Study on the complexity of reservoir parameters inversion in partially saturated porous media

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Summary

The main purpose of this paper is to further clarify the complexity of the inversion method by using Niche Genetic Algorithms (NGA) to inverse the petrophysical property parameters. The improved BISQ model, presented in our earlier work, is chosen for the forward model in NGA. In this paper, the relationship between the sample number of the given wave response data and the inversion results, such as the precision and stability, is detailedly discussed by means of numerical experiments. It is found that, with respect to the data examined, the precision of inversion results is mostly satisfied when the sample number of given data is chosen as $N=5$. The simulation results also show that the inversion results of the porosity are most stable, which relative error is less than 1.17% at all cases.

Keywords Parameters inversion, Niche Genetic Algorithms

Introduction

Our previous work offered an inversion method by using NGA to inverse the parameters of the reservoir based on the improved BISQ model. The classical BISQ theory, simultaneously considering the Biot-flow and squirt-flow mechanisms in porous medium, adequately explains the observations of large dispersion and strong attenuation, because it combines well the macroscale parameters of the reservoir and the microscale fluid properties. In recent years, the BISQ theory has been widely paid attention and many results have been obtained. Our improved forward model can be used to investigate the wave propagation in partially saturated porous rocks, and its validity has been checked. It is extraordinarily valuable for expanding the application range of the classical BISQ theory from the fully saturated assumption to the case of partial saturation.

In fact, the essence of inversing reservoir parameters is an optimization problem of seeking the adequate model parameters to make the theoretical predicted results accord with the experimental data. For the model of two-phase system, complex program and high cost of computation are ascribed to the complicated equations of motion; however, the traditional Genetic Algorithms (GA) can simplify the calculation, only using the error information of the object function. Unfortunately, sometimes, the simple GA is also easy to trap into a local extremum. As a modified GA, NGA well maintains the population variety, and holds the properties of preventing premature convergence. So NGA is more advantageous to the nonlinear optimizations problem in geophysical prospecting than others inversion algorithms.

The present work is developed on the basis of our earlier study, in which the complexity of the inversion algorithms is investigated by mean of the numerical simulation. From the full discussion of the relation between the sample number of known data and inversion results, some general conclusions will be given finally.
Improved BISQ Model and Niche Genetic Algorithms

In this section, we provide the formulae of the phase velocity and attenuation obtained from the forward model, and expound the fundamental principle of NGA in the inversion algorithm for the reservoir parameters.

In 1993, according to the assumption of two-phase system theory, Dvorkin et al. offered a poroelasticity model for the Biot/squirt flow in rocks, which can simultaneously consider both the Biot-flow mechanism and the squirt-flow mechanism. Based on the idea of the equivalent theory, we derived the improved BISQ model by introducing the saturation parameter into Dvorkin’s BISQ model. For the wave propagation in partially saturated porous media, our BISQ model described the partial problem by the given equivalent bulk modulus and equivalent density of the fluid phase. From the improved BISQ model, the phase velocity of the fast P-wave and slow-P wave can be obtained as

\( V_{p,3} = \sqrt{2/\text{Real}(\sqrt{b \pm c})} \),

where coefficient \( b \) and \( c \) are function of the porosity, saturation, permeability, porous media modulus, and wave frequency (see in Ref[2]).

The NGA is a modified Genetic Algorithms (GA) based on the idea of the niche. In order to overcome the shortcoming of trapping in local minima, it is greatly useful to apply the Niche technique into the traditional GA. The NGA can well maintain the variety of the population due to using the improved standard fitness sharing method, and finally give the global optimal solution. The sharing function is defined \([7]\) as

\[
S_b = \begin{cases} 
1 - d_{ij}/\sigma & d_{ij} < \sigma \\
0 & \text{other}
\end{cases},
\]

where \( \sigma \) is the given niche radius, \( d_{ij} \) is the distance from the individual \( i \) and the individual \( j \). Then the sharing fitness \( f'_{i} \) can be obtained from the original fitness \( f_{i} \) as

\[
f'_{i} = f_{i} / \sum S_b .
\]

The formulae (2) and (3) show that the smaller the sharing fitness of one individual will become, the larger the distance between it and another individual is in a niche. In NGA, the individual of high fitness can hardly to be eliminated. So the sparse parent individuals could easily propagate, which may help to maintain the variety of the final solutions during the evolutionary process. This property can prevent premature convergence and hold the properties of global optimum and fast convergence, especially for the complex multi-modal optimization problem of inversing the reservoir parameters.

