Research of hydraulic reliability of water supply network based on the simulation of EPANET

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Abstract. Based on cascading failure, the model of EPANET is used to analyze the system reliability of water supply network and node impact evaluation and pipeline evaluation. Then three conclusions are obtained by calculation. The first conclusion is the hydraulic reliability of the water supply pipe network is related to the node and the pipe section. And the results of the analysis can correspond to the consequences of pipeline failure which can be used as a basis for evaluating pipeline. The second conclusion is the node can be divided into the failure node and the influence node based on node impact evaluation of the water supply network. And the failure node can be set to monitor the water supply system focus because of the sensitivity of these two types of nodes to cascading failure. The third conclusion is the pipeline evaluation is a comprehensive evaluation of pipeline operation and node influence, and pipeline can be divided into key sections, the main pipe, the general pipe, and the key pipe and the main pipe are the greatest threats to the hydraulic reliability of the water supply pipe network, so they should be considered as the key part of system optimization and system monitoring.

1. Introduction
As the city's lifeline, the security and reliability of urban water supply network are increasingly subject to the majority of scholars and city managers attention. Damelin firstly applied the theory of the reliability to the optimization design of urban water supply network, and discussed the reliability of the pipeline [1,2]. The reliability of water supply network is the possibility of the water supply pipe network must be delivered with the required water, water pressure within the specified time. And the reliability analysis is a key issue in water supply systems[3]. Alekseev reveale that the main factors that affect on operational reliability are largely associated with the competent organization of operating conditions of water supply systems[4]. Mazumder proposes a framework for modeling the time-dependent reliability of Water Distribution Systems(WDSs) with cast iron pipes. The results of the case study show that pipe corrosion can significantly impact the reliability of a WDSs as it ages[5]. Bin Mahmoud leverages a recently proposed non-iterative pressure driven demand simulation approach in conjunction with EPANET hydraulic solver for the assessment of WDS performance in failure states[6]. Hydraulic reliability calculations generally use simulation[7,8]. It should be noted that EPANET, a software for improving and optimizing the water supply network, can simulate the hydraulic water quality behavior of urban water supply networks. In addition, the software has the advantages of fast operation speed and good simulation effect.

2. Cascading failure
Water supply network as a complex network system, only its normal working conditions to carry out research is not enough. So some scholars put forward the concept of cascading failure
Cascading failure is a conductive failure process. When the network is subjected to natural or man-made disasters, that is, when the network is attacked, small abnormal events somewhere in the network system often spread to the entire network system, causing a wide range of chain reactions and secondary failures. In general, the maximum network traffic carrying capacity of nodes in the network is limited. When the disturbance causes the network traffic to be redistributed, the reassignment traffic of some nodes may exceed its maximum capacity, causing congestion or collapse of these nodes, resulting in a new round of traffic redistribution, causing some new nodes to collapse. That is the network has a little failure, and this failure is caused by the transmission chain reaction and secondary failure phenomenon. For the complex system of water supply network, if a pipeline fails, its flow and pressure will have the phenomenon of chain reaction and secondary failure. From this point of view, the water supply network satisfies all the elements of the cascading failure, so it can be carried out the assumption and analysis of the relevant cascading failure.

3. Reliability analysis

3.1. Model of reliability evaluation

According to the relevant literature [11,13-16], the failure rate of each pipe in pipe network is related to pipe diameter and pipe length, the specific equation is as follows:

$$\xi_i = \frac{0.6858}{D_{i}^{1.26}} + \frac{2.7158}{D_{i}^{1.313}} + \frac{2.7686}{D_{i}^{1.5792}} + 0.042$$  \hspace{1cm} (1)

Where: $\xi_i$ equals the failure rate of unit length on pipe $i$ (l/(a.mile)); $D_i$ is the diameter(inch) of pipe $i$.

