OPTIMIZATION TECHNIQUES FOR WATER SUPPLY NETWORK: A CRITICAL REVIEW

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ABSTRACT

The supply of clean and safe water in adequate quantity at desired end pressure is the prime concern of all municipal bodies. The large amount of money is involved in laying of pipe network and its maintenance. Nearly 80-85% of the cost of total water supply system is invested in water transmission and distribution network. Hence efficient and cost effective design of pipe network is of utmost importance and challenging task for engineers. Various optimization techniques have been used in last three decades by different investigators to analyze and optimize pipe network problem. The thorough review of the research work related to pipe network analysis and optimization techniques is presented in the present paper.

Keywords: Newton Raphson Method, Linear Theory Method, Optimization, Genetic Algorithm, Particle Swarm Optimization, Hybrid Method.

INTRODUCTION

Water is an essential commodity for all living beings on earth surface and therefore water supply systems are the most important public utility for safe supply of potable water. As major part of total cost of water supply is spent on distribution network, there is need to use rational methods for designing the water distribution network which will result in considerable saving.

The history of transporting water for human civilization is as old as the civilization itself. It begins around 3500 years ago when for the first time the pipes were used in island of Crete [5]. Its existence also presumed when the bathrooms, bathtubs and drains were made in the Indus Valley. Water distribution network analysis provides basis for the design of new systems and the extension of existing ones. The design process of the network is not an explicit method, as the design criteria’s such as minimum flow rates and pressure distribution across the network are
affected by the layout, length and size of pipe. That's why many scientist and researchers are working on pipe network analysis and optimization. The researchers not only developed the methods for solving and analyzing the complex water supply network problems but also tried to develop different optimization techniques to design a network which can fulfill the head and discharge requirements at optimum cost and resilience.

According to literature, the problem of water supply network is split in two parts. One part deals the research and development work on pipe network analysis and in other part, optimization techniques are adopted to optimize the network meeting various constraints and bounds.

**REVIEW ON WATER SUPPLY NETWORK ANALYSIS**

The oldest method for solving pipe network is Hardy cross method [7], which has been used since 1936. In this method, continuity of flow i.e. at any pipe junction the algebraic sum of flow must be zero and the algebraic sum of pressure at any loop must be zero. The major drawback with this method is its linear and slow convergence. Later, Newton Raphson has developed method for pipe networks [1] which overcomes some of the drawback of Hardy Cross Method. In this method, flow and head values are to be determined using Jacobean matrix. It has quadratic convergence behavior. i.e. each reduced error is proportional to the square of the previous one and results are very much dependent on the initial approximation. The drawback of this method is that it requires the evaluation of first derivative of each unknown flow parameter, which sometimes becomes more tedious even with the help of computerized techniques.

Linear theory method (1972) is modified version of earlier two methods, it has rapid convergence rate without having any dependency on initial flow estimation and complex differential equation. It transforms non linear equations into linear, and give more accurate results within few iteration. In linear theory method flow is dependent variable of pressure at the nodal points which is the major limitation of this method.

Bralts (1983) and Bralts and Segerlind (1985), first introduced finite element method in irrigation pipe network. In 1991, Paul Boulos and Tom Altman [2] developed an explicit algorithm to optimize the non linear pipe network. In This work incremental Newton Raphson method was used as the basic solution procedure due to presence of non linearity in the equation. Using an example they showed that the solution is optimal since the decision parameters have been calculated to meet the specified pressure and flow constraints. This approach is well suited for every type of distribution system for a defined value of boundary nodes and pipe sections within certain range of operating conditions. Later different commercial and non commercial software were also developed based on different pipe network analysis methods. Development, utilization and statistical evaluation of Hardy Cross pipe network analysis software was done by Lukman Salihu in 2012 [43] and concluded that, the HARDY CROSS1 is the best option, because it gave the highest coefficient of determination, lowest total errors, and lowest reliability value. Its better performance is related to the algorithm utilized for head loss computation.

