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Back-analysis of Pavement Thickness Based on PSO-GA Hybrid Algorithms

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Abstract. The thickness of pavement structural layer is one of the key indicators of pavement quality detection, which has a great impact on the normal use of the pavement. Among the algorithms that calculating this indicator, particle swarm optimization algorithm has low inversion accuracy while genetic algorithm has low inversion efficiency. This thesis put forward a hybrid inversion analysis method based on particle swarm optimization and genetic algorithm. By taking the advantages of the above two algorithms and combining the characteristics of selection, crossover, mutation of genetic algorithm and fast convergence of particle swarm optimization, this method could improve the accuracy of inversion under the condition of ensuring the computational efficiency. The analysis of the inversion results of theoretical model and field core sampling results verified the accuracy of inversion results, and the feasibility and effectiveness of the proposed algorithm were proved.

1. Introduction

The thickness of pavement structural layer is one of the key indicators of pavement quality detection. Traditional detection methods, such as core drilling sampling and manual measurement, have disadvantages of tedious process, long time consuming, low representativeness, destructive to the pavement, etc. Therefore, it is particularly important to develop non-destructive testing technology for pavement structural layer quality detection. Ground Penetrating Radar (GPR), as a non-destructive testing method, has the advantages of non-destructive, high efficiency, low cost and high resolution imaging. It has been a hot topic internationally since 1980s.

Particle swarm optimization (PSO) and genetic algorithm (GA) are both intelligent algorithms based on population evolution. Both of them have their own advantages as well as shortcomings in the process of calculation. Genetic algorithm has strong ability of global search and cross-mutation, but its local search ability is poor, which leads to low search efficiency and overall computational efficiency. Particle swarm optimization (PSO) algorithm has fast convergence speed, but the diversity of population decreases too fast in the process of searching; coupled with its poor global search ability; it is prone to premature convergence and resulting in low calculation accuracy. With the increasing requirement for the algorithm, the defects of the standard are becoming more and more prominent. Genetic algorithm and particle swarm optimization algorithm have their advantages in some aspects. This thesis proposed a hybrid inverse analysis method which combines the advantages of above two



algorithms. Based on the finite difference time domain method, the accuracy of the hybrid inversion method was verified by comparing the results of theoretical model inversion with those of field core drilling sampling. The feasibility and validity of the hybrid inversion algorithm were proved.

2. The Hybrid algorithm based on particle swarm optimization and genetic algorithm

2.1. Particle swarm optimization

Particle swarm optimization (PSO) is a global optimization algorithm developed in recent years. The basic idea is to assume that in a D-dimensional search space, m particles form a community. The first particle represents a D-dimensional vector, which is denoted as $M_i = (m_{i1}, m_{i2}, \dots, m_{iD})$, $i = 1, 2, \dots, m$, that is, the i-th position M_i in the D-dimensional search space. The position of each particle is a potential solution. The location of each particle is a potential solution. The fitness value of M_i is calculated by taking M_i into an objective function constructed to satisfy the problem. Then, the fitness value of M_i is weighed according to the fitness. The i-th particle is the best position to be found so far, $T_i = (t_{i1}, t_{i2}, \dots, t_{iD})$, also known as T_{best} . The optimal position of the whole particle swarm optimization algorithm searched so far is marked as $T_g = (t_{g1}, t_{g2}, \dots, t_{gD})$, also known as g_{best} . The calculation formula of PSO algorithm is as follows:

$$M_i(k+1) = M_i(k) + N_i(k+1)\Delta t \quad (1)$$

$$N_i(k+1) = wN_i(k) + c_1r_1(T_i - M_i(k)) / \Delta t + c_2r_2(T_g - M_i(k)) / \Delta t \quad (2)$$

Where, $i = 1, 2, \dots, m$, learning factors C_1 and C_2 are nonnegative constants, r_1 and r_2 are random numbers between [0, 1]. w is inertia weight and is a constant in interval [0,1]. k is the number of iterations, m_i is the position vector of the i-th particle; N_i is the velocity vector; Δt is the time interval, often taken as the unit time.

