Interferometric Synthetic Aperture Radar Data Inversion for Reservoir Monitoring

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Abstract: As a modern geodetic method SAR interferometry measurement has an ability to estimate a high spatial coverage of displacement maps and provides an excellent opportunity to analyze physical processes by modeling the source of deformation**.** Based on model of Okada, we successfully inverted surface uplift obtained from InSAR data to reservoir deformations. Using genetic algorithms we were able to estimate the location of displacement sources. While a penalty function with smoothing factor was used to efficiently invert the distribution of displacement from the surface uplift data. From the genetic algorithms the depth of displacement sources is 296 meters. It has a good agreement with the depth from well data. The maximum vertical displacement rate at the depth obtained from the penalty function technique with a smoothing factor of 0.1 is 4.5 cm. Moreover, surface deformations from forward modeling are comparable to observed data estimated by InSAR. In addition, the total volume change rate is 148346.6692 m^3 a year from 2007 to 2008 considered as the growth of steam chamber. As conclusion, for monitoring reservoir deformations under production using inversion techniques the InSAR technology is very useful to provide ground surface deformations.

1. Introduction

GPS is one of the most suitable conventional techniques of surface deformation monitoring because it has not only high accuracy, but also provides three components of deformation *(Dixon, et al., 1997)*. However, GPS surveys over a large area are labour intensive and very time consuming. Fortunately, a modern geodetic method, Synthetic Aperture Radar Interferometry (InSAR) technology, provides its capability for imaging the ground surface deformations over large area (several 10s of km) with very small (1 cm or less) surface changes all weather conditions in daylight or at night *(Burgmann, et al., 2000)*.

In this study we made use of ground surface deformations estimated by differential Synthetic Aperture Radar Interferometry technique (*Khakim et al., 2010*). The surface deformations have valuable information about the dynamic reservoir and are most likely to occur in the production of hydrocarbon even if the reservoir is kilometers deep. Reservoir deformation is induced largely by pressure reduction or increase which reduces or increase the reservoir`s compressive or expansive strength and allows subsidence or uplift of the overlying rock into the reservoir. Characterization of the deformation sources based on the InSAR measurements has become major importance in related reservoir monitoring activity. In study we analyzed oil sand reservoir under steam injection, Steam Assisted Gravity Drainage (SAGD), which the reservoir pressure and temperature increase inducing surface heave. From the surface heave we inverted to estimate slip distributions as displacement sources using a finite rectangular fault model by Okada (1985).

2. Methods

Ground surface deformations from InSAR provide an excellent opportunity to analyze physical processes by modeling the source of deformation especially steam chambers in our study case. Ground surface displacements do not exhibit a spherical shape such as shown in Figure 1 and thus it does not seem to be the best approximation. As a more appropriate model, we used a rectangular dislocation in elastic, homogeneous, and isotropic half-space (*Okada, 1985*) for tensile fault movements. This model is non-linear and characterized by a great number of parameters.

There are two steps to estimate the distribution of source displacements. First step, we used an optimization technique of Genetic Algorithms (GAs) (*Holland, 1992*) to invert for fault geometry from the ground surface deformations acquired by SAR interferometry processing in order to estimate the depth of a fault plane, which we interpreted as the steam chamber. Strategies of GAs are based on the simulation of biological evolution in order to find the fittest individual by defining cost function in the evolutionistic sense. Initial population was randomly generated and subjected to several changes by systematically approaches the best solution among many investigated solutions. Major genetic algorithm operators are evaluation, selection, cross-over and mutation to allow modification of the population to search the best solution. The searching process ended when a number of iterations or generations were achieved as a stopping criterion. In this analysis, we used a Poisson ratio of 0.25 and a rigidity of 10 GPa. Second step, using a penalty function technique with smoothing factor (*Du, et al., 1992*) we modeled the distribution of displacement source and subdivided the fault plane into a 40 x 40 grid.

