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Calibration of Pipe Friction Factor Based on Particle Swam Algorithm

Wang Yu-Xue, Zhou Shao-Hua, WEI Shu-Hui and Wang Yin-Feng
School of Mathematical Science and Engineering, Northeast Petroleum University,
Daqing, Heilongjiang, China

Abstract: This study presents a method to calibrate pipe friction factor in oilfield water injection pipeline based on particle swarm algorithm. Particle swarm algorithm is simple and easy to implement without gradient information, especially its natural characteristics of real number encoding is suitable for processing the continuous optimization problem. Particle swarm algorithm possesses good capability to avoid the local extremum and obtain the global extremum. Grouping method is used is to reduce the number of optimization variables. Finally, a practical example verified the feasibility of the presented method.

Key words: Water injection pipeline, friction factor, particle swam algorithm

INTRODUCTION

Oil field water-injection network plays a role of allocating water in water injection stations to different oil wells in accordance with the requirements of production. If pipe friction factors are known in oil field water-injection network, the pressure values of the nodes can be obtained through solving a system of nonlinear equations. We can also achieve the purpose of energy saving through operation optimization studying in oilfield water-injection network. In simulation and operation optimization, raw pipe friction factors are applied in mathematical model now. Oil field water-injection network is the high-pressure system and the pipelines' diameter are relatively small and they have been corroded seriously and they have been built for a long time, so the pipe friction factors have been changed. The practical pressure and calculated pressure would be inconsistent if adopting original friction factors. So we need to correct friction factors. Scholars both at home and abroad have done a lot of research on correction methods of urban water distribution network model (Liggett and Chen, 1994; Shayya and Sablani, 1998; Sablani *et al*., 2003).

MATHEMATICAL MODEL

In correction problem of the pipe friction coefficients, optimization methods are used most and relatively reliable, mainly optimization model of the friction coefficient of correction is established and then to solve the model.

Scholars at home and abroad do a lot of work in this aspect and achieved some results, mainly by increasing number of operating mode, reducing the number of calibration variables, improving the running efficiency of optimization algorithm.

Wang (2010) has theoretically proved that pipe friction factor vector C has infinite solutions for single operating mode which enable nodes computing pressure and the measured pressure equal. So optimization model for single operating mode can not give satisfactory results. It is necessary to establish the optimization model of correcting friction factor with multi-mode data, in which the operating mode number is obtained by the number of pump stations, pressure values as basic data, the range of friction factor value as constraint condition.

For the same oil field water injection pipeline network the pump station need to be examined and repaired, this pump station will be closed in the process it can produce different operating model. In general, if the water injection pipe network has m pumping stations, at least m+1 kinds of operating models can be produced.

There are m pipelines, n nodes, L operating modes. C_j denotes the j-th pipe friction factor, H_i^l denotes the j-th node pressure in the l-th operating mode. $C = (C_1, C_2,...,C_m)^T$ denotes pipe friction factor vector. If the friction factor vector C is known, take any component of H_0^l as a reference point pressure, corresponding node pressure H^l can be obtained by solving the node equations. So pressure vector H^l is the function of friction factor vector. The objective function is:

$$f(C) = \sum_{l=1}^{L} \| H^l(C) - H_0^l \|_2^2 \quad (1)$$

scope of each pipeline friction factor is:

Corresponding Author: Wang Yu-Xue, School of Mathematical Science and Engineering, Northeast Petroleum University, Daqing, Heilongjiang, China

$$C_k^{min} \leq C_k \leq \max C_k^{max} \quad (2)$$

Overall analysis, the optimization model of correcting friction factor with multi-mode datas is:

$$\min_C f(C) = \sum_{l=1}^{L} \| H^l(C) - H_0^l \|_2^2$$
$$\text{s.t. } C_k^{min} \leq C_k \leq \max C_k^{max}, \ k = 1, 2, \cdots, m \quad (3)$$

SOLVING METHOD OF MATHEMATICAL MODEL

Dimension reduction of optimization model: For mathematical model (3), Friction factors of all pipes are regarded as decision variables if network scale is smaller; if the network size is larger, when each pipe friction coefficient is regarded as the optimized variable it will form large-scale optimization problem. It is difficult to obtain satisfactory solution in speed and precision by using the optimization algorithm. So it is necessary to reduce dimension of the optimization model (3) for the large scale network which reduced the number of optimization variables.