3.1.1. Node reliability. The reliability of a node is often defined as the probability that a node will satisfy the user's hydraulic element within a given time period and hydraulic condition. The hydraulic factors mainly include the flow and the water pressure. Considering that the flow has certain correlation and certain difference, the hydraulic driving theory is calculated. Water pressure of the minimum ($P_{\text{min}}$) is water pressure that the node will lose its service function less than the water pressure, which is the node bottom limit failure water pressure. Water pressure of calculation ($P_{\text{cal}}$) of node is less than the water pressure that does not do the reliability calculation of node, which is the measured water pressure of the node (pseudo-failure point). Water pressure of service ($P_{\text{ser}}$) is water pressure of the node that can meet the normal service water demand, the node can work normally when water pressure of the node is higher than water pressure of service. Water pressure of the maximum ($P_{\text{max}}$) is the maximum water-pressure that the node can bear, and if the system is bigger than $P_{\text{max}}$, the hydraulic system will fail again and it is water pressure of the super failure.

$$P_{\text{cal}} = (1-a_1)P_{\text{ser}}$$ and $$P_{\text{max}} = (1+a_2)P_{\text{ser}}$$  \hspace{1cm} (2)

Where: $a_1$ and $a_2$ are the tolerance parameter of the node. The larger the value of $a$, the lower the probability of node failure.

Using hydraulic drive analysis method [16-19], considering the relationship between flow and water pressure, the relationship between the water pressure and flow of the node is obtained as follows:

$$e Q_j^{\text{act}} = \begin{cases} 0 & P_j \leq P_j^{\text{cal}} \\ \frac{P_j - P_j^{\text{min}}}{P_j^{\text{ser}} - P_j^{\text{min}}} P_j^{\text{cal}} \leq P_j \leq P_j^{\text{ser}} \\ Q_j^{\text{req}} & P_j^{\text{ser}} \leq P_j \leq P_j^{\text{max}} \\ 0 & P_j \geq P_j^{\text{max}} \end{cases}$$  \hspace{1cm} (3)

Where: $j = 1,2,3, \ldots, n$ (n is the number of nodes). $Q_j^{\text{act}}$ is the flow of the actual water of node j, $Q_j^{\text{req}}$ is the flow of supply capacity when node j is in cascading failure (if $Q_j^{\text{req}}$ is greater than $Q_j^{\text{req}}$, ...
$Q_{j^{av}}$ equals to $Q_{j^{req}}$. $P_j$ is the actual value of water pressure of node $j$. $P_{j^{cal}}$ is the measured of water pressure value of node $j$. $P_{j^{ser}}$ is the service value of water pressure of node $j$. $P_{j^{max}}$ is the maximum value of water pressure of node $j$.

3.1.2. **System reliability.** The reliability of the system is related to the actual flow of the failed pipe and the node [20-24]. Therefore, the coefficient of the system reliability is defined as follows:

$$R_k = \frac{\sum_{j=1}^{n} Q_{k,j}^{req}}{\sum_{j=1}^{n} Q_{k,j}^{req}}$$

(4)

Where: $k=1,2,3, \ldots, m$ (m is the number of pipes)

3.2. **Criteria of evaluating for nodes and pipes.**

There are two aspects of pipe evaluation. One is the transmission flow effect of cascading failure which is called system reliability. And the other is the effect of water pressure of cascading failure, it is the number of failure nodes and the number of nodes affected. In view of the purpose of the evaluation, the pipe will be divided into three categories according to cascading failure of the pipe: The first category is the key pipe (KP), because it will cause the whole system failure, its problems must be prohibited. The second category is the main pipe (MP), because it will result in a certain number of node failure, its problems should be avoided. The third category is the general pipeline (GP), and it will appear on the node flow impact, but its impact is generally not fatal.

3.2.1. **Criteria of evaluating for nodes.** If water pressure of the node is less than $P_{cal}$ or higher than $P_{max}$, this node is defined as the failure node. If water pressure of the node is higher than $P_{cal}$ and less than $P_{ser}$, this node is defined as the influencing node. The purpose of introducing failure nodes and influencing nodes is to analyze the sensitivity of nodes in the analysis of cascading failure.

3.2.2. **Criteria of evaluating for pipes.** There are two aspects of pipe evaluation. One is the transmission flow effect of cascading failure which is called system reliability. And the other is the effect of water pressure of cascading failure, it is the number of failure nodes and the number of nodes affected. In view of the purpose of the evaluation, the pipe will be divided into three categories according to cascading failure of the pipe: The first category is the key pipe (KP), because it will cause the whole system failure, its problems must be prohibited. The second category is the main pipe (MP), because it will result in a certain number of node failure, its problems should be avoided. The third category is the general pipeline (GP), and it will appear on the node flow impact, but its impact is generally not fatal.

