la surveillance de la déformation de surface peut être appliquée de manière indirecte pour surveiller les déformations du sous-sol. Dans cette étude, deux modèles numériques ont été développés basée sur la technique de déformation unidirectionnelle: 1) modèle direct: prédit les déformations de surface induites par les changements volumétrique de réservoir, 2) modèle inverse: simule les variations de volume du sous-sol en utilisant des mesures de déformation de surface. Afin de résoudre le problème inverse mal posé, une technique de régularisation a été développée dans cette étude. Une analyse de sensibilité bien détaillée a été aussi effectuée pour déterminer la plus convenable façon de mesure de déformation de surface, ce qui produit une meilleure simulation inverse. Nous avons trouvé que les mesures de pente est meilleur choix de paramètre mesuré que les déplacements verticaux pour la modélisation les déformations du sous-sol.

1 INTRODUCTION

It has long been recognized that the withdrawal or injection of any kind of fluid or material from or into the subsurface will generate underground deformations. Such subsurface deformations induce ground level movements. Induced surface movements have significant environmental impacts and have been an issue of concern in hydrocarbon related projects. Failure of underground utility lines, well casings, and pipelines; structural damage and foundation settlements (Hu et al., 2004); and wetland loss are some common impacts of induced surface deformation occurring in hydrocarbon related projects. It is thus significantly important to be able to predict induced deformations. Calculating surface deformations using subsurface volumetric changes in the reservoir rock is referred to as solving for the direct case. Two approaches have been commonly applied in literature for modeling subsurface deformations: a) nucleus of strain approach (Geertsma, 1973); through which subsurface deformations are modeled as single point sources that expand or compact in all directions, representing expansion or compaction; b) unidirectional deformation technique (Okada, 1985).

Induced ground surface deformations are measurable quantities and are typically measured as: vertical displacements; horizontal displacements; and tilts, which are the gradient of surface deformations. Being easy to monitor and sensitive to subsurface pressure changes (Geertsma, 1957; Segall, 1985; Vasco, 2004), surface deformation data can be used to indirectly monitor subsurface deformations. Inverse monitoring has considerable potential use in fast-paced projects (steam injection/steam-assisted gravity drainage; waste injection projects) in which continuous monitoring of subsurface deformation is vital. Applying surface deformation measurements to solve for the subsurface deformation sources is referred to as solving for the inverse case.

Forward and inverse models have been previously studied and reported on in the literature (Bruno et al., 1992; Dusseault et al., 2002; Vasco et al., 2002; Rothenburg et al., 1994; Vasco et al., 2008; Kroon et al., 2008; Carnec et al., 1999; Klemm et al., 2010); Most of these models are based on the nucleus of strain approach (Dusseault et al., 1993; Kroon et al., 2008; Vasco et al., 2002). Previous studies on direct and inverse simulations in the hydrocarbon related projects were mostly focused on measurements of vertical displacements (Bilak, 1989). Fewer studies have focused on horizontal deformations or tilt measurements: The reason is that displacements induced as a result of reservoir compaction/dilation majorly occur in a vertical direction, because of the geometry of geotechnical reservoirs (Bruno et al., 1992). In this study however, different combinations of tilt measurements and vertical displacements were considered as input for reservoir deformation modeling.

A unique solution would be available for solving for the location and magnitude of subsurface sources/discontinuities, assuming subsurface deformations are transferred linearly to the surface. However, the presence of random error in the observation data along with limited number of surface deformation data points, would result in the solution to be non unique and ill-posed (Dusseault et al., 2002).

Two new numerical models were developed in this study: a direct and an inverse model. The models were developed based on unidirectional deformations in well-defined locations. In order to solve the inverse ill-posed problem, a regularization technique was developed. A detailed sensitivity analysis was performed in this study, in order to identify the set of measurements that would result in the best simulation of the inverse problem. The results are presented in this paper.

2 METHODOLOGY

The models developed in this study are based on expressions for calculating ground surface displacements and tilts induced as a result of unidirectional dislocations taking place along a rectangular plane below the surface of an elastic half-space (Okada, 1985). Okada's solutions include responses to expansion or contraction that occur in one direction perpendicular to the plane. Modelling deformation in all directions using Okada's method requires the superposition of Okada solutions in three directions. The superposition of equal uniaxial movements corresponds to the nucleus of strain solution. In geologic reservoirs, which are the main focus of this research, the thickness is significantly smaller compared to the depth or the width. Reservoir deformations are thus mostly one dimensional in these cases; therefore, displacement discontinuity provides a better simulation for modeling geologic reservoirs.