2.2. Genetic Algorithms

The genetic algorithm was first proposed by Professor Holland of the United States in 1975. It is a random search algorithm based on natural selection and natural genetic mechanism in the biological world.

For a particular problem, genetic algorithm codes each solution as a chromosome individual. In this way, an initial group is defined in the solution space, and all the individuals in this group represent a region in the solution space. All search spaces are defined as the whole solution space, in which every possible solution can be coded as a chromosome. Before the search begins, a group of chromosomes are randomly selected from the search space to form the initial population. Next, all fitness values in a population are calculated by a specific objective function. According to their fitness values, individuals are selected in a competitive way to perform genetic operations.

By simulating natural selection and natural genetic process, and continuing genetic operations such as reproduction, crossover and gene mutation, the overall quality of chromosomes obtained is bound to be better than that of generations. Repeated genetic operations are performed until termination conditions are met, and the optimal chromosomes in the last generation are decoded into final solutions.

2.3. Hybrid algorithm based on particle swarm optimization and genetic algorithm

By comparing the calculation process of particle swarm optimization and genetic algorithm, it is found that the main difference between the two algorithms in operation lies in two aspects. Firstly, the new generation of individual selection strategies is different. Particle swarm optimization (PSO) algorithm

is to generate a new generation of individuals by optimizing the reproduction of all individuals and groups. Secondly, in the new generation of individuals, genetic algorithm will have mutation operation, while particle swarm optimization has no mutation operation.

The hybrid algorithm proposed in this paper was based on the particle swarm optimization (PSO) algorithm, in which the selection, crossover and mutation of genetic algorithm were added.

(1) Selection and crossover process: By the method of roulette selection, M (even number) individuals are randomly selected from the new generation of individuals, and then the selected M individuals are paired in pairs to perform crossover operation. In the crossover process, a real number r in the $[0, 1]$ interval is randomly generated. The crossover operation was carried out with the following formula:

$$\begin{cases} \hat{M}_1^a = r \cdot M_1^a + (1-r) \cdot M_2^a \\ \hat{M}_2^a = r \cdot M_2^a + (1-r) \cdot M_1^a \\ \hat{N}_1^a = r \cdot N_1^a + (1-r) \cdot N_2^a \\ \hat{N}_2^a = r \cdot N_2^a + (1-r) \cdot N_1^a \end{cases} \quad (3)$$

Where, a represents the number of iterations, m_1^a , m_2^a 和 n_1^a , n_2^a represent the position and velocity vectors of the selected two paternal individuals respectively, \hat{m}_1^a , \hat{m}_2^a 和 \hat{n}_1^a , \hat{n}_2^a represent the position and velocity vectors of the offspring separately after crossover.

(2) Mutation operation: the following mutation operation is performed on each new individual \hat{m}_k^{gap} who has completed crossover operation with probability p_m :

$$M_K^{a+1} = \begin{cases} \hat{M}_k^a + C_k & \text{if } \text{fitness}(\hat{M}_k^a + C_k) > \text{fitness}(\hat{M}_k^a) \\ \hat{M}_k^a & \text{otherwise} \end{cases} \quad (4)$$

$$N_k^{a+1} = \hat{N}_k^a \quad (5)$$

Where, c_k is a random number with uniform distribution on the interval $[m^L - \hat{m}_k^a, m^U - \hat{m}_k^a]$, m^L and m^U are the upper and lower bounds of search space respectively; $\text{fitness}(\cdot)$ is the fitness function. The procedure of the hybrid algorithm is as follows:

① Initialize the particle swarm optimization algorithm;
 ② Update the speed and position of each individual and calculate their fitness;
 ③ If the fitness meets the final requirement, terminate the program and output the results, otherwise continue.

④ Random selection of M (even) individuals according to fitness values, cross-operation of selected individuals, and obtain M new individuals.

⑤ Perform mutation operation on all individuals; select the N with the highest fitness from the M+N population to enter the next generation, and then return step ② to continue.