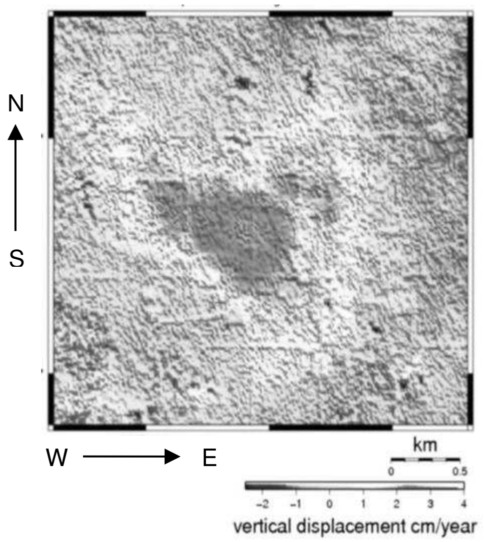
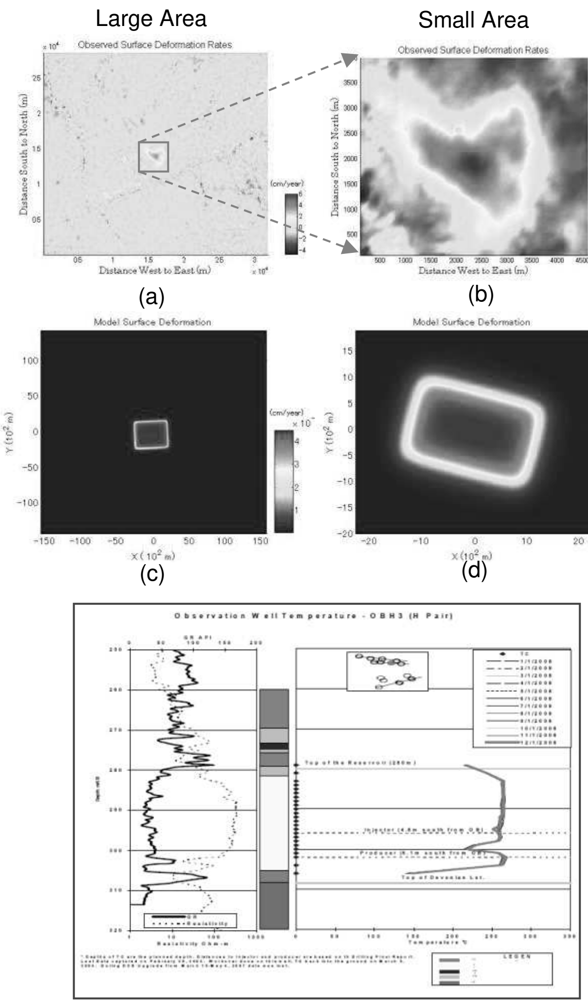


Figure 1. Ground surface vertical displacement (*Khakim, et al., 2010*)

3. Results

For a geometry inversion using the genetic algorithm we compared a large area of ground surface displacement to small one for an input to estimate fault geometry as shown in Figure 2a and 2b. We constrained the lower and upper bounds of length, width, depth, chamber development and strike of the fault (considered as steam chamber in this case) to 4.2-5.0 km, 3.5-4.5 km, 280-300 m, 0-20 cm and 0º-360º, respectively in search space. We also considered the dip angle of zero as one of the inversion parameters and used the initial population of 500 individuals and a number of generations are 500. After all parents had been paired off from selected population, a random number between 0 and 1 was generated. This random number was compared to a specified crossover probability of 0.7. If the number was less than the crossover probability, the two parents were crossed over. Position of crossover in which part of the right crossover bit-string is exchanged between parents was also randomly selected along the bit-string representation.



(e) (*Anonymous, 2009*)

Figure 2. Observed surface vertical displacements for (a) large area, (b) small area, modeled one for (c) large area, (d) small area and (d) well log showing the depth of injection

Like crossover operation, mutation also needed probability to maintain some random character in the search process. We specified the mutation probability of 0.4; therefore, if a random number less than the mutation probability, a tested bit was flipped in parity. From the genetic algorithm we obtained the best-fit model predicted the rectangular fault with length, width and depth of 4.629 km, 3.767 km and 296 m, respectively with root-mean-square error (RMSE) of 6.977E-005 for large area input and of 2.413 km, 1.533 km and 297 m, respectively with RMSE of 6.271E-005 for small one. RMSE of large data input is higher than that of small one because large area included more noises than that of small area. The depth of displacement source is in good agreement with real data related to the depth of injection wells (Figure 2(e)).