A number of assumptions were made for the modeling of the direct and inverse problem. The surrounding media was assumed to be elastic, isotropic, homogenous, and the surface was assumed to be stress free. Although many factors which affect surface deformations were neglected (i.e., inhomogeneity), the results are believed to provide a good first order approximation, reasonably describing complex processes (Segall, 2010). Although reservoir deformations may be plastic and irreversible locally, the behaviour of the overburden material can be modeled elastically (Dusseault et al., 2002): with respect to hydrocarbon reservoirs, the strains induced in the overburden are very small and in an order of 10^{-4}, even when huge vertical deformations are observed on the surface. It is thus acceptable to assume that the overburden material acts elastically in most cases. In hydrocarbon reservoirs, the lateral extension is normally much larger than its thickness. Therefore, the reservoir was modeled as a thin rectangular plate. The subsurface sources inducing surface deformations were simulated as finite rectangular sources. Therefore, in order to simulate subsurface deformations, the reservoir was divided into smaller rectangular elements.

Induced surface deformation at a given observation point can be generally described as the integration of the effects of volume changes that occur in each reservoir element (Eq. 1).

$$u(\boldsymbol{x}) = \int_a^b K(\boldsymbol{x},\boldsymbol{s})Z(\boldsymbol{s})d\boldsymbol{s} \quad c \le \boldsymbol{x} \le d \qquad [1]$$

where $u(x)$ is the surface deformation, $Z(s)$ is the subsurface volume change, and the kernel $K(x,s)$ is an operator between u and Z. Eq. 1 is a form of Fredholm integral of the first kind (Tikhonov et al., 1977).

Inverse problems can generally be described in the form of Eq. 2.

$$KZ = u \qquad [2]$$

where u is the "external parameter" that is measured and known; Z is the "internal parameter" which cannot be measured or is difficult to measure directly; and K is a given operator between u and Z (Engl et al., 1987). The classic solution to Eq. 2 can be described in the form of Eq. 3.

$$Z = K^{-1}u \qquad [3]$$

In actual cases, the external parameter is measured experimentally, and thus would always contain error. Small variations in the measured data (u) will result in large discrepancies in the solution, making the solution unstable. Therefore, the exact solution cannot be used for the approximate input data set (Tikhonov et al., 1977). The problem is thus referred to as ill-posed. A regularization technique was applied in this study to seek an approximate solution for the ill-posed problem. The solution involves modifying the original problem in order to reconstruct a new problem that contains the following characteristics: approaches the original problem for small values of error present in the measured data, and is stable under small discrepancies in the observed data (Tikhonov et al., 1977). In order to construct this new problem, two parameters are to be defined: regularizing operator $R(u,\beta)$, and regularization parameter β.

2.1 Construction of the regularization operator

In order to construct a suitable regularization operator for the Fredholm integral, the least square approach, through minimizing a defined functional referred to as *the smoothing functional*, was implemented in this study. This functional is written based on the difference between the actual deformation values and those measured. However, the problem being ill-posed and unstable, a second term is added to stabilize the equation (Eq. 4).

$$M(u,Z) = \int [u(\boldsymbol{x}) - \int k(\boldsymbol{x},\boldsymbol{s})Z(\boldsymbol{s})d\boldsymbol{s}]^2\, d\boldsymbol{x} + \beta\Omega(Z) \qquad [4]$$

$u(x)$ is the measured surface deformation, $\int k(x,s)Z(s)ds$ is the exact surface deformation, $\Omega(Z)$ is the stabilizing functional, and *M(u,Z)* is the smoothing function. The stabilizing functional presented in Eq. 5, (Tikhonov et al., 1977) was implemented in this study.

$$\Omega(Z) = \int (\nabla Z \cdot \nabla Z) d\boldsymbol{s} \qquad [5]$$

where ∇Z is the gradient of Z with respect to its vector variable ***s***. Eq. 4 is the objective function in this study. The rationale for choosing a derivative-related smoothing functional is to force the solution towards functions with smooth variation, i.e. having smallest derivatives while still satisfying the original equation with a reasonable accuracy. Minimization of *M(u,Z)* with small β ensures that the original least square problem is solved on a set of functions that have no sharp variations in their derivative. This is achieved by adding $\Omega(Z)$.

