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PMA Partition Method of Water Distribution Network Combined with Gragh Theory

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Abstract

A method are proposed combining PMA partition and graph theory with four parts. Using adaptive Affinity Propagation (AP) clustering algorithm with consideration of economic benefit to preliminarily partition water distribution network(WDN) and reasonably determine the partition number. Calculate the shortest path between the clustering centre and water source by Dijkstra algorithm and determine water supply inlet of each region. Establish topology discrete optimization model to determine partition boundary, then applying simulated annealing algorithm to solve the model. Vertically and horizontally combining the partitioned areas to ensure the safety of water supply. This method has been applied to the WDN of Y city to control the pressure for the areas with a certain results.

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Keywords: *Water distribution network, leakage control, PMA partition; graph theory, AP clustering algorithm, Dijkstra algorithm, simulated annealing algorithm.*

Recently, the thought of water supply network partition has become a hotspot in the field of leakage and been recognised internationally for "divide and conquer". Transforming passive controlling leakage into active, main reasons of leakage can be found effectively after partitioning, which can strengthen the management of water quality

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monitoring and pressure[1-4]. Relevant scholars and researchers from domestic and foreign have actively explored the methods of partitioning control leakage, mainly including regional partition, pressure partition, and management partition, among which pressure partition is considered the most economic.

In general, pressure network has positive correlation with tube-burst ratio, leakage and the failure rate of pipe fittings and other equipment. It has great significance to real-time commend pressure distribution in water supply network for controlling leakage, reducing tube-burst accident and water consumption, in which PMA partition is the basic[5]. PMA partition is a parallel partition way and has never relay pumping with next area in this case every partition can be controlled alone by pressure. In addition, compared with traditional manual partition of trial-and-error, PMA partition has larger search space and better applicability. In this paper, combining with project practice, graph theory was applied to PMA partition through transforming water supply network into graph structure.

1. PMA partition

Partition number of water supply network directly affects the merits of partitioning scheme. With few partitions, pressure management can not thoroughly that lead to many nodes with high pressure and reduce leakage effects. With excess partitions, water supply network will not be stable for destabilized topology and investment cost will increase. Considering economic benefits, adaptive AP clustering algorithm is applied in preliminary partition to determine partition number. In the process of partitioning, the investment cost mainly refers to decompression station installation cost. As shown in figure 1, investment cost has a linear relation with partition number, economic benefit increases faster with partition number in the beginning, and slow down gradually. Thus, the relationship between investment return and partition number is a downward parabola. Adaptive AP clustering algorithm is put forward for the fist time by Fery B J and Dueck D in 2007. In this algorithm, cluster number need not be specified and objective function is the sum of distance between all points in the graph and their class-center. The position and number of clustering center are constantly searched and commuted with iteration to make the objective function minimum. Reasonably determining partition number to maximize investment returns according to characteristics of adaptive AP clustering algorithm in this paper.

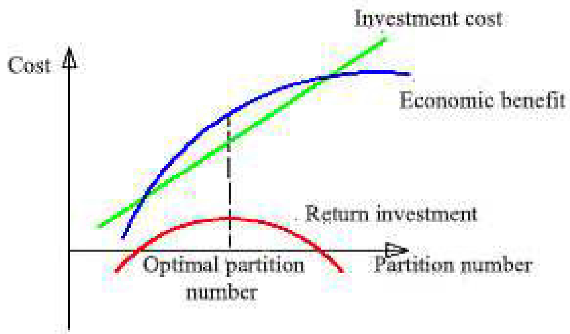

Fig.1 the relationship of partition number and investment returns

Three parameters including X coordinates, Y coordinates and free head of water nodes, are used to define three-dimensional position of nodes after being normalized calculation to determine partitions. At the beginning of algorithm, P_i value should be set which has a positive correlation with clustering number.and is usually the average of all other nodes similarity or be set by its own. Starting with equal P_i values is necessary because each node is possible to be clustering center before clustering. In the process of clustering, input these parameters for the first clustering algorithm, class attribution and cluster number of all points can be obtained; calculate leakage reduction potential of nodes in each class, economic benefit in clustering scheme can be gained; combine with the investment payback period to adjust P_i values for the next AP clustering until preliminary clustering is calculated with the shortest payback period.

