Review on health assessment of urban water supply network

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Abstract. With the rapid increase of urbanization level in China, the accidents related to urban water supply network occurred frequently due to the impacts of pipeline aging, environmental change and human factors, thus the health assessment of urban water supply network has become one of the hot topics of global scholars in recent years. Based on analysing the concept of health assessment of water supply network, this paper summarizes several main methods and principles of health assessment of water supply network, and discusses the shortcomings and limitations of the existing methods. Finally, this paper points out that the mechanism oriented dynamic health evaluation system, with the core of quantitative and universal considering the factors of three aspects including the pipeline attributes, hydraulic characteristics and external environment, is the development trend.

1. Introduction

Water supply network is an important part of urban infrastructure, as well as a necessary foundation for ensuring normal life and production development. With the rapid development of urbanization, the contradiction between supply and demand of water resources has become increasingly prominent in many cities in China. Due to the aging of water supply network and the change of pipeline environment as well as the influence of human factors, water supply network accidents have frequently occurred in recent years, which not only waste precious fresh water resources, but also have great influence on human life and social and economic development. Therefore, the health assessment and related technologies of urban water supply network have emerged, and have become one of the hot topics among worldwide scholars. Whether based on the needs of urban water supply safety and public safety, or for social and economic development and construction, it is of great practical application value and theoretical significance to evaluate the health status of urban water supply network. However, a set of effective evaluation system and methods for the health assessment of water supply network has not been formed at present. Related researches mostly refer to qualitative and static analysis, and cannot objectively reflect the health status of pipe network due to neglecting or simplifying the influence of internal hydraulic condition on the health of the pipe network system. Thus it is difficult to provide technical support for leakage reduction as well as maintenance and updating of pipe network.

On the basis of summarizing current researches of health assessment on water supply network in China, this paper discusses the basic principles as well as advantages and disadvantages of several health assessment methods on water supply network, and puts forward the key development direction of future research in view of the existing problems in order to promote and guide the health assessment research on water supply network in China.
2. Concept of the health of water supply network

The health of water supply network is an analogy concept of health. Many scholars have different understanding on the concept since considering different influence factors of pipeline damage degradation or studying from different perspectives. Generally speaking, the health of water supply network refers to the ability of the pipeline to resist the interference of all kinds of external adverse factors, and meet the demand of users on water quantity, water quality and water pressure in a safe, stable and continuous way in a certain time and space[1,2].

Related researches on the theory and technology of health assessment began in the 1970s in China. There are many achievements in the field of electronic and electrical and biological research, but less on the health assessment theory of water supply network. At present, the related researches mainly focused on the analysis of the reliability and vulnerability of the water supply network [3]. The researches of the reliability of the pipe network were mostly aimed at the mechanical reliability and hydraulic reliability of the pipe network, and the evaluation of the vulnerability of the pipe network were mainly about water quality of the pipe network [4,5]. Different from the traditional evaluation of water supply network based on the vulnerability and reliability analysis, the health assessment of water supply network focuses on the analysis of the state of the water supply network system. Based on the basic data of the pipeline network operation, the state of the network can be evaluated through the analysis and dynamic tracking of various key factors affecting the pipeline.

3. Health assessment method of urban water supply network

In recent years, the health assessment of water supply network has been paid much attention by researchers in different countries, and a series of research results have been obtained. The health assessment methods of water supply network are mainly divided into two categories: mathematical statistics method and direct detection method.

3.1. Mathematical statistics method

With the development of science and mathematics, the applied mathematical model has been widely introduced into the research and development of many fields. In recent years, the methods used in the quantitative research on the health assessment of urban water supply network mainly include: index evaluation method, mechanism analysis modeling method and aging failure prediction model.

3.1.1. Index evaluation method. The health state of the water supply network is a dynamic process. In order to evaluate the health state of the pipe network system, a series of quantitative and qualitative indexes related to the health state of the pipe network are selected, including the external influence indexes (such as soil type, soil thickness and ground load, etc.), the influence indexes of pipe network itself (pipe material, pipe age, pipe diameter and interface form, etc.), hydraulic characteristics indexes (water quantity, water pressure, water supply capacity, etc.) and water quality indexes (node residual chlorine, node water age, etc.). According to the analysis of historical data and real-time collection and monitoring information, the scores of various indexes are obtained, and then the weight of each index is determined by mathematical statistics or expert experience, and the health degree of the pipe network is calculated quantitatively, and the comprehensive evaluation results of the pipeline health state are obtained. Through grading, the health status of the pipe network can be divided into several scoring areas from good to inferior, and the health status is evaluated according to the actual score and rating results, and the optimal maintenance management measures are put forward for each health grade. This method is simple and easy to operate. The common evaluation methods include fuzzy theory, analytic hierarchy process and multiple linear regressions.