One way is by using the method of sensitivity analysis to determine the pipe whose pipeline friction coefficient did not change or changes very small, these pipe friction coefficient values are the experience values, so it reduces the number of optimization variables.

Another method which is commonly used is to adopt grouping method to reduce the number of optimization variables. All the pipes are divided into several groups according to certain rules, each pipe friction coefficient value is the same in the same group. If network is divided into n groups, the number of decision variables in optimization model is n, thus the number of optimization variables is greatly reduced. Grouping way are "American" way of grouping and "British" way of grouping (Kapelan, 2002; Schaetzen, 2000). "American" grouping principle is to take pipes which have the same basic characteristics (pipeline diameter, pipeline material and embedding ages) into a group. “British” grouping principle is to take pipes which can effectively form a single hydraulic pipeline into a group, these pipes have the same basic characteristics. "British" grouping method is more careful than "American" grouping method and its grouping number is many more. In this paper "American" way of grouping is adopting.

Solving mathematical model by using particle swarm algorithm: The mathematical model (3) is be solved by using the particle swarm algorithm. Particle swarm algorithm (PSO) is proposed and developed by Kennedy (1997) and Eberhart and Kennedy (1995) it is a kind of intelligent optimization algorithm from swarm intelligence and learning process of human cognition.

Particle Swarm Optimization (PSO) algorithm can be expressed as follows:

- The searching space is D-dimension, the number of all particles is n. The I-th particle position is $X_i = (x_{i1}, x_{i2},..., x_{iD})$ historical optimal position of the i-th particle is $p_i = (p_{i1}, p_{i2},..., p_{iD})$, p_g is the best position in all p_i (i = 1,..., n). The velocity of the i-th particle is $V_i = (v_{i1}, v_{i2},..., v_{iD})$. Position of each particle change according to the following equation:

$$v_{id}(t+1) = \omega v_{id}(t) + c_1\xi[p_{id}(t) - x_{id}(t)] + c_2\eta[p_{gd}(t) - x_{id}(t)] \quad (4)$$

$$x_{id}(t+1) = x_{id}(t) + v_{id}(t+1), 1 \leq i \leq n, 1 \leq d \quad (5)$$

c_1 and c_2 are both positive constants, called learning factors, ξ and η are both random numbers in interval [0, 1]; $\omega$is called as inertial factor, when ω is larger it is suitable for a wide range detection; when ω is smaller it is suitable for small area search.

Particle swarm method can randomly generates initial position and speed and iterate by equation 4 and 5 until finding a satisfactory solution.

The standard particle swarm algorithm process is as follows:

- **Step 1:** Initializing all particles. The initial position and velocity of the particles random are set within the allowed scope
- **Step 2:** Computing function value of each particle
- **Step 3:** For each particle its function value compares to the function value of historical best particle, if better it is as a particle of individual historical optimal value and the current position updates individual historical best position
- **Step 4:** For each particle its historical optimal function value compares to the optimal function value in group, if better it is the current global best position
- **Step 5:** According to the particle swarm velocity and position, the equation is changed to adjust the particle velocity and particle position
- **Step 6:** If satisfying the maximum iteration times number or accuracy, the iteration will be terminated, otherwise return to step 2

EXAMPLE

Example 1: There are 2 water injection stations, 16 nodes, 24 pipes, 9 rings in an ideal pipe network. The pipe