It can be shown using the Calculus of Variation, that the function *Z(**s**)* minimizing Eq. 4, satisfies Eq. 6 (Dacorogna, 2004):

$$\int k^*(\boldsymbol{x},\boldsymbol{s})Z(\boldsymbol{s})d\boldsymbol{s} + \beta\Delta Z = u^*(\boldsymbol{x}) \qquad [6]$$

where $k^*(\boldsymbol{x},\boldsymbol{s}) = \int k(\boldsymbol{x},t)k(t,\boldsymbol{s})dt$, and $u^*(\boldsymbol{x}) = \int k(\boldsymbol{x},t)u(t)dt$. *k** matrix might be singular or the solution might still be close to being singular. Therefore, the inverse of *k** might not exist. The singular value decomposition method was thus implemented in this study, in order to deal with this issue.

2.2 Selection of β

β is a number between zero and one, obtained through trial and error. The effect of β on the inverse solution is illustrated in Figure 1. If β is chosen to be zero or very small, the problem would still be ill-posed or close to being ill-posed, and large values of noise is observed in the results. However, using a large value for β would significantly affect the solution, and result in an unrealistically smooth solution. Previous studies have mentioned that increasing β from zero would result in a decrease in the simulation error up to a point after which this error will generally increase (β_{opt}, minimum root mean square error)(Bilak, 1989; Du et al., 2001; Dusseault et al., 2002, Fokker, 2002). However, finding this minimum point is not easy and in some cases there might be several minimums present in the range of β from zero to one. The trial and error procedure should thus be repeated several times.

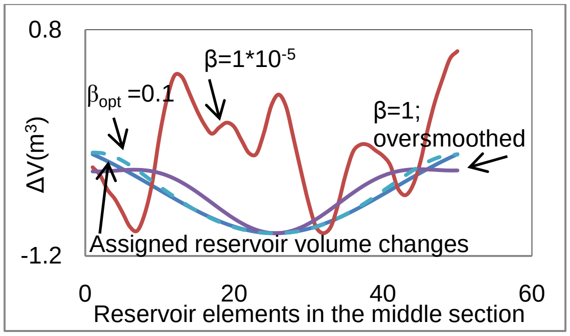

Figure 1. Effect of β on inverse solution.

2.3 Direct/Inverse Model

The general inputs of the developed model are: the geometry of the reservoir (width, length, depth, azimuth, and dip angle); number of reservoir elements; number and distribution of observation points; Lame's constants of the overburden material; and reservoir's volume change distribution. Surface deformation (vertical displacement and tilts in both directions) are calculated based on the assigned volume changes. In order to simulate measured field data containing error, random error is added to the calculated surface deformation values. Reservoir volume changes are back-calculated and compared to the initial volume changes for verification. This is done through: calculating the root mean square error (RMSE, Eq. 7); and plotting the initial and back-calculated volume change distribution for each reservoir section.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{n=1}^{N}(\Delta V_{\mathrm{initial}} - \Delta V_{\mathrm{back\ calculated}})^2}{N}} \qquad [7]$$

The inverse model allows for more degrees of freedom in the middle elements than in the corner elements of the reservoir, hence discrepancies are easier observed in the results of the corner elements. Therefore, in order to obtain an enhanced analysis of the results, the volume change distribution plots for the first section and the middle section of the reservoir are presented in this paper, representing the worst and best resolution achievable respectively.

In order to verify the direct numerical model and its accuracy, the induced surface deformation values obtained through the direct model were compared to a checklist presented by Okada. As for the verification of the inverse model, RMSE along with graphs of calculated and assigned volume change distributions were used to verify the numerical model, and illustrate its accuracy for different input data sets.

2.4 Sensitivity Analysis

In order to determine the most suitable surface deformation data set that would result in the best reconstruction of subsurface volume change distribution, a detailed sensitivity analysis was performed in this study. The parameters chosen for this sensitivity analysis are as follows:

2.4.1 Choice of input parameter/s (surface deformation data)

Different combinations of induced surface deformation data sets can be implemented as input for back-calculations. Determining the data set that would result in the best resolution is of interest.

2.4.2 Error present in the input data

The effect of the error present in different types of surface deformation data, on the inverse solution was studied. The goal was to determine the maximum percentage of error that would not affect the inverse solution significantly. This would help identify the best deformation measurement for indirect monitoring and also optimize the monitoring procedure. A suitable data collection method with desired accuracy can thus be chosen based on the results of this sensitivity analysis.