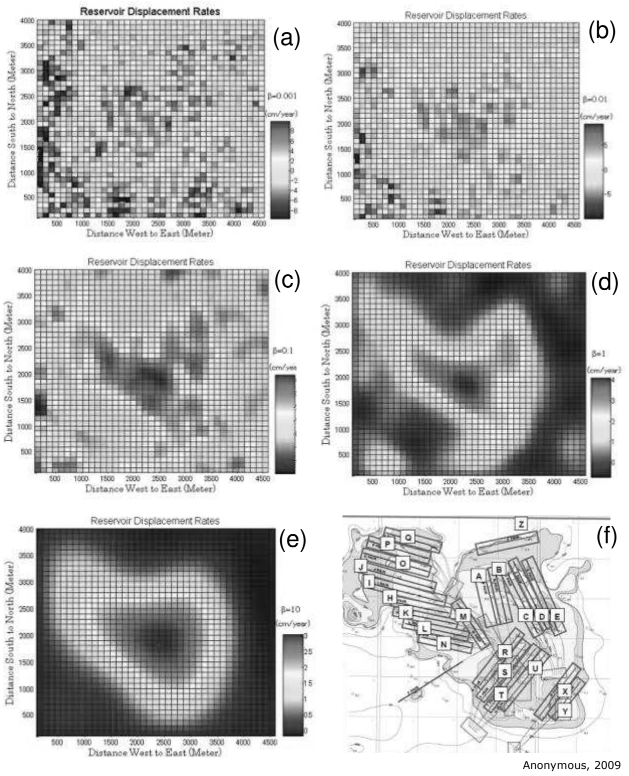


Figure 3. Reservoir displacements with the variations of smoothing factor of (a) 0.001, (b) 0.01, (c) 0.1, (d) 1, and (e) 10, and (f) configuration of production and injection wells

For the estimation of the displacement source distribution from observed-surface-deformation data from SAR interferometry measurement we used a penalty function technique with smootness. The best-fit-single fault model from the genetic algorithm inversion was enlarged to 4.6 x 4.0 km horizontal fault. The enlarged-fault plane was then discretized into 100 x 100 m patches for inversion of distributed-source displacement. This displacement is interpreted as steam-chamber development under SAGD process. In this study, we used penalty function technique with five smoothing factors, i.e. 0.001, 0.01, 0.1, 1, and 10. From this inversion, the maximum of source displacement rate was around 4.5 cm/year with smoothing factor of 0.1 (Figure 3(c)). For a lowest smoothing factor (0.001) the reservoir vertical displacement rate is highly oscillatory with maximum displacement rate of around 9 cm a year (Figure 3(a)), but for a highest smoothing factor (10) the reservoir vertical displacement is overly smooth with maximum rate of around 3 cm/year (Figure 3(e)).

The reservoir displacement pattern in Figure 3(c) is closely related to well pair locations in Figure 3(f). We also compared it to 4D seismic that the displacement pattern is a good agreement with estimated steam chamber area (Figure 6).

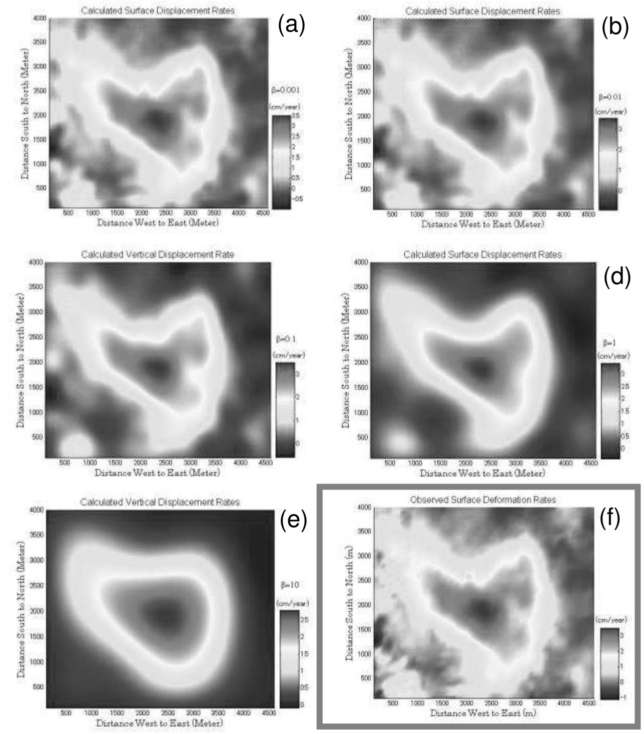


Figure 4. Modeled surface vertical displacements with the variation of smoothing factors of (a) 0.001, (b) 0.01, (c) 0.1, (d) 1, (e) 10, and (f) observed data from InSAR