2. Determine the entrance of PMA partition

PMA partition is a incompletion partition pattern. Network topology is considered as adjacency matrix in this paper. Dijkstra algorithm is applied to calculate the shortest paths between clustering centers and water source which will be defined as water entrance for each area. All nodes are involved in clustering in the preliminary partition. Finally, nodes in main pipes which are not involved in partitioning must be eliminated. The steps are shown as follows:

(1) Initialize *S* set with a single water source v_0 and all other vertices in the topology are contained in *T* set. Dijkstra algorithm is calculated m times for m water source in model.

(2) Calculate distance between the each vertex and water source point v_0, and vertex *u* with the smallest distance is joined in *S* set.

(3) Calculate distance between vertex *u* and each vertex *t* in *T* set, if that is smaller than the distance between vertex *t* and water source when it does not go through vertex *u*, the distance of *t* will be modified.

(4) Repeat step(2) and (3) until all vertices in network topology are transferred from *T* set to *S* set, and finish the algorithm.

3. Establish and solve the regional boundaries optimization model

After determining regional entrance, closing valves of clustering boundary leads to much disturbance and lots of nodes can not be normally supplied water. Thus, it is necessary to optimize partition boundaries to reduce the disturbance and realize partitioning.

3.1. regional boundaries optimization model

The basic requirement for partitioning is to guarantee the safety of water supply, that is to say that, the connectivity between all nodes and water source should be true. So nodes connectivity in each partition should be judged and meet through changing class attribution of isolated nodes after initial clustering. The disturbance from partitioning is minimized as possible by optimizing boundaries under meeting all nodes connectivity. In this paper, a discrete topology optimization model is established to determine the partition boundaries.

- Optimization variables

Partition boundary points are not fixed in model. During optimizing, changing class attribution of a certain node can lead to other non-partition boundary points nearby it change. Thus, class attributions of all nodes in network topology are seen as optimization variables with a fixed number obtained by AP clustering algorithm. Class attribution matrix of all nodes is shown as formula (1).

$$idx=[a_1,a_2,\cdots,a_{n-1},a_n] \tag{1}$$

Where, $a_1,a_2,\cdots,a_{n-1},a_n \in \{C_1,C_2,\cdots,C_{n-1},C_n\}$;

a_i——class attribution number of i node;C_j ——number of j class.

- Objective function

It is necessary to find out pipes with smaller flow in partition boundaries and close them to drop disturbance and make partition feasible. Therefore pipes flow are defined as weights of adjacency matrix in whole network, and objective function is to make the wights of all boundary pipes minimize, in which fitness function is given as formula (2). However, the basic topology pattern of water supply network has been finished by built the shortest paths of all nodes. Shortest paths often become connected pipes among areas. So pipes flow of shortest path are denoted as 0 to not interfere optimization results during optimizing partition boundaries.

$$f\,(idx\,) = \min\,\{sum\;(\,fedge\;\,)\} \tag{2}$$

Where, f_{edge}——flow of boundary pipes, in which the flow of shortest path pipes is not involved in objective function calculation.

- Constraints

In the optimizing process, security of water supply network can be ensured through pledging connectivity of nodes in each class. That means the constraints is to make cluster center and its internal nodes connected for every generation under optimization iteration.

3.2. solution of regional boundary optimization model

Regional boundary optimization model belongs to topological optimization of discrete variable model. Property of topological nodes should be constantly changed and randomly disturbed in every optimizing iteration process to pick out the best population for next iteration, which can be effectively achieved by Simulated Annealing algorithm that is put forward by Kirkpatrick for NP-complete problem in 1982. AP clustering results as its initial solution. The related parameters of algorithm is set in project, then standard simulated Annealing algorithm is applied to optimize local regions (partition boundary) with the initial solution is obtained by iteration.

4. Merge Partitions

After finishing partition boundary optimization, closing all boundaries pipes to hydraulic calculation can lead to the hydraulic conditions unable to meet user requirement for excessive closure pipes. So, partial regions should be merged based on artificial experience to ensure water supply requirements. Partition merger mainly contains vertical and horizontal merger. After initial partitioning and calculating the shortest path, if a water path is shared with two clustering center, vertical merger should be carried out as figure 2 to ensure the capacity of main pipes to supply water to all regions directly; if completely closing numerous connection pipes between two partitions can lead to insufficient partial pressure of water supply network, horizontal merger is necessary to comprehensive control pressure in two entrances or calculate anther water supply pipeline through shortest path like figure 3.