The procedure of the algorithm is shown in figure 1.

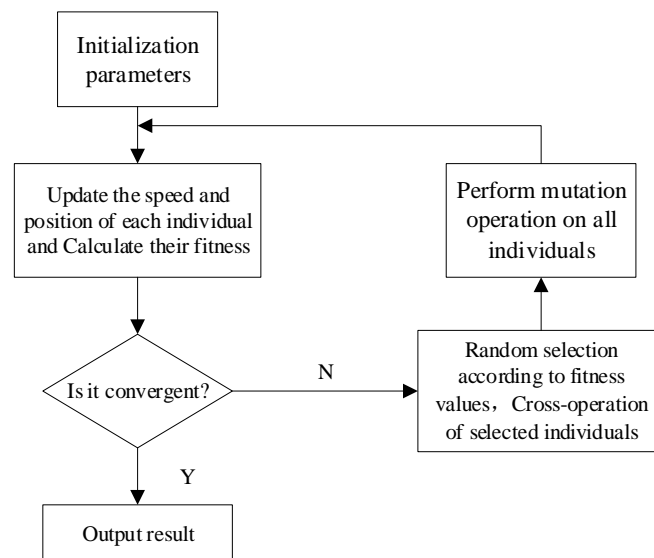


Figure 1. Flow chart of hybrid algorithm.

3. Calculation Process of Pavement thickness Inversion

Established the model of pavement structure to be inverted and carried out the forward calculation by finite difference time domain method. Then established the fitness function to be optimized according to the input and output results of the model. The minimum value of the objective function was optimized by hybrid algorithm, and the parameters of pavement structure to be identified were obtained. The specific steps are as follows:

① Input the actual detection radar waveform, carry out forward calculation by using the finite-difference time-domain method, then the simulated reflection waveform of pavement structure layer can be obtained.

② Establish the fitness function by using the calculated forward analog waveform and the mean square error of the same position amplitude of the actual received signal and the forward signal as the fitness function to be optimized.

③ Solve the minimum value of the fitness function established in step (2) by using hybrid inversion algorithm.

This algorithm sets three termination iteration conditions: (1) the fitness function achieves the preset acceptable level; (2) search results have not been improved after N times of continuous updates; and (3) the total number of iterations has reached the preset upper limit.

④ Output inversion results

The flow chart of the inversion process is shown in figure 2.

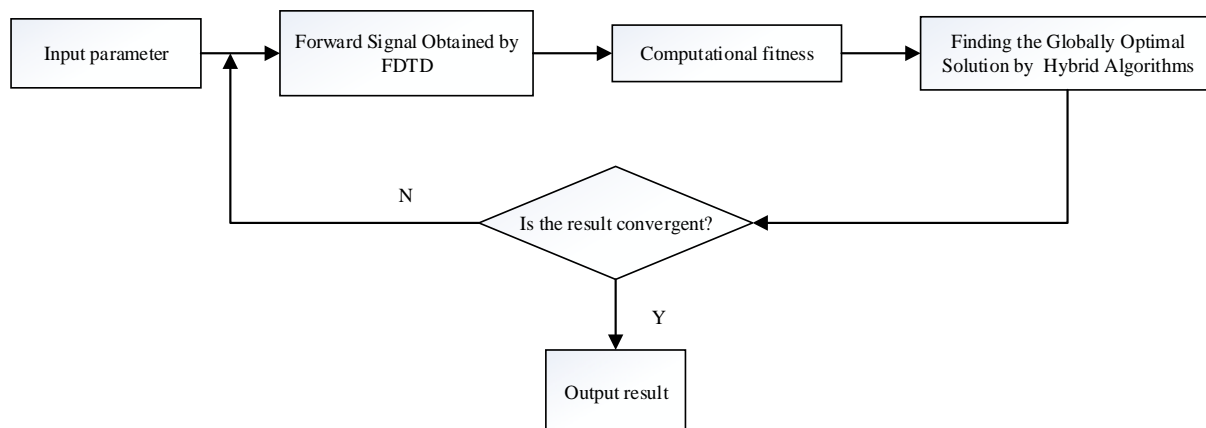


Figure 2. The flow chart of the inversion process.