Based on the data of water supply network in Xi’an, Wu constructed a network safety evaluation index system taking "pipe network risk assessment" as the core, combining quantitative and qualitative analysis, and considering both internal and external factors of pipeline [6]. Through analyzing and identifying the risk and unfavorable factors in the pipe network system, the damage degree of the pipe network system is evaluated, and thus can provide scientific basis for reducing and preventing pipe
network accidents. Wang introduced the improved analytic hierarchy process to determine the index weight, built up the evaluation system of water supply network accident based on the fuzzy comprehensive evaluation method and theory, established the evaluation grade and objectively analyzed the possibility and safety grade of the risk in the water supply network system of Qingdao, and thus provided basis for the foundation of a safe urban water supply system [7]. Yin established a comprehensive evaluation system of pipe network performance on the premise of the static evaluation of water supply network based on Bayesian theory, combining with the dynamic evaluation of hydraulic and water quality [8]. Taking the water supply network of a development area in North China as the research object, this study verified the comprehensive evaluation system of the comprehensive network performance, and may provide scientific basis for the scientific management of pipe network and guarantee of water supply safety. Tian used experts grading method, fuzzy analytic hierarchy process, optimality theory and particle swarm optimization to screen indexes for network performance evaluation, and established the optimization model of the network [9]. Chang et al. built up a model based on BP neural network to assess health conditions of water supply pipes, and pipe material, age, diameter, length and junction type were chosen as input variables, the output variable was the risk coefficient of pipe damage [10].

The European Commission for research and development has proposed a computer aided water supply network repair system, which determines the running state of the pipeline by analyzing the running data of the water supply pipeline [11,12]. The Louisville Water Company (LWC) of the United States proposed the evaluation model of the pipeline network in the report, using 23 key pipeline indicators to evaluate the health state of the pipeline [13]. The running state of the long distance water pipeline was evaluated from the aspects of leakage, corrosion and water pressure in Norfolk of the United States in 2006, and the maintenance plan of the pipeline was further established [14].

3.1.2. Mechanism analysis modeling method. The mechanism analysis modeling method refers to the process of building up a mathematical model for the simulation of the water supply network system, and accurately simulating the running dynamics of the water supply pipe network from the micro angle (hydraulic and water quality) through the establishment of the mathematical function relation based on the actual situation of the water supply network system. The distribution of any factor in time and space in the pipe network can thus be obtained. The establishment of the mechanism model can reveal the hidden danger of the pipe network accident and solve the difficult problems. It is of great significance to strengthen the safety of water supply, reduce the economic loss, and realize the efficient management and maintenance of the water supply network. Using professional modeling software to establish hydraulics and water quality model of water supply network system can greatly improve the modeling efficiency. At present, the commonly used modeling software includes WaterCAD, EPANET2.0, FINESSE, CFX, CARLA, et al.

The modeling of water supply network has been studied since 1970s in China. Many Chinese scholars have accumulated rich experience on the application and practice of water supply network mechanism modeling [15-22]. In recent years, the research on modeling of water supply network system has been further developed. Wu established the dynamic model of the foundation beam under the dynamic change of the traffic load, as well as the reliability analysis model of the pipeline under the complex conditions based on the macroscopic stress damage mechanism of the pipeline [23]. Zhang carried out the response analysis of the longitudinal internal force and lateral internal force of the water supply pipeline, established the response model of the internal force of the pipeline, put forward the judgment criterion and the failure judgment method of the pipe failure, and introduced an example application [24]. Xu et al. established a dynamic water quality model of pipe network with residual chlorine and three halogen as water quality indexes based on the analysis of water quality change law of water supply network system, and used the Lagrange method to solve the model [25,26].