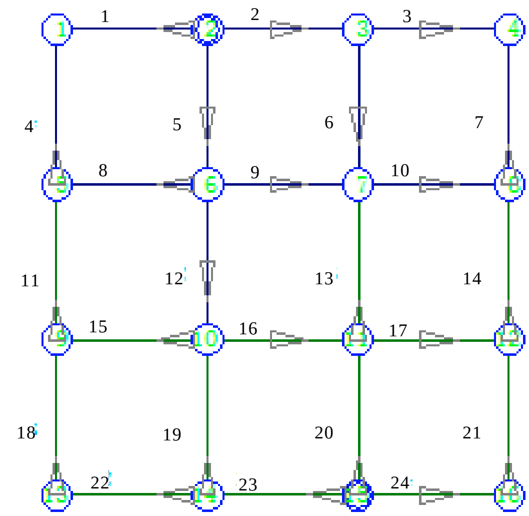

Fig. 1: Simple graph of ideal pipe network

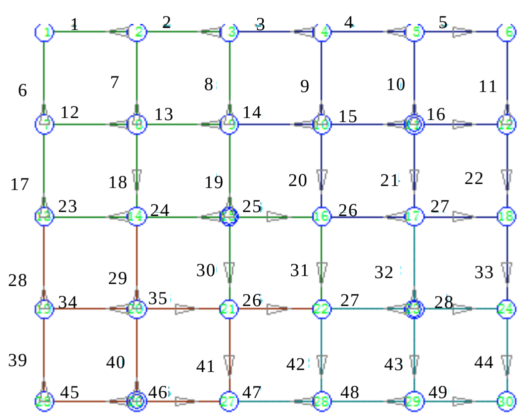
Fig. 2: Simple graph of ideal pipe network

network is simulated for 3 operating modes: Pumping station fully open, turn off a pump station in order. The simple graph of ideal pipe network is shown in Fig. 1.

The mathematical model is solved by the particle swarm algorithm and the calibration results are shown in Table 1.

According to these dates in Table 1, the result was satisfied, the average value of errors between the real friction factor and calculating friction factor is 1.08.

Example 2: There are 5 water injection stations, 30 nodes, 49 pipes, 20 rings in an ideal pipe network. The nodes whose number is 8, 11, 15, 23 and 26 is pumping stations location. The pipe network is simulated for 6 operating modes: pumping station fully open, turn off a pump station in order. The simple graph of ideal pipe network is shown in Fig. 2.

Table 1: Correction results of friction factors

Pipe ID	The real friction factor	The calculating friction factor	Error
1	85	85.3	0.3
2	85	83.4	1.6
3	95	94.5	0.5
4	85	83.2	1.8
5	85	84.2	0.8
6	95	93.5	1.5
7	95	96.5	1.5
8	85	83.2	1.8
9	85	85.0	0.0
10	95	96.5	1.5
11	85	84.4	0.6
12	105	105.0	0.0
13	115	113.8	1.2
14	95	95.3	0.3
15	105	103.7	1.3
16	105	107.0	2.0
17	115	113.0	2.0
18	105	106.0	1.0
19	105	104.3	0.7
20	115	113.2	1.8
21	115	114.2	0.8
22	105	105.0	0.0
23	115	113.3	1.7
24	115	113.0	2.0

Table 2: Groups of pipe network

Grouping No.	Containing pipeline No.
1	1, 2, 6, 7, 8
2	3, 4, 5, 9, 10, 11
3	23, 24, 25, 26, 27
4	34, 35, 36, 39, 40, 41, 45, 46
5	33, 37, 38, 42, 43, 44, 47, 48, 49
6	12, 13, 17, 18, 19, 20
7	14, 15, 16, 21, 22
8	28, 29, 30, 31, 32

Considering the pipeline number of pipe network has reached 49 and it is difficult to get satisfactory results in precision and speed for optimization problem with 49 variables. So it is necessary to group at first, then solve the model. The pipelines of pipe network are divided into 8 groups, pipe friction factors of each group are regarded to be same, the explicit group is seen in Table 2.

After pipe network is grouped, assuming pipe friction coefficients in each group are same, there is only 8 variables in the optimization model. The model is solved by particle swam algorithm with 30 particles, the maximum number of iterations is 1000 times. The calibration results are shown in Table 3.

According to these dates in Table 3, the result was satisfied. The friction factors which are solved are almost consistent with the real ones. The average value of errors between the real friction factor and calculating friction factor is 0.3125.

The variables number of this optimization problem is 8 and the optimal objective function value which is solved by particle swam algorithm is 10^{-16}. Due to the grouping

Table 3: Correction results of friction factors

Grouping No.	Real friction factor	Calculating friction factor	Grouping No.	Real friction factor	Calculating friction factor
1	85	85.4	5	115	114.7
2	95	95.2	6	85	85.0
3	105	104.9	7	95	94.9
4	110	110.0	8	105	106.2

of solving reduces multiplicity of solution in the optimization problem, so it is reasonable that calculating friction factors are almost consistent with real ones.

CONCLUSION

Node pressure is assumed known to the premise, the number of operating mode is determined based on the number of pumping stations in the actual oil field water injection system. The optimization model of correcting friction factor with multi-mode data is established. The mathematical model is solved by particle swam algorithm, the calculating results show the effectiveness of the method.

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