4. **Cases and analysis**

4.1. **Overview**

The Water consumption of the status of the county is 5.61 million m$^3$ per year, and the highest daily water consumption is 18,400 m$^3$/d, and Water population of 91,800 people. According to the norms and the development of the plan[25], the total water consumption of the planning of the county in 2020 is determined to 80,000 m$^3$/d, and water consumption index of the highest unit of the population is 320L / person • d. The layout of water supply pipe is shown in Figure.1:

Considering the complexity of the node flow calculation, the node flow calculation and allocation process is omitted here. In view of the relatively flat terrain of the county, the elevation of nodes are considered 65m, which means total water pressure of 65 meters, and roughness coefficient C is 130.
According to the above conditions, we establish hydraulic adjustment model of EPANET, and this model uses constant pressure water supply that is high pool. Using EPANET can be run on analysis of the pipe network, and set the constraints for 80,000 m³. The simulation results are shown in Table 1:

![Figure 1. Floor plan of water supply network.](image)

| ID of Node | flow (L/s) | pressure (m) | ID of Node | flow (L/s) | pressure (m) | ID of Node | flow (L/s) | pressure (m) | ID of Node | flow (L/s) | pressure (m) |
|------------|------------|--------------|------------|------------|--------------|------------|------------|--------------|------------|------------|--------------|
| 2          | 24.790     | 28.700       | 15         | 18.230     | 27.332       | 28         | 27.710     | 37.566       | 42         | 3.350      | 32.252       |
| 3          | 44.890     | 28.479       | 16         | 23.630     | 26.105       | 29         | 23.000     | 26.784       | 43         | 34.840     | 31.624       |
| 4          | 51.180     | 27.304       | 17         | 21.990     | 24.453       | 30         | 22.640     | 26.429       | 44         | 38.940     | 29.880       |
| 5          | 47.610     | 25.445       | 18         | 18.860     | 25.319       | 31         | 24.940     | 25.567       | 45         | 24.400     | 29.172       |
| 6          | 27.400     | 25.052       | 19         | 16.390     | 24.752       | 33         | 5.780      | 27.017       | 46         | 21.980     | 28.463       |
| 7          | 35.450     | 29.600       | 35         | 18.930     | 27.331       | 34         | 18.910     | 25.329       | 47         | 18.320     | 27.074       |
| 8          | 65.090     | 29.080       | 36         | 42.490     | 29.998       | 35         | 23.120     | 28.224       | 48         | 18.090     | 26.342       |
| 9          | 73.110     | 27.873       | 37         | 24.260     | 26.212       | 36         | 24.940     | 27.522       | 49         | 10.640     | 26.103       |
| 10         | 20.950     | 27.584       | 38         | 19.730     | 25.120       | 37         | 23.550     | 26.778       | 50         | 0.000      | 32.651       |
| 11         | 19.300     | 26.167       | 24         | 23.500     | 24.442       | 38         | 23.870     | 26.189       | 51         | 0.000      | 32.561       |
| 12         | 27.290     | 25.725       | 25         | 58.680     | 29.503       | 39         | 16.320     | 25.672       | 52         | 0.000      | 27.091       |
| 13         | 18.070     | 25.253       | 26         | 18.170     | 24.817       | 40         | 25.240     | 31.263       |           |            |              |
| 14         | 25.070     | 24.793       | 27         | 50.450     | 28.764       | 41         | 11.200     | 32.344       |           |            |              |
4.2. Pipe failure rate and system reliability analysis
Using the formula 1, the results of the failure rate of each pipe (after normalization) are shown in Figure 2. When the cascading failure occurs in the corresponding pipe (the pipe sections 69, 77, 79 cannot fail, otherwise the whole system will not work normally), $P_{\text{min}}$ is taken as 10m according to the firefighting requirements, and $P_{\text{ser}}$ is taken as 24m, and $\alpha_1 = 0.25$ and $\alpha_2 = 0.6$, the reliability of the system is calculated by using formula 2, formula 3 and formula 4, the results are shown in the following figure:

![Figure 2. The failure rate of each pipe and the reliability of cascading failure.](image)

We can find out from Figure 2: the system reliability of six pipes is poor, that is, after the failure of the water supply system should not be protected in general, six pipes should be improved in the planning and design to improve and in the future operation.