Tesfamariam et al. quantitatively analyzed the effect of pipe material, geometric size, temperature change and support loss on the mechanical properties of pipeline considering different factors
including temperature, load, and soil incomplete support [27]. Rodriguez et al. proposed a model based on BP neural network, and studied the attenuation law of the residual chlorine in the water supply network system, this study expanded the research idea of the water quality model [28].

3.1.3. Aging failure prediction model. Based on a large number of relevant historical pipelines data, the aging failure prediction model simulates the life curve of pipeline using statistical method, predicts the probability or time of the possible leakage of the pipeline, and further evaluates the state of the pipeline. Zhang et al. studied the correlation between the leakage events of the pipeline and the causes that lead to the leakage of the pipeline using the multiple linear regression analysis theory taking the leakage of the pipeline as the dependent variable while all the factors causing the leakage as the independent variables, and put forward the prediction model of the initial leakage loss of the water supply pipeline, so as to turn the leakage management mode from passive reply to active prediction [29]. Yan analyzed the leakage cause of water supply pipeline, forecasted the safe use time of water supply pipeline using particle swarm optimization algorithm to optimize the BP neural network model, improved the convergence speed and precision of the model which played the role of leak detection and early warning for water supply pipeline [30].

Qing et al. established the prediction model of the pipe burst, which can effectively screened out the pipe with larger detonator risk rate, using the logistic generalized linear model with two classification properties based on the statistical analysis of historical pipe burst data of water supply pipe network, and evaluated the current situation of the pipe network according to the predicted value of the model [31].

Davis et al. studied the failure phenomenon of UPVC water supply pipeline in Australia considering the initial crack randomization model [32]. Shamir and Howard explored the relationship between pipeline breakage rate and pipe age using linear and exponential regression model, and proposed the optimal time model of pipeline renewal through the correlation analysis of pipeline maintenance renewal cost and pipeline breakage rate [33].

3.2. Direct detection method
Direct detection method includes two kinds of methods: destructive testing and non-destructive testing. Destructive testing method generally gets the real performance data of the pipe network through the destroying experiment, and can judge the state of the pipe network more effectively. Destructive testing method mainly includes sampling detection and controlling damage detection. Non-destructive testing method can evaluate the pipeline state by detecting defects in the inner and surface of the pipeline without damaging the pipeline. Destructive testing can truly and effectively judge the state of pipe network, but the investment of non-destructive testing is smaller. There are many researches on pipe network detection technology, some researchers have developed an intelligent detection device in pipelines based on leakage flux method and ultrasonic method. Permalog, developed by Palmer Company in England, is the most advanced water leakage detection and early warning system in the world, which can effectively prevent the occurrence of pipe burst and provide a timely and reliable scientific basis for the emergency plan of urban water supply emergencies. In China some developed cities have established a relatively perfect network information management system, but the overall pipeline detection technology is still relatively backward, it is necessary to further improve pipeline detection technology and research sophisticated detection equipment.

3.3. Comparison of the advantages and disadvantages of different methods
The comparison between the advantages and disadvantages of the above-mentioned mathematical statistics and direct detection methods is shown in Table 1.
Table 1. Comparison of health assessment methods for water supply network.

| Category                  | Name                                      | Idea                                                                 | Advantage                                      | Disadvantage                                      | Factors                                   |
|---------------------------|-------------------------------------------|----------------------------------------------------------------------|------------------------------------------------|--------------------------------------------------|-------------------------------------------|
| Mathematical statistics method | Index evaluation method                   | Calculate index score based on historical data and monitoring data, and assessment combining with weights | Simple, easy to operate and widely used          | No unified standard, strong subjectivity         | Outside and inside the pipe network       |
|                           | Mechanism analysis modeling method         | Simulate the operation of the pipeline network from a microscopic perspective | Real-time reflection of the running condition of pipe network | Consider only one aspect of the pipe network     | Inside the pipe network                   |
|                           | Aging failure prediction model            | Simulate life curve of pipeline network based on historical data, predict failure probability or time | High accuracy, can provide an effective and economic restoration plan | High data demand                                 | Outside the pipe network                   |
| Direct detection method   | Destructive testing                        | Obtain performance data of pipe network by damage experiment         | Accurate and effective judgment of the state of pipe network | A great deal of manpower, material and financial resources | Outside the pipe network                   |
|                           | Non-destructive testing                   | Detecting the inner and surface of the pipe                          |                                                 |                                                  | Inside the pipe network                   |