3 RESULTS

In order to indentify the data set that would result in the best resolution, the entire surface deformation field, which is a function of reservoir depth and dimensions, was taken into account. Identical cases with different input data sets were simulated. The results of RMSE versus β are presented in Figure 2. Figure 3 demonstrates the effect of input data on the reservoir volume change results, for the first reservoir section.

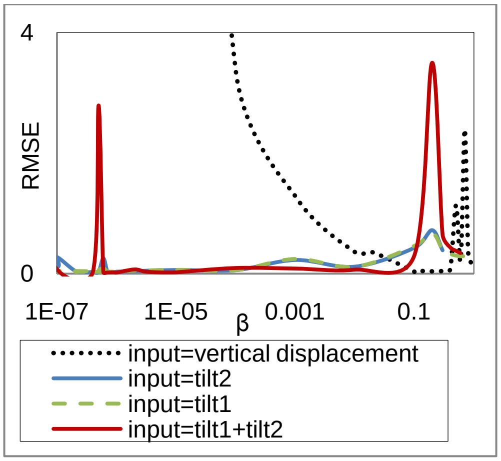

Figure 2. RMSE plotted VS β for different inputs

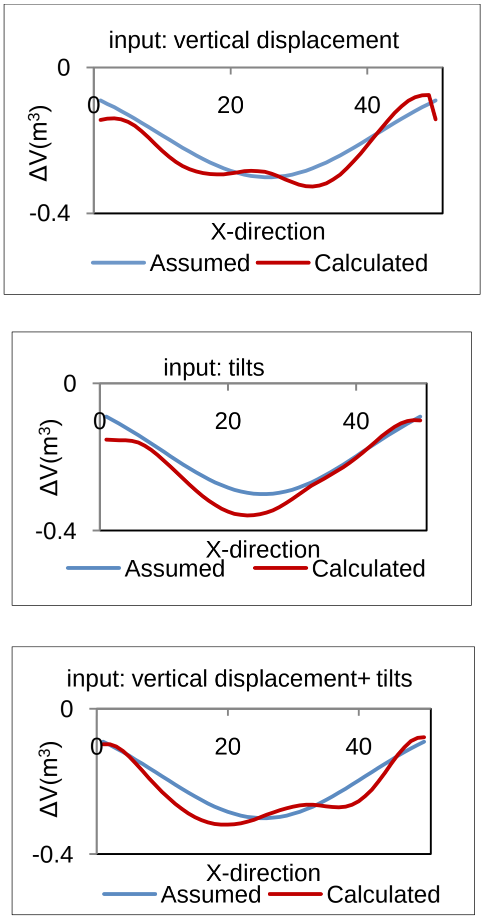

Figure 3. ΔV distribution using different input data sets.

A detailed sensitivity analysis was performed to study the effect of the error present in tilt measurements on the solution of the ill-posed problem. The results are presented in Figure 4.

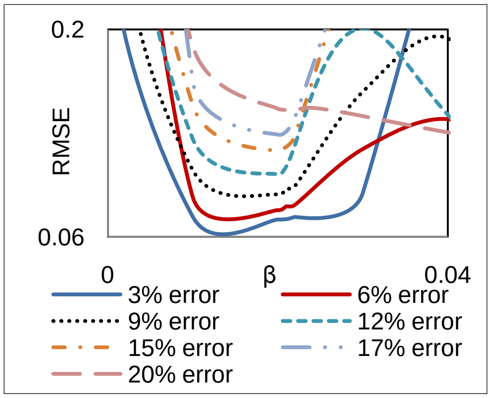

Figure 4. The effect of error on inverse simulation

Figures 5, 6, and 7 illustrate the initial and back-calculated volume changes for the first and the middle section of the reservoir, for identical cases with different input data sets containing error.

