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Submission date: 13-Jun-2023 07:18PM (UTC+0700)
Submission ID: 2115214045
File name: Article_RAEG2010_MYusupNKh_-_Copy_B.pdf (1.85M)
Word count: 2263
Character count: 11841

SURFACE and SUBSURFACE MONITORING at OIL FIELD USING SYNTHETIC APERTURE RADAR INTERFEROMETRY(InSAR)

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SAR interferometry method has not only an ability to estimate a high spatial coverage of displacement maps but also provides an excellent opportunity to analyze physical processes by modeling the source of deformation**.** Ground surface deformations were estimated by using differential InSAR (DInSAR) technique. Based on a tensional rectangular dislocation model, 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. A penalty function with smoothing factor was used to efficiently invert the distribution of displacement from the surface uplift data. The results are comparable to other data. We conclude that for monitoring reservoir deformations under production the InSAR technology is very useful to provide ground surface deformations and accurately monitor reservoir deformation using inversion techniques.

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 deformation1). However, GPS surveys over a large area are labor intensive and 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 night2).

In this study we made use of ground surface deformations estimated by differential Synthetic Aperture Radar Interferometry technique3). 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 in kilometers deep. Reservoir deformation is largely induced by pressure reduction or increase which reduces or increases 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 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 subsurface reservoir deformation (i.e., open crack) as displacement sources using a finite rectangular fault model4). In addition, we also apply this method not only to real data but also to synthetic data.

2. METHODOLOGY

Ground surface deformations from InSAR provide an excellent opportunity to analyze physical processes by modeling the source of deformation especially steam chambers. 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 for tensile fault movements. This model is non-linear and characterized by a great number of parameters and is frequently used in the characterization of earthquake faults.

In this study, we applied inversion technique to synthetic data and real one of oil-sand field under Steam Assisted Gravity Drainage (SAGD). There are two steps to estimate the distribution of source displacements. Firstly, we used an optimization technique of Genetic Algorithms (GAs)5) to invert for fault geometry from the ground surface deformations acquired by SAR interferometry processing in order to estimate the depth of a dislocation 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[6] we modeled the distribution of displacement source and subdivided the dislocation plane into a 40 x 40 grid.

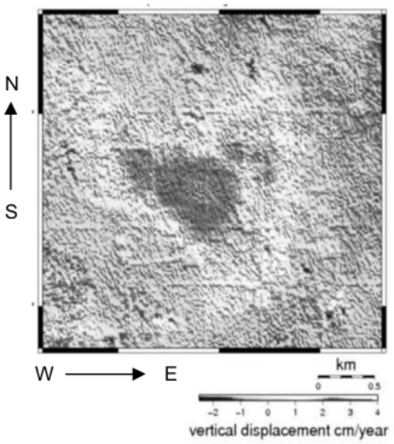

Fig. 1 Ground surface vertical displacement (*Khakim et al., 2010*).

3. RESULTS

(1) Synthetic model

In order to examine the ability of inversion techniques, both GAs and least square inversion, we built synthetic rectangular opening dislocation model to estimate the geometry, position, depth, and orientation of rectangular opening dislocation shown as Fig. 2(a). From these model parameters, we applied forward modeling to obtain synthetic uplift map, Fig. 2(b). Using initial models and GAs inversion parameters, we obtained the results that can be expressed with six parameters as shown in table 1.III.

Tabel 1 Inversion parameters

I	**Initial Model and Inversion Parameters**	
1	Length	1.5 - 2.5 Km
2	Width	0.5 - 0.7 Km
3	Depth of opening source	0.482 - 0.51 Km
4	Source Opening	0 - 10 cm
5	(x,y)-position	(-20 - 18, -20 - 18)
6	Strike	0 - 360 deg
7	Crossover probability	0.7
8	Mutation probability	0.4
9	Number of generation	300
10	Number of individual	800
II	**Synthetic Model Parameters**	
1	Length	2.0 Km
2	Width	0.6 Km
3	Depth of opening source	0.5 Km
4	Source opening	3 cm
5	(x,y)-position	(-15,-5)
6	Strike	90 deg
III	**Inversion Results**	
1	Length	1.967 Km
2	Width	0.607 Km
3	Depth of opening source	0.516 Km
4	Source opening	3.2 cm
5	(x,y)-position	(-14.93,-4.8)
6	Strike	93 deg

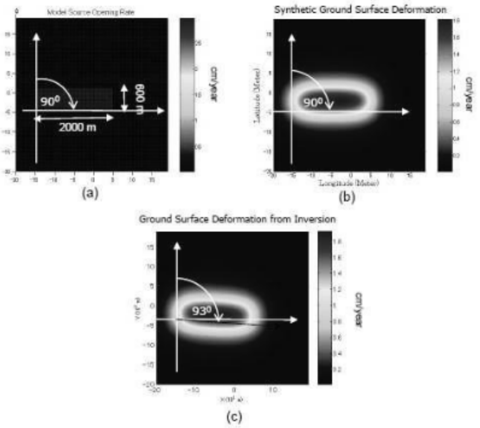

Fig. 2 GAs inversion (a)synthetic model, (b)forward modeling from synthetic model, and (c) inversion result.