The present infrastructure development is based on sustainable, energy efficient and cost effective methods. As pipe network is also the part of civil engineering works, reducing the total energy cost and improving the efficiency by optimization of pipe network is a major objective now a days. Various optimization techniques are used for optimizing the pipe network such as genetic algorithm technique, ant colony optimization, particle swarm optimization etc. The literature available on pipe network analysis can be discussed according to the various techniques available for pipe network optimization:
Genetic algorithm (G.A.) was invented by John Holland in 1975. It is a population based heuristic method based on “Survival of the Fittest”. Genetic algorithm is very useful tool for search and optimization problem.[5,51]. In genetic algorithm, a set of population is generated randomly, then fittest population is selected for reproduction, using cross over and mutation operator. New chromosome is again evaluated for the fitness generation, this process is repeated until the termination condition is reached. [9,51]. In 1994, L. J. Murphy and A.R. Sympon [4], have applied this approach on pipe network optimization of a given flow requirement at nodal points by satisfying the maximum and minimum pressure constraints. The various options such as cleaning, lining, duplication or deleting the existing pipe are proposed to get the best optimized solution. Some of the researchers who worked on the optimization of New York City Pipe network distribution since 1969 are:

- Lai and Schaake (1969), have used linear Programming and found the least cost of the network as $ 73.3 million.
- Quindry et al (1981), have used linear Programming and found the most optimized cost as $63.6 million.
- Gessler (1982), have used an enumeration algorithm for discrete as well as for continuous diameter pipe network and got the optimized cost as $41.8 million and $41.2 million respectively.
- Morgan and Goulter (1985) found the optimal cost of $39.2 and $38.9 million respectively using Heuristic linear Programming based procedure.
- In 1990, Fujiwara and Khang have determined the least cost of $36.6 million by generating a series of local optimal solution using linear programming gradient method embedded in two phase decomposition method. But this was failed in verification as it could not satisfy the pressure constraint.
- In 1989, Goldberg worked on the pipe network optimization using a mechanism based on natural genetics and found much better than the previous traditional optimization techniques. Genetic Algorithm uses the objective function value of the proposed network. It selects, combines and manipulates the possible solutions to the pipe network to get the minimum cost of network. It is a robust search method and very useful particularly for pipe network optimization. In 1996, Graeme C. Dandy et al [8] introduced the power gradient and fitness function, creeping mutation operator and grey codes in place of bringing code in simple G.A. This improved G.A. was used for optimization of pipe network and results obtained were found to be significantly improved.

In 1998 Indrani Gupta et al [9] suggested a methodology based on genetic algorithm for low cost design of new and existing water distribution network. The results obtained from the new method were compared with non linear programming method (NLP). The cost obtained by the method based on GA was lower than NLP method.

In 1998, Abebe et al [10] optimized a network using global optimization tool with various random search algorithm, this model can handle both static and dynamic loading condition. They found two algorithms for giving promising solution which are adaptive cluster covering and genetic algorithm.
In 1999, Guoling Xue et al [11] had worked on the problem for computing the minimum cost of the pipe network, in which wells and treatment sites of given capacity were interconnected with powerful interior point algorithm to find the minimum cost.

In 2001, Z.Y. Wu et al [15] used genetic algorithm for optimization of the large water distribution system using messy genetic algorithm to enhance the efficiency of optimization procedure. They concluded from results that convergence in messy genetic algorithm is faster than genetic algorithm.

In 2004, Keedwell et al [18] worked on CANDA-GA (Cellular Automata for Network Design Algorithm Combined with genetic algorithm). In this approach the initial best solution was found by CANDA and then GA is applied to refine the solution. It is found from 3 different case studies that better optimized solution is obtained in less time.

