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# Water hammer assessment techniques for water distribution systems

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**Abstract**

The water hammer hazards are mainly in four aspects: the high water pressure bursting pipes, the vacuum flattening pipes and leading to water pollution, the cavitation damaging the pipes and pump impellers, as well as the transient force loosing the pipe joints. We presented a method to calculate five risk factors: the above four factors plus a composite risk factor. The pipe rupture risk assessment method and procedure were proposed through a water supply pipe network risk prediction flow chart. A real engineering case of CD city of China was used to illustrate the assessment method. The technology was proved correct, and the pipe rupture risk prediction and classification maps can be used to provide technical guidance for the water distribution network design and operation maintenance.


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*Keywords:* Water distribution network; Modelling; Water hammer; Pipe rupture; Early Warning; Risk Classification;

## 1. Introduction

The main reason of pipe rupture is water hammer caused by the hydraulic transient shock and cavitation. The water hammer hazards are mainly in four aspects: the hydraulic transient high water pressure bursting pipes, the vacuum flattening pipes and leading to water pollution, the cavitation damaging the pipelines and pump impellers, as well as the impact force loosing the pipeline joints.

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For the research on hydraulic transient, from the mathematical derivation of the 18th century, to the graphical analysis of the mid-20th century, and to the current computer digital simulation, the people already made a lot of research results. The major achievements are getting the relationship between multiphase and multicomponent transient flow state equation and the wave velocity, water hammer equations and the control equations, such as Joukowsky equation (Ghidaoui et al., 2005). Based on the transient flow simulation theory, Colombo et al. (2009) proposed an aqueducts fault detection technology, Lee et al. (2007) proposed the pipe network leak and deterioration over time detection technology by the time domain reflectometry (TDR), Arbon et al. (2007) proposed pipeline corrosion and blockage detection technology, Stephens et al. (2008) proposed cement mortar lining spalling detection technology, Zamanzadeh et al. (2007) analyzed the risk of water pollution, burst pipe and clogging, Gong et al. (2012) proposed a detection technology for pipe friction, wall thickness, velocity, position and the length of the pipes, Ferrante, et al. (2009) presented a leak detection method with coupling wavelet analysis and a Lagrangian model techniques, and Meniconi, et al. (2011) presented a pipe system diagnose method with the small amplitude sharp pressure waves.

The early warning system is mainly composed of four layers, namely, information collection layer, data transportation layer, data processing layer and application layer. It is widely used in the industries outside the water industry, such as weather, geological disasters, and disease plague control fields, e.g. FEWS (Famine Early Warning System). The main case used in water industry is water quality warning. CUAHSI HIS has established mechanism of storing, publishing, sharing, and exploring the hydrological data (Horsburgh, 2009). China has established 100 automatic water quality monitoring stations in seven major rivers, such as the East River raw water three-layer early warning system which is used in Dongguan city of China (Zhang et al. 2012). In water distribution system field, Ostfeld et al. (2004) presented a methodology for getting the optimal layout of an early warning detection system for terrorist hazard intrusion by genetic algorithm framework integrated with EPANET. Kroll (2010) analyzed the methods and criteria for evaluating the early warning systems of water quality problems. Mutikanga et al. (2013) analyzed the methods and tools for managing water losses. But there were not many early warning researches on the pipe burst of water distribution systems.

## 2. Theory and methodology

### *2.1. Problem solving*

Combining the basic water hammer equations with the pipe energy equations, the node continuity equations, the pump characteristic curve equations, and the water hammer protection facilities' characteristic equations, we derived the basic programmable MOC equation is as following (Wang 2011):

$$H_i + \alpha_i Q_i = h_i + \alpha_i q_i \tag{1}$$

In which capitalized letters represent the values at the current node and current time-step, lowercase letters represent the values of the adjacent nodes at the previous time-step. H is water pressure, m; Q is pipe flow, m^3/s. $\alpha = a/gS$, a is the acoustic wave speed in water, m/s; S is the cross sectional area of the pipe, m^2.

When the pressure falls below the vaporization pressure at the water temperature of the current time, the vaporization phenomenon occurs. It will form a water hammer of water column separation and cavities collapsing. The vapor volume calculation formula at the nodes and mid-points of pipeline is:

$$X = \sum X_i\,, \text{and } \frac{dX_i}{dt} = -Q_i \tag{2}$$

In which X is the vapor volume, m^3. Q is the pipe water flow, m^3/s. i is the index of pipes which connected to the node.