5. Case study

The basic operating information of water supply network in Y city is collected, and free head of the highest and lowest time are shown as figure 4 and 5. It indicates that in order to meet pressure at the end of water supply network, the entire network is in a high pressure condition which is the main reason for serious leakage. Therefore, the method of PMA partition is applied in water supply network of Y city based on graph theory to mark out depressurized potential regions for controlling pressure and explore its feasibility and applicability.

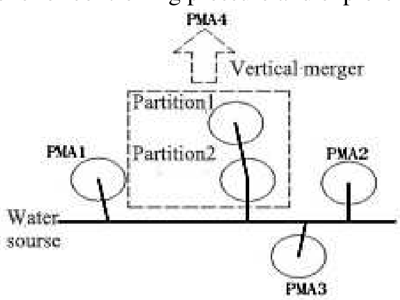

Fig.2 schematic diagram of vertical merger

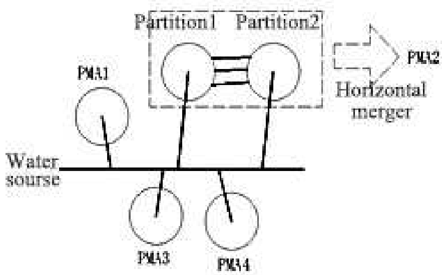

Fig.3 schematic diagram of horizontal merger

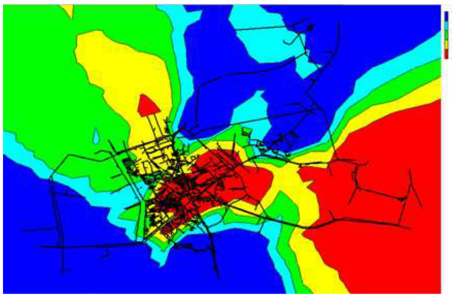

Fig. 4 free heak of the highest time

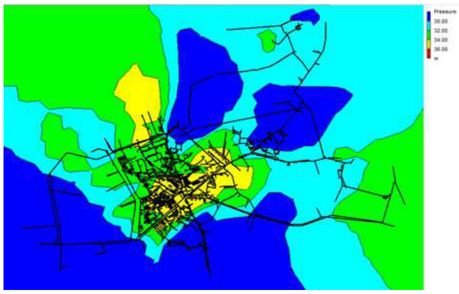

Fig. 5 free heak of the lowest time

5.1. AP clustering for preliminary partition to determine the number

According to practical research in Y city, water cost is 0.65 yuan/t, the purchase and installation of decompression station costs total 200 million yuan, operating cost of pressure control equipment is 10 million yuan/y. In addition, 20m free head is the minimum pressure in local. In optimizing process, if the number of partition is over 20, pipeline renovation cost increases exponentially with partition number, or else, the cost is 0.

In the optimization model, variable is *P* value in adaptive AP clustering algorithm and optimization objective is making economic benefits maximize. Advance-retreat method is applied to successively calculate the single variable *P* value whose initial value is the default value -0.0634 of AP clustering algorithm and initial step length is 0.1. Step length is halved iteration gradually in the break points of economic function. Result has been shown as figure 6 in which *P* value is -2.2928, payback period is 1.8 years and partition number is 17.

AP clustering algorithm is executed according to the attributes of X, Y coordinates and free head until *P* value is -2.2928. The preliminary partitioning result is shown as figure 7 with different colors for 17 regions.

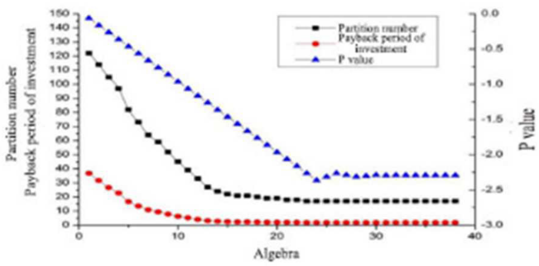

Fig. 6 Result of economics combined with AP clustering algorithm

Fig. 7 result of preliminary partition

5.2. the shortest path from clustering center to water source

The shortest paths from water sources to 17 clustering centers obtained from initial clustering are calculated respectively by Dijkstra algorithm. Head loss of pipes is acted as the weights between calculating midpoint of shortest paths and other points. That means the length of shortest path is the sum of head loss and shown in table 1.It indicates that mostly shortest paths from clustering center to two water plants are the same. So, no matter which water plant is considered, the entrance of partitions are not affected.