4.3. Evaluating for nodes
The cascading failure analysis is carried out for each pipe according to the section 3.2. The number of failure nodes and nodes affected by cascading failures are shown in the following figure:

![Figure 3. The number of failure nodes and nodes affected.](image)

From Figure 3 it can be seen that when the failure of the five pipes is caused by the failure of the corresponding pipe system respectively, the pipe 75 is the most influential pipe section. In order to facilitate the comparison of the hydraulic pressure analysis, drawing pressure distribution of six pipe of the pipe 3, the pipe 4, the pipe 70, the pipe 71 and the pipe 75:

From Figure 4, it can be seen that when the pipe 3 fails, and the water pressure of node 5 and node 6 is less than $P_{\text{min}}$, so that is they are failure nodes, and the total of ten nodes are influence nodes.
When pipe 4 fails, the water pressure of node 6 is smaller than $P_{\text{cal}}$ which is a failure node, the total of five nodes is nodes affected. When pipe 70 fails, the water pressure of thirty-six nodes is smaller than $P_{\text{cal}}$ which are failure nodes, the total of four nodes are nodes affected; when the pipe 71 fails, the water pressure of seventeen nodes is smaller than $P_{\text{cal}}$ which are failure nodes, the total of thirteen nodes are nodes affected. When the pipe 72 fails, the water pressure of eleven nodes is smaller than $P_{\text{cal}}$ which are failure nodes, the total of sixteen nodes are nodes affected. Combined with the failure of the water pressure pipe 75, the entire upper right of the water supply network belongs to the system more vulnerable areas. In order to further observe the affected situation of nodes, statistical analysis is carried out for each node, the specific statistics are as follows:

**Figure 4.** Pressure distribution of cascading failure.
From Figure 5, it can be seen five nodes is totally independent of cascading failure which are the pipe 21, 25, 40, 41 and 43. Six nodes are affected only by cascading failure which are the pipe 2, 3, 4, 8, 28 and 42. And thirty-six nodes are affected by cascading failure thirty-four of which are pseudo-failure nodes.

![Figure 5. Statics of node impact.](image)

### 4.4. Evaluating for pipes

The Section 2.3.2 is used to analysis for each pipe, and the results of each pipe is shown as table 2:

| Classification | Pipe Category | ID of pipe     | number | rate of failure % |
|----------------|---------------|----------------|--------|------------------|
| The first      | KP            | 69,76,77,79    | 4      | 14.69            |
| The second     | MP            | 3,4,72,73,74   | 5      | 6.89             |
| The third      | GP            | others         | 70     | 78.42            |

As shown in Table 2, GP up to 78.42%, while the key conduit for such protection must be effective pipeline failure probability of only 14.69%. To sum up, the water supply network, you can shorten pipe length of KP and GP to reduce failure probability of KP and MP, and thus increase the reliability of the system.

### 5. Conclusion

The In summary, the reliability analysis of water supply network is an important part of the water supply network system. The analysis process can be divided into three types: pipe analysis, node impact analysis and system reliability. The model simulation and discussion results show that EPANET is a powerful calculation model of pipe impact analysis, system reliability analysis and pipe type analysis of pipe network besides pipe network adjustment. The node effect analysis can provide targeted monitoring node for water supply system monitoring, pipeline type analysis and system reliability analysis can provide a theoretical basis for monitoring, system optimization and targeted improvement of water supply guarantee rate of the system. Due to the constraints of its own water pressure constraints, the failure of most nodes in the water supply pipe network will lead to cascading effect, and the failure of key nodes will cause a significant drop in pipe network performance. Under the condition that the bearing capacity of the node is limited, the small disturbance of the water supply pipe network has a great influence on the water supply function. And the greater the maximum water pressure at the node, the better the cascading failure resistance of the water supply network. Therefore, in the maintenance of the pipe network, the key pipe sections that are likely to cause large-scale cascade failure should be avoided; and the reliability of the pipe network should be evaluated according to the properties of the water supply pipe network and the failure characteristics of the cascade to improve the ability to withstand disasters.
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