If the results are compared to the synthetic model, the result parameters are highly closed to synthetic model with root-mean-square error (RMSE) of 4.372×10^{-6}. From the inversion results, we also applied the forward modeling to estimate surface uplifts, Fig. 2(c). The surface uplift map is closely similar to that of synthetic model.

Beside GAs inversion, we also examined a penalty function with smoothing factors in least square inversion. The larger the smoothing factor we apply, the smoother the opening dislocation is. However, a normalized-sum-square difference (NSSD) is larger. Therefore, we need a trade off curve between roughness and NSSD with smoothing factor variation. Based on the trade off curve we chose the best smoothing factor of 0.1 for the inversion process.

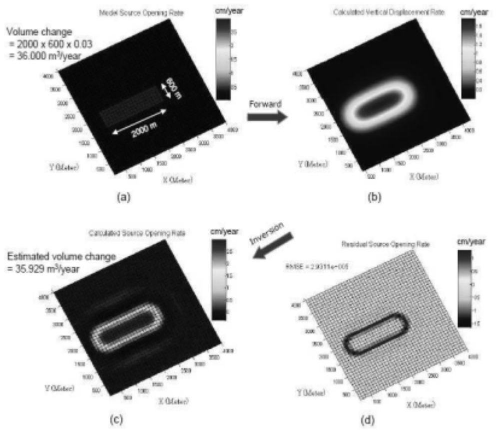

Fig. 3 Least square inversion (a) synthetic model, (b) forward modeling from synthetic model, (c) inversion result, and (d) residual between synthetic model and its inversion.

Based on these inversion examination to the synthetic model, we can summarized that both GAs inversion and penalty function with smoothing factors in least-square inversion show very good abilities to estimate some parameters as explained above.

(2) Real data

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 4(a) and 4(b). 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 0°-360°, 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.

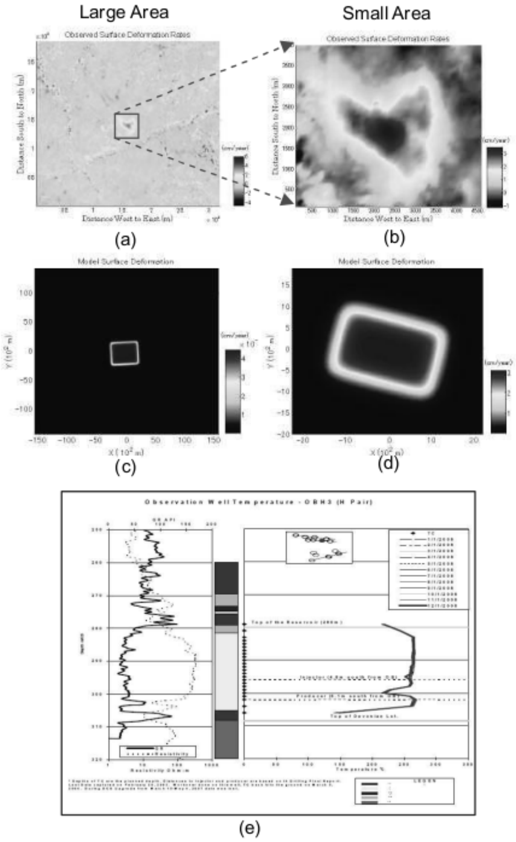

Fig. 4 Observed surface vertical displacements for (a) large area, (b) small area, modeled one for (c) large area, (d) small area and (e) well log showing the depth of injection[7].

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 dislocation plane with length, width and depth of 4.629 km, 3.767 km and 296 m, respectively with

RMSE of 6.977x10^{-5} for large area input and 2.413 km, 1.533 km and 297 m, respectively with RMSE of 6.271x10^{-5} 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 4(e).

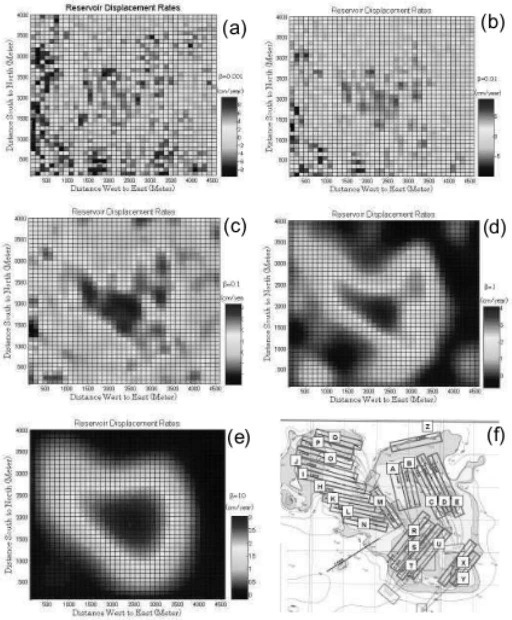

Fig. 5 Reservoir displacements with the variations of smoothing factor of (a) 0.001, (b) 0.01, (c) 0.1, (d) 1, and (e) 10, and (f) configuration of production and injection wells$^{7)}$.