Table 1 shortest path from clustering center to the two water source

Class number	Node number	Length of shortest path to the first water plant (m)	Length of shortest path to the second water plant (m)
1	2571	4.299 654	7.738 481
2	7591	4.392 645	7.831 472
3	8603	9.229 041	10.97 399
4	8777	5.570 809	9.009 635
5	12491	2.483 682	5.922 509
6	20355	4.920 983	8.359 809
7	21462	2.203 216	5.657 158
8	25889	1.458 040	4.887 281
9	26258	2.011 419	3.670 348
10	26366	3.083 273	4.828 222
11	31898	5.205 412	8.644 238
12	32102	7.927 301	11.36 613
13	41126	5.415 440	8.856 311
14	41286	3.085 164	6.523 990
15	41360	0.926 913	2.978 746
16	41699	7.010 608	10.44 943
17	41773	12.434 510	15.873 340

5.3. partition boundary optimization model

Simulated annealing algorithm is used to optimize partition boundary, in which variables is the class attribution of all nodes; fitness function is the sum of all boundary pipes flow among divided 17 regions; keeping all nodes connected of each area in the process of optimizing is the constrains. In addition, 300 is the maximum iterative algebra and 20 consecutive generations not accepting the new is set for termination condition. The final flow of fitness function is 42.94 L/s and the connected pipes among regions in optimal solution are shown in table 2.

Table 2 the number of connected pipes in regions

number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0	0	0	4	2	2	9	0	0	0	0	0	13	13	0	1	0
2	0	0	0	0	5	2	0	4	0	0	9	7	0	0	0	1	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
4	4	0	0	0	0	5	0	0	0	0	0	0	0	0	0	4	0
5	2	5	0	0	0	4	2	7	0	0	0	2	0	23	0	0	0
6	2	2	0	5	4	0	0	0	0	0	1	0	0	0	0	23	5
7	9	0	0	0	2	0	0	7	2	0	0	0	17	9	0	0	0
8	0	4	0	0	7	0	7	0	0	4	0	6	0	2	1	0	0
9	0	0	0	0	0	0	2	0	0	0	0	0	2	0	1	0	0
10	0	0	0	0	0	0	0	4	0	0	0	0	0	0	9	0	3
11	0	9	0	0	0	1	0	0	0	0	0	9	0	0	1	2	2

12	0	7	0	0	2	0	0	6	0	0	9	0	0	0	0	0	8
13	13	0	0	0	0	0	17	0	2	0	0	0	0	2	0	0	0
14	13	0	0	0	23	0	9	2	0	0	0	0	2	0	0	0	0
15	0	0	1	0	0	0	0	1	1	9	1	0	0	0	0	0	0
16	1	1	0	4	0	23	0	0	0	0	2	0	0	0	0	0	4
17	0	0	0	0	0	5	0	0	0	3	2	8	0	0	0	4	0

5.4. Merge Partitions

There are several nodes completely distributed in main pips can not be pressure controlled that do not join in merger. The connected pipes number of partitions between 6 and 16, 5and14, 1 and 13, 1 and 14, 7 and 13 is more enough according to table 2. Shortest path structure and clustering center number are shown as figure 8. The areas with plentiful connected pipes are usually adjacent in topology space from figure 8, so merger is feasible. In figure 8, 2, 12 and17 can be merged because 2 and 12 partition are distributed in the same main pipe with 8 connected pipes and 17 partition is not suitable to be separated with less nodes; 1,5,7,13,14 partition are merged with much more connected pipes, and 4 partition can join in this merger closing to 5 partition; 6 and 16 partition are merged because so many connected pipes can not completely be closed to ensure sufficient pressure. The merged partition of 6 and 16 partition will be supplied water through two main pipes on which pressure control equipment should be installed to prevent rich pressure; Most nodes of 9 and 15 partition are distributed in main pipes and close water source, so the two partitions are not merged. Thus, 7 PMA partitions are obtained after merging and shown as figure 9.