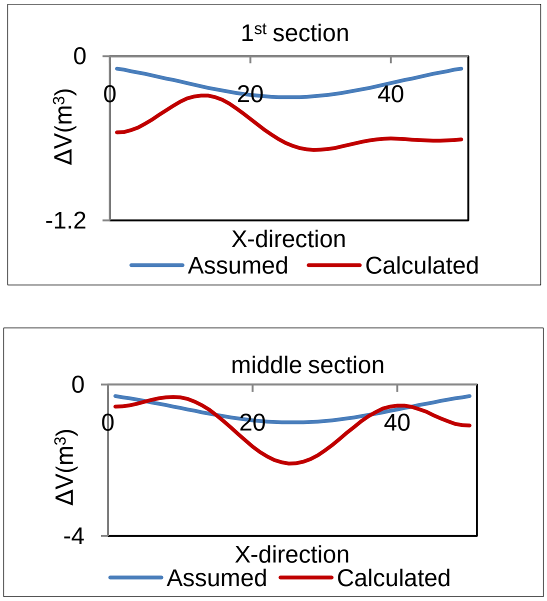

Figure 5. ΔV distribution; displacement+0.55% error as input.

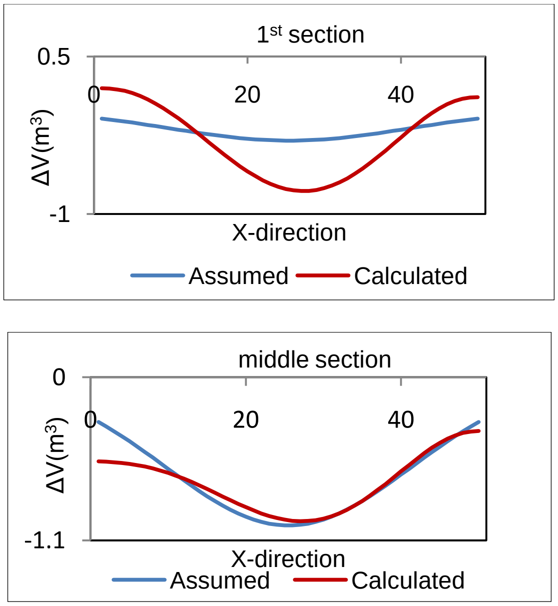

Figure 6. ΔV distribution; tilts+20% error as input

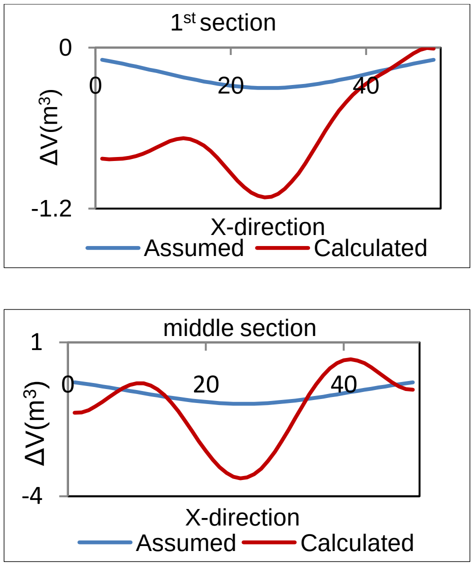

Figure 7. ΔV distribution; displacement+1%+tilts+1%error as input.

Figure 8 provides a summary of the results.

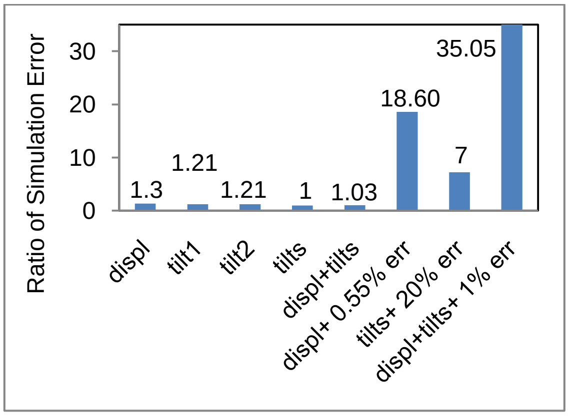

Figure 8. Relative reconstruction error from the sensitivity analysis performed on the type of input data and error present in the data

4 DISCUSSION

Direct monitoring of subsurface deformations is a costly and time consuming procedure. Therefore, inverse modeling has significant potential use in fast-paced projects. Results from inverse simulation (i.e., volume changes) can be applied to predict subsurface pressure changes induced as a result of hydrocarbon related operations. Therefore, results from inverse modeling can be implemented to indirectly monitor: steam concentration zones in the subsurface, potential areas of induced fracture in waste injection projects, and behaviour of the reservoir with respect to production and reinjection processes. Surface deformation monitoring, thus enables continuous screening of subsurface deformations. Most common surface deformation monitoring techniques implemented in hydrocarbon related projects are: tilt meter monitoring, global positioning system (GPS), and interferometric synthetic aperture radar (InSAR). Tiltmeter monitoring is one of the most popular monitoring techniques in hydrocarbon industry. Tiltmeters have two main advantages over other methods of surface deformation monitoring: 1) very high precision and the ability to detect motion in the order of 10^{-5} m; 2) continuous data collection capability that enables the closely monitoring of deformations due to production, injection, or other field operations (Du et al., 2005).