To estimate the displacement source distribution from observed-surface-deformation data from SAR interferometry measurement we used a penalty function technique with smoothness (*Du et al., 1992*). 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, in Figure 5(c), was ~4.5 cm/year with smoothing factor of 0.1 which was based on analysis of trade off curve between roughness and NSSD. For a lowest smoothing factor (0.001) the reservoir vertical displacement rate is highly oscillatory with maximum displacement rate of ~9 cm a year (Figure 5(a)). For a highest smoothing factor (10), however, the reservoir vertical displacement is overly smooth with maximum rate of ~3 cm/year (Figure 5(e)).

The reservoir displacement pattern in Figure 5(c) is closely related to well pair locations in Figure 3(f). Furthermore, comparison with 4D seismic data demonstrated that the displacement pattern is a good agreement with estimated steam chamber area (Figure 8).

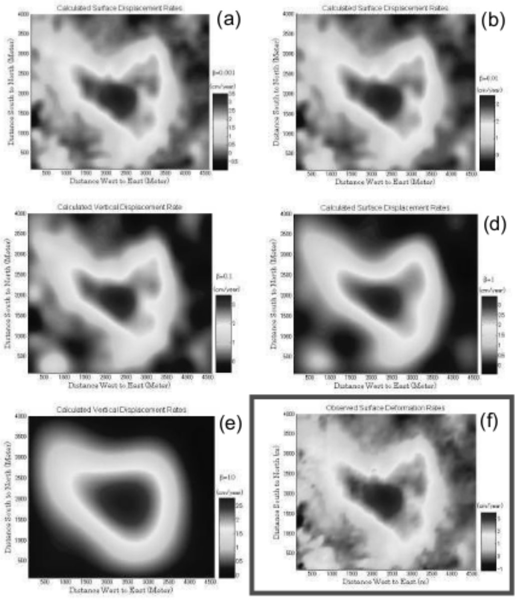

Fig. 6 Modeled surface vertical displacements with the variation of smoothing factors of (a) 0.001, (b) 0.01, (c) 0.1, (d) 1, (e) 10, and (f) observed data from InSAR.

The observed and modeled surface displacements are comparable in which has root-mean-square error of 1.2498 x10^{-5} such as shown in Figure 6(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 m^3 a year. This volume change rate is considered as steam chamber growth during SAGD process.

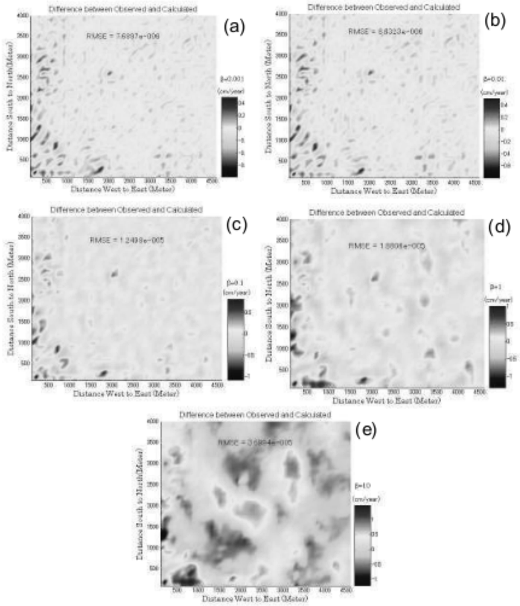

Fig. 7 Residuals between observed and modeled with smoothing factor variations of (a) 0.001, (b) 0.01, (c) 0.1, (d) 1, and (e) 10.

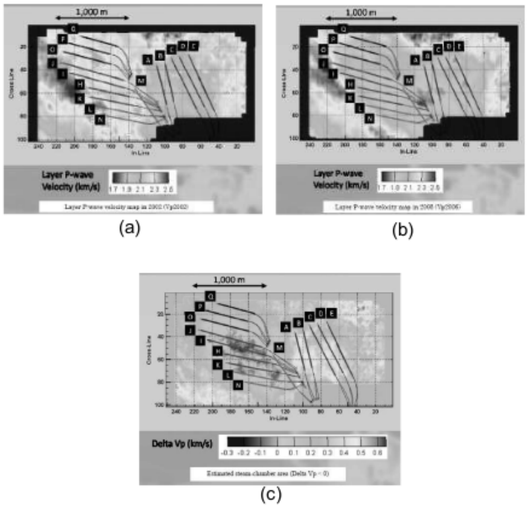

Fig. 8 Steam chamber area estimated from 4D Seismic data$^{7)}$.

5. 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 m3/year considered as the growth of steam chamber.

ACKNOWLEDGMENT: We wish to thank the Earth Remote Sensing Data Analysis Center (ERSDAC) for providing ALOS PALSAR data. METI and JAXA have the ownership of the ALOS PALSAR original data. The PALSAR Level-1.0 products were produced by ERSDAC, Japan. I would also like to thank K. Ishitsuka (Kyoto Univ.) for inversion discussions.

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