The essence of inversing reservoir parameters by GA is an optimization problem of seeking the adequate model parameters \( p(p_1, p_2, \ldots, p_n) \) to make the theoretical predicted results of P-wave and S-wave accord with the experimental data. The objective function is defined as:

\[
E(p) = \frac{1}{N} \left( \sum_{i=1}^{N} \left[ 1 - \frac{V_p(p,i)}{V_{p}^*(i)} \right]^2 + \sum_{i=1}^{N} \left[ 1 - \frac{V_s(p,i)}{V_{s}^*(i)} \right]^2 \right)
\]

where \( V_p(p,i) \) and \( V_s(p,i) \) express the \( i \)th predicted velocities, \( V_{p}^*(i) \) and \( V_{s}^*(i) \) are the \( i \)th measured data, and \( N \) is the number of sample. The fitness function is the minimum of the objective function \( \min E(p) \).

Numerical example
The inversion method mentioned above has been presented in our previous research\cite{1}. The chief aim in this section is to further investigate the complexity of reservoir parameters inversion based on the above method. In the forward model, the porosity, the permeability, and the saturation are the inversion parameters. The variation range of these three parameters are: $5\% \leq \phi \leq 40\%$, $1\text{mD} \leq k \leq 50\text{mD}$, $10\% \leq S \leq 100\%$. We choose the real value of these three parameters in the improved BISQ model as: the porosity is $\phi_0 = 25\%$, the permeability is $k_0 = 5.0 \text{mD}$, and the saturation is $S_0 = 65\%$. The other model parameters are selected to be the same as those presented in Ref. [3]. Those parameters are: $K = 16\text{GPa}$, $\nu = 0.15$, $\rho_s = 2650 \text{kg/m}^3$, $K_s = 38\text{GPa}$, $\rho_f = 1000\text{kg/m}^3$, $\rho_o = 420\text{kg/m}^3$, $\eta = 0.001\text{Pa} \cdot \text{s}$, and $R = 1 \text{mm}$. The parameters of NGA are selected as: the number of the population is 4, the number of individuals every population is 50, the crossover probability is $P_c = 0.9$, the mutation probability is $P_m = 0.05$, the ratio of selection from the parent population is 60\%, and the generation number is 30. We repeat the inversion process 25 times in every case of the given sample data number because of the randomicity of producing the initial individuals.

Figure 1(a) shows that the average relative errors of these three inversed parameters in the case of different number of given sample data, and figure 1(b) indicate the convergent trend of the objection function. From figure 1, we can see that almost the inverted errors get smaller and smaller while at the same time the sample number of known data increases further and further. This relation isn’t absolutely monotone decreasing, however, the aggregate error of the objective function will increase if the sample number is more excess, which may result in depressing precision of inversion result. It is clearly that the inversed result of the porosity is most stable, which relative error is only 1.17\%. The error of the permeability is largest, which is 34.19\% as the sample number is $N=2$, and it reaches 3.92\% while $N=5$. It is satisfied with the saturation inversed results. Its maximum error is 3.66\% when the sample data number is selected as $N=2$, and the minimum is only 0.836\% at the case of $N=6$. Therefore, with the situation of the objective function, we consider that it is better to choose the sample number of wave respond data as $N=5$ in the case of three parameters inversion.

In order to further make clear the relation of the stability of inversion results and the sample number, we plot the results of the porosity, the permeability, and the saturation in Figure 2 while the data number is $N=5$, and $N=2$. Figure 2 directly prove that the inversed stability and precision for the case of $N=5$ is superior to that for the case of $N=2$.

![Figure 1. Relations between the inversion results and the sample numbers](image-url)
Figure 2. Results of inversion parameters versus times of inversion

the sample number is N=5 in figures (a), (c), (e), and in figures (b), (d), (f) that is N=2

Conclusion

We have investigate the relationship between the inversion precision and stability and the sample number of the given wave respond data, based on NGA and the improved BISQ model. From the example of numerical simulation in the case of three parameters inversion, we draw the conclusion that excess data or deficiency could induce reducing the precision and the stability of inversed results, and it is better to choose the sample number of the known data as N=5 than other situations.
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Reference