To solve the above problems is very complex. You cannot get the correct results directly by solving the equations because it needs a lot of assumptions, boundary conditions, and a large number of digital computations.

In order to improve the computing speed and adapt to the large scale pipe network, problem solving is divided into three levels.

When we do not consider the pipe head loss and node cavitation, we assume fi=0, H=Hi, and get the equation as following:

$$\mathbf{A}\mathrm{H}=\mathbf{B} \tag{3}$$

In which, $\mathrm{A} = \sum {}^{1}\!/_{\alpha_i}$ and $\mathrm{B} = \sum({}^{h_i}\!/_{\alpha_i} + q_i)$.

When we consider the pipe head loss, but do not consider the node cavitation, the problem can be solved through an iterative process, the iterative formulas are:

$$\mathbf{AH^{(k)}} = \mathbf{B} - \mathbf{C^{(k-1)}} \tag{4}$$

In which,$\mathrm{H}_i^{(k)} = \mathrm{H}^{(k)} + f_i Q_i^{(k-1)}\left|Q_i^{(k-1)}\right|$, and $\mathrm{C}^{(k-1)} = \sum({}^{f_i}\!/_{\alpha_i})Q_i^{(k-1)}\left|Q_i^{(k-1)}\right|$.

When we consider pipe head loss and node cavitation, we assume the node as the fixed head junction. The problem is still solved through an iterative process, but the iterative formula is:

$$\mathbf{X_i^{(k)}} = \mathbf{X_i^{(k-1)}} - {}^{\mathbf{1}}\!/_{\mathbf{2}}\,\mathbf{\Delta T}(\mathbf{Q_i^{(k)}} + \mathbf{Q_i^{(k-1)}}) \tag{5}$$

In which ΔT is the time step, s.

### *2.2. Water hammer risk assessment*

On the basis of data collection of GIS, construction drawings, water consumption records, pipe rupture records and other water supply network related information, the physical information of the pipe network is converted into digital data, and the computerized pipe network model is established. The model is connected to the real time monitoring system, regular meter reading system, and the running and historical record database. After validating the parameters with the collected data, the model is ready to use for the transient flow simulations. The next step is to design the scenarios which can trigger the hydraulic transient. The scenarios include pumps startup and shutdown, valves opening and closing, pipelines flushing, fire accidents, and large users overhaul, etc. Then run the model based on the designed scenarios, extract the results of computation, and conduct a comprehensive analysis of the simulation results. The analysis includes calculating all the risk factors of pipe rupture factors, sending the data back to model with user data extension function. Finally, the pipe network risk map is created with color coding in the model. The map can provide decision-making references to the water supply network operation and maintenance. The pipe rupture risk classification analysis process is shown in Fig. 1.

After getting the maximum and the minimum water pressure, and the maximum vapor volume of each pipe and each node, and the impact force of each node, the pipe rupture risk to the water supply network was evaluated from the following six aspects:

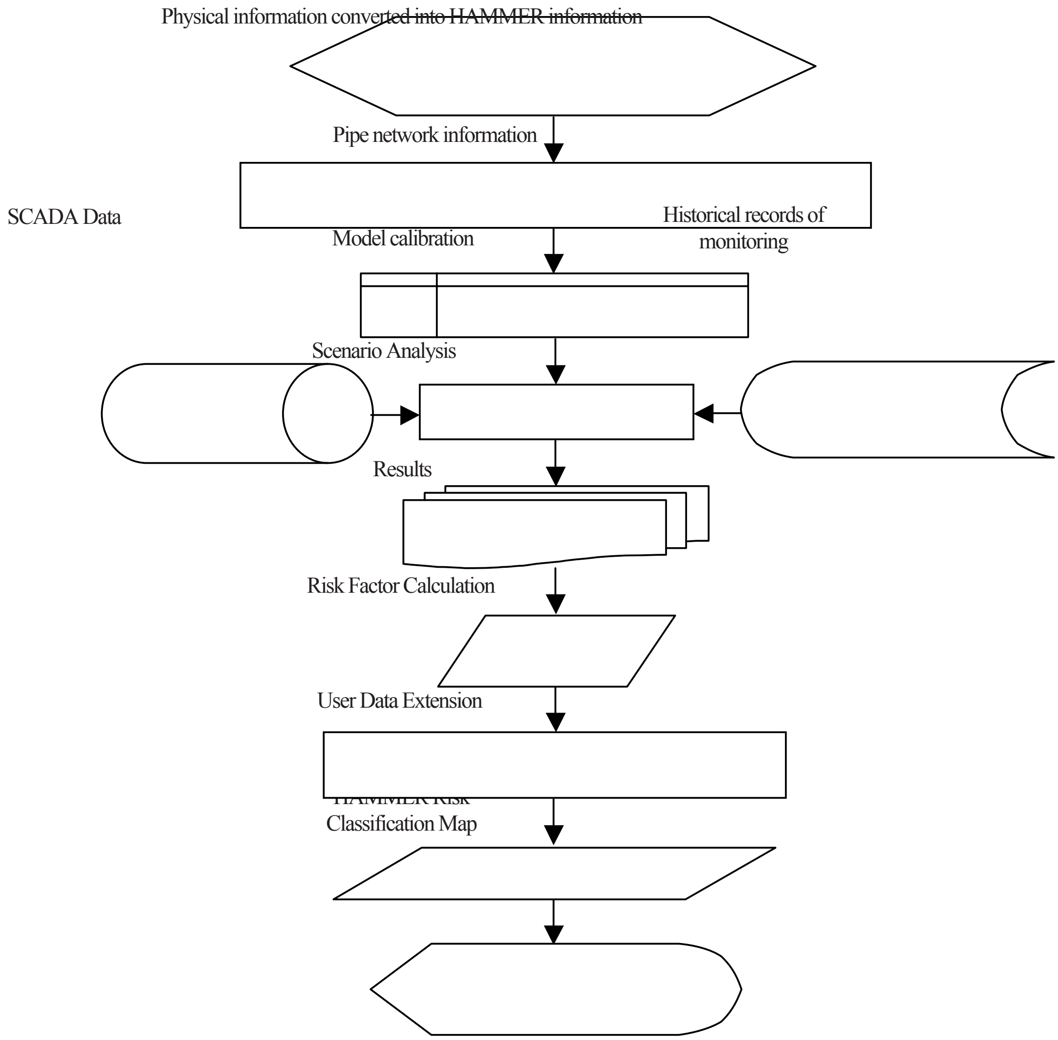


Fig. 1. Pipe Rupture Risk Assessment

- Risk factor of maximum water pressure of each node and each pipe

Pipe rupture risk because of water pressure depends on two aspects, namely, the maximum water pressure and designed safety pressure of each pipe. Depending on the pipe materials, the pipe wall thickness, and the production process, the pipe designed safety pressure is not fixed. The pipe rupture risk because of high-pressure is calculated as the following formulas:

$$\mathbf{R_1 = (P_{max} - P_b)/P_b} \tag{6}$$

Where $R_1$ is the pipe rupture risk factor based on water pressure, when $R_1<0$, $R_1=0$. $P_{max} = \max(P_1, \ldots, P_i)$ is the maximum pressure of each pipe and each node among the scenarios calculated by hydraulic transient simulation, Mpa. $P_b$ is the design safety pressure of each pipe or each node, Mpa. $P_i$ is the maximum pressure of each pipe and each node of the scenario i calculated by hydraulic transient simulation, Mpa.

For the designed safety pressure $P_b$, you can get by the following methods:

1) When you have the design information, the design pressure can be used. But you need to consider pipe conditions of corrosion and service time.

2) It can be calculated by the formula for the metal pipes according to the diameter and wall thickness:

$$\mathbf{P_b} = \frac{\mathbf{2(\sigma ES)}}{\mathbf{D+S}} \tag{7}$$

Where σ is the pipe material's allowable stress at the design temperature, Mpa. E is the welded joints coefficient, normally is 0.8. S is the thickness of a pipe wall, mm. D is the pipe diameter, mm.

3) It can be the maximum calculated pressure based on the EPS (Extended Period Simulation) of the steady state simulation. Using $P_b$ = 1.25 x maximum calculated pressure.

- Risk factor of maximum vacuum of each node and each pipe

$$R_2 = P_{min} / P_v \tag{8}$$

Where $R_2$ is the pipe rupture risk factor based on vacuum, when $R_2<0$, $R_2=0$. $P_{min} = \min(P_1, \ldots, P_i)$ is the minimum calculated pressure among the scenarios, Mpa. $P_v$ is the maximum vacuum, and generally -0.1, Mpa. $P_i$ is the minimum pressure of the scenario i, Mpa.

- Risk factor of maximum vapor volume of each node and each pipe

$$R_3 = V_{maxi} / V_{max} \tag{9}$$

Where $R_3$ is the pipe rupture risk factor based on vapor volume. Vmaxi = $\max(V_{1j}, \ldots, V_{ij})$ is the maximum calculated vapor volume of scenario i, m^3. Vmax = $\max(V_{max1}, \ldots, V_{maxi})$ is the maximum calculated vapor volume of the entire network of the nodes or the pipes, m^3, $V_{ij}$ is the calculated vapor volume of node j or pipe j under scenario i, m^3.