One objective of this study was to simulate reservoir deformations through inverse modeling by applying different surface deformation measurements as input. Two numerical models were developed to calculate induced surface deformations and also simulate the initial subsurface volume changes using surface deformation data. In order to obtain an acceptable solution for inverse modeling, the concept of determining β_{opt} through minimizing $RMSE_{min}$ was applied. The disadvantage of estimating the smoothing functional using RMSE is that there would no longer be a statistically independent check on the quality of the solution available. The RMSE therefore, is not a sufficient factor for evaluating the solutions. Consequently, in this study, the quality of the solution was verified through plotting the calculated volume changes for different sections of the reservoir.

In order to study the effect of the type of surface displacement measurement on the inverse simulation, different input data sets composed of tilts and vertical displacements were considered. Figure 2 clearly illustrates a significantly wider range for the solution space (acceptable solution; $RMSE_{min}$), when using tilt measurements compared to when vertical displacements were applied as input. Moreover, tilt measurements were found to result in a better reconstruction of the initial volume changes compared to vertical displacements (Figures 3 and 8). A comparison between the results from tilts in two different directions clearly indicated that tilt measurements from two different directions will result in approximately the same solution: β_{opt} and $RMSE_{min}$ are almost identical (Figures 2 and 8).

Inverse simulation involves using experimental measured data as input. Therefore, the input data will always contain error. The effect of this error on the inverse solution was examined through a detailed sensitivity analysis. As can be seen in Figure 4, increasing the error results in an increase in the $RMSE_{min}$ (the solutions deviate farther from the exact solution), and the general trend is almost identical for different values of error. The results from the β_{opt} and $RMSE_{min}$ (Figure 8) and volume change distribution graphs (Figure 5) clearly indicate that adding only 0.55% of the maximum displacement value as error would significantly affect the magnitude and distribution of the simulated volume changes. However, when using a combination of tilt measurements as input for back calculations, an error of as high as 20% of the maximum value of the recorded tilt, would still result in an acceptable reconstruction of reservoir volume changes (Figure 6). It should be noted that an error of 10% is considered reasonable for tilt measurements.

The results of this study, as discussed above, clearly indicate that tilt measurements are more suitable data for inverse simulations compared to vertical displacements, and that the behaviour of the reservoir may be better simulated by incorporating tilt measurements. However, it should be pointed out that in order to determine the most suitable observation technique(s) for different projects, other factors should also be taken into account (e.g. monitoring purpose, site conditions, and in situ situations below the surface).

5 CONCLUSIONS

Two numerical models were developed in this study: 1) direct model, in order to predict induced surface deformations based on subsurface volume changes; 2) inverse model, in order to simulate subsurface deformations based on surface deformation measurements. To verify the direct model, the results of the direct simulations were compared to Okada’s numerical checklist, which matched perfectly. For examining the accuracy of the inverse model, the results of back-calculations were compared to the initial volume changes (RMSE and distribution graphs). The calculations are all based on generic subsurface changes in volume; the results and conclusions can thus be generalized for a variety of applications and different types of reservoirs (e.g., hydrocarbon, underground water, geysers, waste reinjection projects, steam injection).

The results of the inverse modeling and detailed sensitivity analysis clearly indicate that tilt measurements are better input data than vertical displacement measurements for indirect reservoir monitoring: The computed RMSE value is smaller when using tilt measurements as input compared to when using vertical displacements; The distribution of the calculated volume changes is significantly closer to the initial assigned volume change distribution, particularly for the corner reservoir elements, when using tilt measurements; The inverse simulation was found to be significantly less sensitive to measurement errors when using tilt measurements as input data: The presence of small errors in the measured displacement data (<0.55% of the maximum surface displacement) generates significant deviations in the solution, however, errors up to 20% of the maximum tilt value, did not affect the solution significantly.

The volume change distribution curves and also the $RMSE_{min}$ and β_{opt} clearly indicate that applying either tilt measurements from both directions would result in almost identical simulations.

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