4. Problems in health assessment of urban water supply network

The above four health assessment methods have their limitations during the evaluation process. For index evaluation method: 1) there are many factors affecting the health of the pipeline network, including the nature of the pipeline itself as well as the threat from the external environment. As scholars have different understanding of the essence and connotation of the concept of urban water supply network health, the starting point and purpose of the assessment are also different, there is no unified health assessment index system for water supply network yet. 2) there is no set of recognized standard in the selection of index, and evaluation results also have no reasonable quantitative judgment standard. 3) the determination of index weight directly affects the evaluation results. At present, the methods of determining the weight of the index mainly include analytic hierarchy process and Delphi method, which both face the problems of strong subjectivity, and do not consider the hydraulic mechanism in the pipeline, resulting in a deviation between the health status assessment results of the pipeline network and the actual situation.

For mechanism analysis modeling method: 1) using this method to judge the health of the pipe network is unavoidable to be one-sided and limited, since the pipe failure is often caused by the joint action of many factors, while the mechanism model often considers only one aspect of the pipeline. 2) the mechanism analysis model is mostly concentrated in the hydraulic model, while the dynamic simulation of water quality in water pipe network is relatively few. 3) the model evaluation method cannot directly reflect the influence factors of the pipe network failure, and it is not conducive to improve the health state of the pipeline considering the influence factors. 4) the more refined the model, the greater the workload and the longer the time of the calculation.

There are often evaluation deviations when using mathematical statistics method which evaluates the running state of water supply pipelines by mathematical derivation. In addition, this method needs years of accumulated and systematic historical operation data support, and it is more difficult to implement. If the data is not sufficient, inaccurate or even difficult to obtain, it will lead to the discrepancy between the evaluation results and the actual situation.
Compared with the mathematical statistics method, the direct detection method can be more accurate and effective to judge the state of the pipeline. However, because of the complexity of the urban water supply network system, it often needs to consume a lot of manpower, material and financial resources, and most of the pipe network system is buried underground, and the actual detection work is difficult to realize. In addition, the obtained results using the direct detection method are often qualitative, since the hydraulic mechanism in the pipe network and related influencing factors are not considered.

5. Research prospect

Together with the continuous updating of the pipeline detection equipment, the continuous construction and improvement of the mathematical model in the health assessment of water supply network provide a broad space for the health assessment method of water supply network. But at present, the methods of evaluating the health status of water supply network usually only consider the influence of water hydraulic, water quality and reliability on the health of water supply network, and few researches analyse the inevitable relationship between the local health status and the overall health status of the water supply network system. The operation of water supply network is a complex dynamic process. The running state of the water supply network in various working conditions is changing at all times and is full of uncertainty, and the pipe failure is often caused by the joint effect of many factors. The health assessment of urban water supply network not only include the static structure evaluation based on the external environmental indexes such as pipe material, pipe age, pipe diameter, roughness and other external environmental indicators, such as temperature, soil thickness, road grade, load and so on, but also the dynamic evaluation based on the hydraulic characteristics such as water quantity, water pressure, and water supply capacity, as well as the characteristics of water quality such as the residual chlorine and water age of nodes. Therefore, it is an important development direction for the health assessment of urban water supply network to build a mechanism oriented dynamic health evaluation system with the core of quantitative and universal considering the factors of three aspects including the pipeline attributes, hydraulic characteristics and external environment. It is necessary to explore new ideas and methods for the construction of mathematical models, pay attention to the combination of mathematical statistics and direct testing, and give full play to the advantages of various evaluation methods.

Compared with the existing related evaluation methods and techniques, the aforementioned mechanism oriented dynamic health evaluation system with the core of quantitative and universal focuses on the quantitative analysis of various influencing factors in the operation process of the pipe network, the identification of the key factors affecting the health of the water supply network, and analyzing the relationship between the key factors and health state of the system. The method may realize the dynamic tracking and the real control of the health status of the pipe network from many angles, as well as a timely alarm, so as to provide technical support for reducing the leakage and realizing the maintenance and renewal of the pipe network.

Acknowledgment

This research is supported by the Chinese National Key Research and Development Project (2016YFC0400605), Chinese National Natural Science Foundation (No. 51522907) and the Research Fund of the State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research (No. 2016ZY02).
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