- Risk factor of maximum transient force of each node

$$R_4 = (F_{max} - F_b)/F_b \tag{10}$$

Where $R_4$ is the pipe rupture risk factor based on transient force of a node, when $R_4<0$, $R_4=0$. $F_{max} = \max(F_1, \ldots, F_i)$ is the maximum calculated transient force among the scenarios, N. $F_b$ is the base of the impact force of each node, N. $F_i$ is the maximum transient force of each node of the scenario i, N. $F_b$ can be the maximum calculated impact force based on the steady state simulation. $F_b$ = 1.25 x maximum calculated impact force of steady state.

- Composite pipe rupture risk factor of a node or a pipe

$$R=\sum_{i=1}^{n}(W_i R_i) \tag{11}$$

$$\sum_{i=1}^{n} W_i = 1 \tag{12}$$

Where R is the composite pipe rupture risk factor of a node or a pipe. $R_i$ is the i-th risk factors of pipe rupture. n is the number of risk factors, For a node, n = 4; for the pipe, n = 3. $W_i$ is the weight of pipe rupture risk factor i, and the total weight of a node or a pipe is 1. $W_i$ varies with the pipe materials and the local pipe networks. For example, PCCP (Pre-stressed Concrete Cylinder Pipe) pipes can stand the negative pressure well, therefore $W_2$ can be 0. However, PE (Polyethylene) pipes can be flattened by the negative pressure easily, therefore $W_2$ should be 0.5. If the user does not have any information about the network, for a node, $W_1$, $W_2$, $W_3$, $W_4$ can be 0.25 separately, and for a pipe, $W_1$, $W_2$, $W_3$ can be 0.33 separately.

- Pipe Rupture Risk Level Classification

We classify the pipe rupture risk through the three-layer early warning division mechanism. That is the warning level, the dangerous level and the severity level. Green indicates less than 0.25 for the safety level, no warning. Cyan indicates 0.25-0.5 for a warning level, means the need to conduct regular inspections. Blue indicates 0.5-0.75 for a dangerous level, means the need a high degree of concern. Red indicates greater than 0.75 for a severity level, means the technical measures need to be taken immediately.

## 3. Cases study

### *3.1. Case introduction*

This example is the clean water transmision pipes of Chengdu, Sichuan Province of China, which contains 2 parts. One part is the DN2600 PCCP pipes from the water treatment plant to the intersection with the outer ring road. The total pipes length is 26 km, and the ground elevation difference between start and stop nodes is 75m. There is a pipe flow control station which contains 2 parallel DN1800 piston valves to adjust the supply flow to the city before the road intersection. The water main is the gravity pipe which directly connected to reservoir of the water treatment plant. The lowest water level of the reservoir is 603.3m, and the highest water level is 608.3m. The other part is water distribution trunk pipes which are steel DN2200 to DN2400 on the outer ring road, and the pipe length is 30km. The total supply water is 1.2 million m^3 per day. The system is shown as Fig. 2, the project inventory is as table 1 and the endure pipe pressures are as table 2.

Table 1. Project inventory

| No. | Stake Range | Numbers |
|---|---|---|
| 1 | Pipes | 406 |
| 2 | Junctions | 200 |
| 3 | Reservoirs | 1 |
| 4 | Air Valves | 127 |
| 5 | Butterfly Valves | 71 |
| 6 | Piston Valves | 2 |

Table 2. Pipe types and test pressure

| No. | Stake Range | Pipe Size and Materials | Wall Thickness(mm) | Max Pressure(MPa) |
|---|---|---|---|---|
| 1 | A - B | DN2600(PCCP) | 185 | 0.6 |
| 2 | B - C | DN2600(PCCP) | 185 | 0.9 |
| 3 | C - D | DN2600(PCCP) | 185 | 1.1 |
| 4 | V-1 - V-2 | DN2600 (steel) | 20 | 1.4 |

Because of the big ground elevation difference among the gravity pipe system, the pipes will bear the high pressure and the water hammer is the potential risk to the system. The requirements of the client are: Are the water pipes safe at the condition of the valves' regular operation? Are there water hammers among the pipes? Are the air valves installed reasonable every 500m on the pipes? Are the sizes of the air valves sufficient? Where are the dangerous points of the pipe rupture and how to control the water hammer?