In July 2007, Apple L.S. Chan et al [21] optimized the pipe network for district cooling system with the use of genetic algorithm combined with the local search technique. They worked to get the optimum configuration of District cooling system with minimum pipe work and pumping cost. The results obtained from genetic algorithm are a global solution. It does not refine the solution efficiently. That's why a local search technique is associated with the G.A., so that best results can be obtained.

In 2011, S. Chandramouli and P. Malleswararao [40] worked on the optimization of pipe network based on the reliability. Their focus was to improve the reliability based on the excess pressure available at demand nodes, using fuzzy logic concept and to incorporate it in the optimal design. For this two objective optimization, they used Genetic algorithm and EPANET tool kit in the Mat lab.

Optimization of pipe network by using GA has some limitations like giving global solution and poor convergence. James Kennedy and Russell Eberhart developed the concept of Particle Swarm Optimization (PSO) in 1995 [7] which has overcome the limitations of GA. Particle swarm optimization is a robust stochastic technique for optimization [16]. In this method, the co-ordinates of each particle represent the possible solution and after each iteration, the particle moves towards optimal solution [33].

PARTICLES SWARM OPTIMIZATION [PSO]

The method of PSO with weighted parameters was first used by Yuhui Shi et al [11] in 1998 and found, this modified PSO gives better solution for weighted parameter ranges from 0.9 to 1.2. In 2008, Joaquin Izquierdo et al [29] have applied PSO in existing problems and concluded that PSO gives better results as compared to other classical methods like dynamic programming.

In 2009, Bansal Jagdish Chand et al [32] have optimized both serial and branched networks using particle swarm optimization. They considered the cost per meter length of pipe as continuous function of pipe diameter. They have demonstrated their work with two different networks [series and branched network] and compared the results obtained with conventional methods i.e, Lagrange’s Approach and Random Search Technique (RST). It was found that PSO either comparable or better than the conventional method.

In 2010, Yousong et al [52] developed hybrid PSO by combining space transformation search with modified velocity model to overcome the drawback of simple PSO and also to get global optimal results. They applied this model in 8 benchmark problem and shown that this method has good performance for solving both unmade and multimodal optimization problem.

Babu Jinesh et al [44] proposed a hybrid PSO model for water distribution network in 2013. They have validated the performance of this model with two benchmark problems and found this model to be very efficient for exploring global optimal results with less computational effort. The
use of other optimization techniques such as Ant Colony Optimization was also used in 21st century for optimizing water supply networks.

ANT COLONY OPTIMIZATION

The optimization of water distribution network by ant colony optimization technique was carried out in 2003 by Holger R. Maier et al [17] and the results were compared with genetic algorithm from two case studies. In one problem, it was found that results from both approaches were closely matching. But in second case study they found ant colony optimization to be more effective than genetic algorithm.

M.H. Afshar [23] used a different approach for pipe network optimization by using ant colony optimization with pheromone trail. An ant algorithm with a minimum number of controlling parameters is introduced for pipe network optimisation problems. This method uses the interrelation between pheromone change and initial pheromone strength to initialize the pheromone trail strength at the start of the computation. This method is shown to be capable of locating the best ever solutions obtained for these problems.

Symeon E. et al [38] applied ant colony optimization in two case studies of pipe routing problem. They observed that this method has quick convergence and hence takes less computational time. In the Ant Colony optimization (ACO)’s mathematical background is outlined and possible implementation strategy was suggested for identifying “shortest paths” in water pipe networks. Such shortest paths could be, not only the minimum pipe lengths between nodes of interest, but also the minimum number of valve operations required to keep a flow path active, the minimum number of customers affected during a flow reroute either because of planned maintenance or unplanned water leak conditions, and the minimum pressure drop along a path during adverse conditions. A case study of a specific urban water distribution network is also described for the proposed ACO virtual multivalent approach.

MULTI OBJECTIVE METHODS

Farmani et al [21] used three objectives: cost, reliability and water quality for evolutionary multi-objective optimization of the design and operation of water distribution network of Anytown’s water distribution system. It was concluded that considering resilience index and water age as objectives, in addition to cost, in the optimum design and operation of Anytown’s water distribution system resulted in networks with high reliability and water quality.