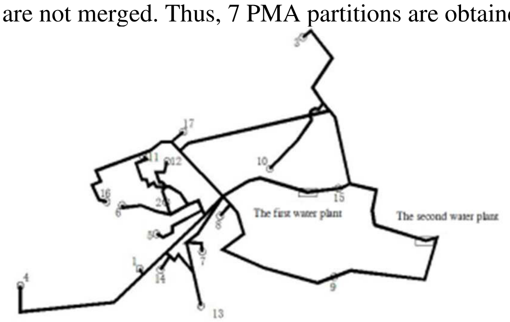

Fig. 8 topology structure of shortest paths

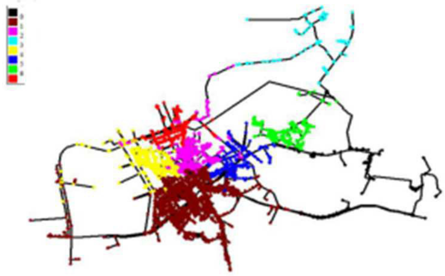

Fig.9 the result of final partitions

5.5. Analysis of partition results

The free head of highest and lowest in water supply network is obtained as figure 10 and11 through closing connect pipes after partitioning. Compared figure 10, 11 with figure 4, 5, the free head of highest and lowest in network are declined for PMA partition, and pressure of each partition meets the requirement shown as table 3, whose normalized variances are smaller than 0.4. In addition, the required free head of larger than 20m has been achieved from table 3. Thus, this partition strategy can be used to guide PMA partition for actual water supply network and control leakage effectively.

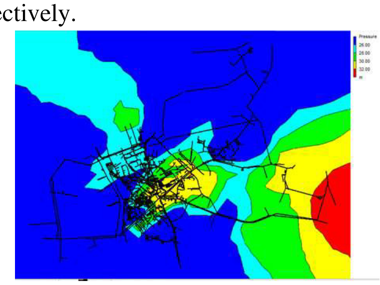

Fig. 10 the highest free head distribution after partitioning

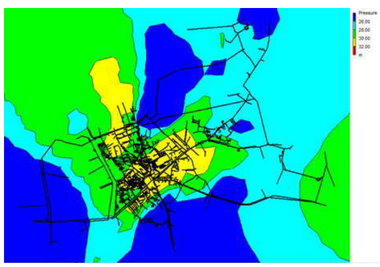

Fig. 11the lowest free head distribution after partitioning

Table 3 Statistical average pressure of each partition

Partition number	Average pressure	Pressure normalized variance	Lowest free head
1	25.82	0.26	22.90
2	27.90	0.38	23.55
3	25.12	0.35	21.96
4	26.91	0.17	23.16
5	26.63	0.21	22.97
6	26.09	0.33	22.49
7	26.27	0.29	22.80

6. Conclusion

A automatic PMA partition method is presented based on graph theory and firstly summarized as three aspects, including partition number, partition entrance and partition boundary which are calculated by corresponding algorithm. Economic calculation is initially introduced to ensure partition number which can avoid existing partition method with unreasonable specified partition number. It is valuable for engineering. Merger partition is conducted with artificial experience to guarantee the safety of water supply, whose principle is merging partitions with unsatisfied hydraulic conditions or water path conflicting.

Acknowledgements

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References

[1] Di Nardo A, Di Natale M, Musmarra D, et al. “A District Sectorization for Water Network Protection from Intentional Contamination,” in Proc. Water Distribution System Analysis 2014, Bari, Italy: Elsevier Ltd., 2014, pp. 515-524.

[2] Di Nardo A, Di Natale M, Santonastaso G F, et al. “Divide and Conquer Partitioning Techniques for Smart Water Networks,” in Proc. Water Distribution System Analysis 2014, Bari, Italy: Elsevier Ltd., 2014, pp. 1176-1183.

[3] De Paola F, Fontana N, Galdiero E, et al. “Optimal Design of District Metered Areas in Water Distribution Networks,” in Proc. Water Distribution System Analysis 2014, Bari, Italy: Elsevier Ltd., 2014, pp. 449-457.

[4] Mamade A, Loureiro D, Covas D, et al. “Spatial and Temporal Forecasting of Water Consumption at the DMA Level Using Extensive Measurements,” in Proc. Water Distribution System Analysis 2014, Bari, Italy: Elsevier Ltd., 2014, pp. 1063-1073.

[5] Mounce S R, Boxall J B, Machell J. “Development and verification of an online artificial intelligence system for detection of bursts and other abnormal flows,” Journal of Water Resources Planning and Management, vol. 136, no. 3, 2010, pp. 309-318.