For the hammer risk assessment as the client required, we designed 5 scenarios as table 3.

Table 3: Designed scenarios

| No. | Stake Range | Valve Size (mm) | Operation Time (S) | Max Pressure (MPa) | Valve Type |
|---|---|---|---|---|---|
| 1 | V-1 | DN1800 | 60 | 1.4 | Butterfly on Branch |
| 2 | V-2 | DN2200 | 60 | 1.4 | Butterfly on Main |
| 3 | V-3 | DN1800 | 60 | 1.4 | Butterfly on Branch |
| 4 | V-4 | DN1800 | 60 | 1.1 | Piston Flow Control |
| 5 | V-5 | DN2600 | 400 | 0.9 | Butterfly on Main |

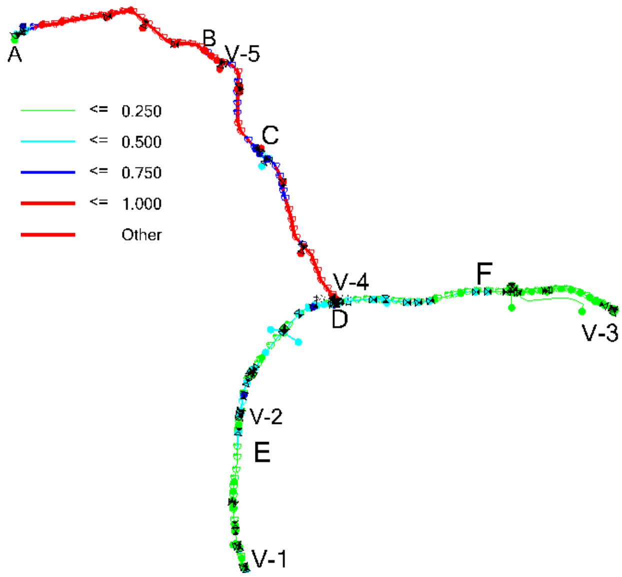


Fig. 2. Pipe Rupture Risk Assessment Color Coding Map

### *3.2. Case analysis*

From Fig. 2, we concluded:

- The pipes on the line from V-1 to E, and from F to V-3 are safe. The client does not need to consider the water hammer risk if the water supply amount, pipe network and water supply conditions do not change.
- The pipes on the line from E to F are on the warning level. The client needs to pay attention on the inspection regularly.
- The pipes on the line from C to the south for 3.3km are on dangerous level. The client needs to store the equipment and supplies on sites for the happening of pipe rupture events.
- Except the pipes on the line from C to the south for 3.3km, all the pipes on the road from water treatment plant to the intersection with the outer ring road are on severity level. We suggest that the clients need to install the essential hammer prevention equipment, such as surge tank, hydro pneumatic tank or surge valve, to prevent the water hammer.
- The combined air valves with inflow diameter of 300mm, large outflow diameter of 300mm and small outflow diameter of 4mm are sufficient. The most dangerous point is at the flow control station of V-4. If surge valves are installed at V-4 and V-5, the water hammer risk will be eliminated and the water mains are safe.

## 4. Conclusions and recommendations

Pipe rupture will destroy the city pipe network, lead to the water supply interruption, and lose of life and property, as well as water quality problems. The pipe rupture risk prediction and classification technology based on water hammer analysis for water supply networks can predict the rough time of a pipe out of service, and easy to formulate pipe network maintenance plan in advance to avoid the occurrence of burst pipes. Based on hydraulic transient flow analysis, pipe rupture risk factors are predicted for maximum water pressure, maximum vacuum, maximum vapor volume, and maximum transient force. The composite risk factor is also can be calculated by the above 4 factors. The color coding map can be created based on the 3-layer early warning technology of Class I (Cyan), Class II (Blue) and Class III (Red). The method and technology are verified by the real engineering project. The results show that the research methods can provide technique support for the designing, operating and managing the water supply networks.

For the severe water hammer damage to the water supply pipe network, it is recommended over the water supply enterprises to pay attention to the following:

- The computer model system can not only improve work efficiency, but also provide the technical support for the operation and maintenance of water supply network from the height of the entire network economically.
- The water hammer hazard assessment can do the risk classification and effectively prevent the occurrence of water hammer incidents for the urban water supply systems;
- Doing the pipe rupture risk prediction and classification planning regularly;
- Monitoring and inspecting the severity level areas, and reserving the appropriate tools and supplies there;
- Selecting the risk factors reasonably according to the actual situation.

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