Reehuis et al [53] used a three objective problem formulation based on cost and reliability for solving three pipe networks i.e, two loop problems, the New York city pipe network and Hanoi city pipe network. The two well established methods, Multi objective Genetic Algorithm (NGSA II) and Multi objective selection based on dominated hyper volume (SMS-EMOA) were applied to solve the three WDN problems and it was found that SMS-EMOA gives better results.

Sriworamas et al [42] used Strength Pareto Evolutionary Algorithm (SPEA), non-dominated sorting genetic algorithm (NSGA), Pareto archived evolution strategy (PAES), population-based incremental learning (PBIL) and particle swarm optimization (PSO) methods for evaluating multi objective functions in water supply network in a city of Thailand and concluded that most of the multi objective evolutionary algorithms are powerful tools for dealing with design and rehabilitation problems of water distribution network. They applied two or three methods simultaneously and found that RMPSO and RNSGA are suitable for small and large networks respectively Piratla et al [46] analyzed the performance of three resilience metrics:
1) Resilience Index (RI); 2) Network Resilience Index (NRI); and 3) Modified Resilience Index (MRI). They employed genetic algorithm based, multi objective optimization formulation for designating two WDN problems in the research: A small network of Green field and expansion of an existing WDN to meet future demand. The results obtained were helpful in installing resilience into existing or new water distribution network.

HYBRID METHODS

Cisty M. [34] proposed the hybrid method by using two algorithmic techniques ie, linear programming (LP) and genetic algorithm (GA). A combination of these two methods determined the limitations of LP (for networks with loops) are used. It was found that proposed method provided more reliable results.

Zheng Feifei [50] has used to make hybrid approach more often for the design of water distribution systems (WDSs) with multiple objectives. In his approach a self-adaptive multi objective differential evolution (SAMODE) algorithm, in which control parameters are automatically adapted by means of evolution instead of the presetting of fine-tuned parameter values. This approach is compared with two full-search optimization methods (the SAMODE algorithm and the NSGA-II) for purely random solutions of three case studies: a benchmark network and two real-world networks with multiple demand loading cases. It was seen that the proposed NLP-SAMODE method consistently generates better-quality Pareto fronts than the full-search methods with significantly improved efficiency.

Creaco E.[48] presented a procedure which encompasses four sub-algorithms operate in a subordinate way. The results of algorithm are optimal solutions in the cost-reliability space, with reliability being compactly expressed through the network resilience metric. He applied this approach to four case studies to show the benefits of the new algorithm in terms of numerical and computational efficiency with respect to a multi-objective genetic algorithm.

Izquiedo J.[49] combined data mining solutions with evolutionary algorithms to extract relevant information from solution spaces analyzed during optimization process of water distribution system (WDS) design. Firstly, results from data mining can be introduced into the evolutionary algorithms to guide the search of solutions. Secondly, data mining techniques is used not only to explore the population of potential solutions but also to exploit data regarding the behavior of WDS under different working conditions.

CONCLUSION

The design of water distribution networks is one of the most challenging problems to test the efficiency of optimization techniques, since it features numerous decisional variables to be considered and numerous constraints to be satisfied. It is found from the review of literature that many approaches has been developed for pipe network optimization. Secondly most of the researchers focused on genetic algorithm to optimize the network. The results obtained indicate that there is need for improvement in optimization techniques. that’s why more and more emphasis is given on the optimization. Many other optimization techniques such as particle swarm method, ant colony optimization, artificial neural network, etc. were being used for pipe network optimization. Data mining and ANNs are recently used for optimizing water distribution network. The application of hybrid method for multi objective optimization of water supply network is a new technique in pipe network optimization. The scope of using three or more techniques simultaneously for optimizing WDN is still in consideration.
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