The observed and modeled surface displacements are comparable in which has root-mean-square error of 1.2498e-005 such as shown in Figure 4(c). These small residuals between observed and modeled displacements may be related to some noises in InSAR data. The total of volume change rate was 148346.6692 m^3 a year. This volume change rate is considered as steam chamber growth during SAGD process.

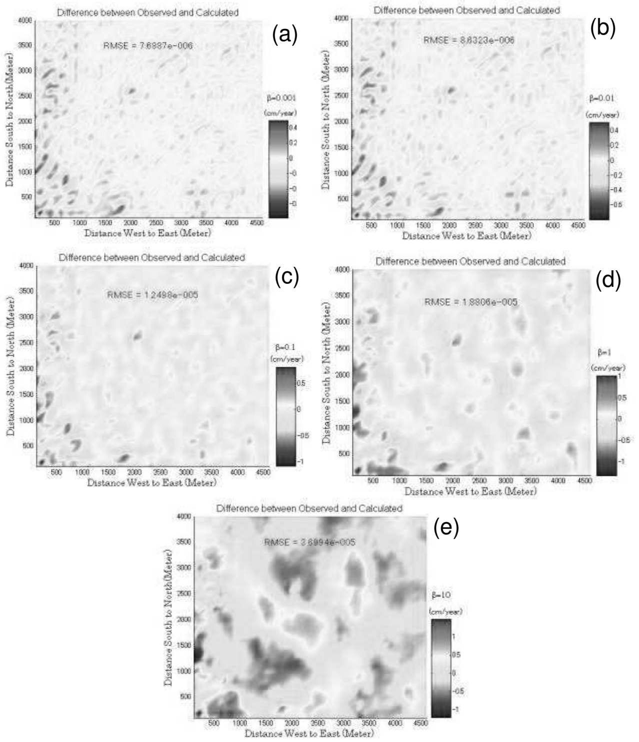
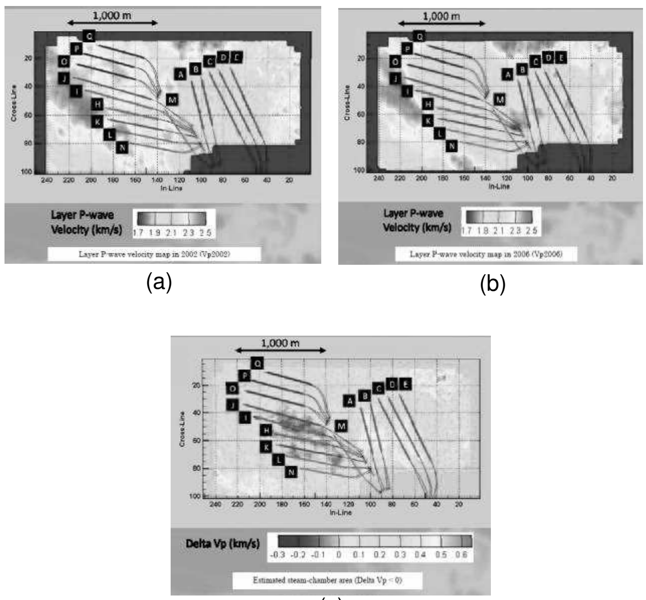


Figure 5. Residuals between observed and modeled with smoothing factor variations of (a) 0.001, (b) 0.01, (c) 0.1, (d) 1, and (e) 10



(*Anonymous, 2009*)

Figure 6. Estimated steam chamber area from 4D Seismic

4. Conclusion

We applied genetic algorithms for estimating deformation source parameters based on surface vertical displacement data from InSAR. The result shows that the depth of deformation source is a good agreement with well data. We also applied a penalty function technique with smoothing factor to estimate the best displacement rate. Based on this technique, the maximum of source displacement rate is about 4.5 cm/year. Finally, we estimated the total volume change rate of 148346.6692 m3/year considered as the growth of steam chamber.

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