4. Checking Computations for the Theoretical Model

A checking computations for the theoretical model was carried out to verify the effectiveness and accuracy of particle swarm optimization (PSO) and genetic hybrid inversion (GA) algorithm. By assuming the thickness of the pavement structure layer of the known theoretical model (Table 1), the theoretical waveform was obtained by forward calculation. Then the theoretical waveform was used as the fitting target of the inversion. The dielectric constant of the pavement structure layer of the theoretical model was calculated by using the inversion algorithm to check the convergence of the algorithm itself.

By comparing and calculating the particle swarm optimization and genetic hybrid algorithm, the results are shown in Table 2 below. The results show that both the two algorithms can converge effectively and they all have a high degree of accuracy with a deviation less than 4%. However, the hybrid algorithm has a higher accuracy degree with a deviation less than 3%, and its time consuming is shorter, less than 90s.

Table 1. Theoretical model parameters

Layer number		Thickness/cm		
1		12.0	16.0	18.0
2		20.0	24.0	30.0

Table 2. Calculation results

True value	PSO-GA	Deviation/%	Time/s	PSO	Deviation/%	Time/s	GA	Deviation/%	Time/s
12.0	11.8	1.67	86	11.6	3.33	64	12.1	0.83	132
16.0	15.7	1.88	78	16.5	3.13	72	16.2	1.25	144
18.0	18.2	1.11	93	17.6	2.22	81	17.9	0.56	152

5. Engineering examples

A newly paved test pavement has 12 cm asphalt mixture surface, 40 cm lime-fly ash gravel and 30 cm lime-soil sub base. GeoScope MK IV Ground Penetrating Radar developed by American 3D-radar Company was used for detection. The working parameters are shown in Table 3 below. At the same time, core drilling (Figure 3) was carried out to verify the accuracy of the inversion results. The results showed that the error between the actual core sampling results and the back calculation results was less than 3%, which indicated that the algorithm had high applicability. The calculation results are shown in Table 4.

Before detection, the GPR wave was processed by two-dimensional filtering such as static correction of moving start time, gain adjustment, de-DC drift and Butterworth band-pass, extracting average channel and sliding average, so as to suppress and eliminate interference wave, highlight effective wave, and finally obtained effective data. In order to achieve better detection effect, radar detection profiles were arranged along the driving direction of the test section to satisfy the effective detection of the test area. The field work is shown in Figure 4 below.



Figure 3. Core Drilling and Sampling



Figure 4. GeoScope MK IV

Table 3. Technical Specifications

Index	parameters
<i>Frequency bandwidth</i>	50-3050 MHz
<i>Channel number</i>	20
<i>Resolution ratio (Time)</i>	0.3 ns
<i>Depth of measurement</i>	3-5m

Table 4. Calculation results.

Number	Actual thickness/cm	Calculation results/cm	Deviation/%
1	0.118	0.115	2.54
2	0.122	0.119	2.46
3	0.121	0.124	2.48

6. Conclusion

In this thesis, particle swarm optimization (PSO) and genetic algorithm (GA) were applied to the inverse analysis of pavement structure layer thickness. The mean square error of wave amplitude between the actual GPR reflection signal and the forward calculation signal was taken as the fitness function. A new inverse analysis method of pavement structure layer thickness based on PSO and GA was proposed. By comparing the theoretical results with the calculated results, the inversion error was less than 3%, and the time consumed was less than 90S. By comparing the results of particle swarm optimization and genetic algorithm, the inverse analysis method based on the above two algorithm proposed in this paper has certain advantages in computational efficiency and accuracy. By comparing the inversion results of field measured data with the results of core drilling sampling, the error was less than 3%, and the inversion results had a high accuracy degree. The results indicate that the hybrid algorithm has practical significance for non-destructive detection of pavement structure layer.

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