Assessment of water pipes durability under pressure surge

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Abstract. Surge phenomenon occurs on the pipeline by the closing valve or pump suddenly lost power. Due to the complexity of the water hammer simulation, previous researches have only considered water hammer on the single pipe or calculation of some positions on water pipe network, it have not been analysis for all of pipe on the water distribution systems. Simulation of water hammer due to closing valve on water distribution system and the influence level of pressure surge is evaluated at the defects on pipe. Water hammer on water supply pipe network are simulated by Water HAMMER software academic version and the capacity of defects are calculated by SINTAP. SINTAP developed from Brite-Euram projects in Brussels-Belgium with the aim to develop a process for assessing the integrity of the structure for the European industry. Based on the principle of mechanical fault, indicating the size of defects in materials affect the load capacity of the product in the course of work, the process has proposed setting up the diagram to fatigue assessment defect (FAD). The methods are applied for water pipe networks of Lien Chieu district, Da Nang city, Viet Nam, the results show the affected area of wave pressure by closing the valve and thereby assess the greatest pressure surge effect to corroded pipe. The SINTAP standard and finite element mesh analysis at the defect during the occurrence of pressure surge which will accurately assess the bearing capacity of the old pipes. This is one of the bases to predict the leakage locations on the water distribution systems. Amount of water hammer when identified on the water supply networks are decreasing due to local losses at the nodes as well as the friction with pipe wall, so this paper adequately simulate water hammer phenomena applying for actual water distribution systems. The research verified that pipe wall with defect is damaged under the pressure surge value.

1. Introduction
Surge phenomenon appears in water distribution systems due to pump suddenly lost power or the closing valve on the pipe [1]. In the water network, the number of valves in the pipeline is much more than the number of pumping stations, so manageable surge phenomenon spread across the pipe network by closing the valve relatively complex [2]. Moreover, water surge after pump have large intense, it is often very tight control but pressure heads are appeared by shutting the valve is usually smaller [3] so that it sometimes ignored during network operation. The study was conducted with three main objectives:
- Simulating the impact area of water hammer due to closing valve on the water distribution system.
- Assessing the impact of pressure surge on the durability of the water supply pipe.
- Predicting zone the risk of cracking on the water supply pipe network.

2. Literature review

Water hammer phenomena have been studied very early and over time the methods of pressure surge calculation is gradual improvement, especially with the development of computer technology, water hammer on water distribution system is more exactly simulated. Table.1 presents a number of water hammer case researches between 1977 and 2015.

| No | Year | Authors | Paper name | Methods |
|----|------|---------|------------|---------|
| 1  | 1977 | Wylie et al. [4] | Fluid Transients | Fortran |
|    |      |         | The dynamic effect of pipe-wall viscoelasticity in hydraulic transients. Part I—experimental analysis and creep characterization | Experiment and Simulation |
| 2  | 2004 | Dídia Covas et al [6] | The dynamic effect of pipe-wall viscoelasticity in hydraulic transients. Part II—experimental analysis and creep characterization | Compare the results. |
| 3  | 2005 | Dídia Covas et al [5] | Comparison of results. | |
| 4  | 2006 | Roman Wichowski [6] | Hydraulic transients analysis in pipe networks by the method of characteristics (MOC). | Experiment and Simulation |
| 5  | 2014 | M. A. Bouaziz et al [3] | Predicting risk of water quality failures in distribution networks under uncertainties using fault-tree analysis | Fortran và ABAQUS software. |

Mathematical models have been used to calculate water hammer in simple pipe system by various methods, such as the geometric method [5], method of characteristic [6] or numerical methods [7]. In addition, the parameters of the surge after the valve phenomenon is also determined by the experiment model [8, 9]. The studies showed that the pressure flow significant change after closing the valve compared with steady condition of the pipe, but the authors have not given a change of values and pressure throughout the water supply network as well as the impact of water hammer to the durability of materials pipes.

Over time, the surface material appear the defect due to soil environmental impact around pipe and working conditions inside it [10]. Corrosion of the material is the result of electrochemical processes that occur on the material when placed in a natural environment [11, 12]. At the defect, the bearing capacity of the material will be smaller than the other places [13]. The great pressure surge ability to impact the high pipe materials [14], or pipe can be destroyed structural material immediately, but with the pressure smaller, may it affect the pipe material? To answer this question must define the distribution of pressure surge on the pipeline. In this paper, changing pressure due to closing the valve is formulated on the water distribution network of Binh Thanh - Phu Nhuan District, Ho Chi Minh City, Vietnam.

3. Materials and methods

3.1 Water hammer in pipe

Assuming the water is a compressible fluid and pipe material on the network is capable of elastic, wave surge propagation velocities are determined by formula (1).

The flow of water and is considered the case unsteady flow, it is often modeled using differential equations (2) (3):
Continuity equation:
\[ a^2 \frac{\partial V}{\partial t} + V \frac{\partial H}{\partial x} = 0 \]  

Momentum equations:
\[ g \frac{\partial H}{\partial x} + \frac{fV}{2D_t} V \frac{\partial V}{\partial t} = 0 \]  

Where:
- \( a \) – wave speed, m/s;
- \( E \) – elastic modulus of pipe wall;
- \( K \) – elastic modulus of water, MPa;
- \( D_t \) – outside diameter;
- \( H, V, t \) – pressure, thickness of pipe, velocity flow.

Combined with the characteristic method [4] the pressure surge values can fully determine the magnitude of the valve closing time. In addition, in order to solve equations (2) and (3) more initial conditions and boundary conditions of flow are required. At time \( t = 0 \), the flow in the pipe is considered as the steady flow, identified pressure and demand of initial \( H_0, Q_0 \) with:
\[ Q_0 = (C_d A_v) \sqrt{2gH_0} \]  

Where:
- \( C_d \) – flow coefficient through hole;
- \( A_v \) – valve diameter, m.

The phenomenon of water hammer affect the pipe wall greater than the operation pressure values, it is not still broken with the pipes are designed right standard and no defects during the installation. However, in the process of operation on the pipe surface is corrosive by the external environment and it reduces the initial bearing capacity [15]. When the greatest pressure during the closed valve acts on these defects where are potentially higher leakage. So the result of this paper is one of the basic to predict the risk of leakage in the water supply network.

3.2 The process of evaluation of the structural integrity (SINTAP)

Pipeline strength assessment methods are commonly used as ASMEB31G Modified [15]; ASMEB31G [16]; DNV-RP-F101 [17], each SINTAP method has its own advantages, however, the method that is thought to be most accurate is SINTAP [18]. SINTAP developed from Brite-Euram projects [19] in Bruelles - Belgium with the aim to develop a process for assessing the integrity of the structure for the European industry. Based on the principle of mechanical fault, indicating the size of defects in materials affect the load capacity of the product in the course of work, the process has proposed setting up the diagram to fatigue assessment defect (FAD). The fatigue curve or curve interpolation is used to assess the safety [18], the fatigue and the safety coefficient of the material. Where material stress curve is continuous, with smaller loads and allows the greatest value, interpolated curve equation is:

\[ f(L) = \left(1 + \left(\frac{L}{L_c}\right)^{1/2}\right) \times \left(0.3 + 0.7e^{-a\delta L}\right); 0 \leq L \leq 1 + \left(\frac{150}{\sigma_0}\right)^{2.5}, \]  

Where:
- \( L_c \) – load parameter;
\( \sigma_f \) - stress the critical.

![Diagram of fatigue assessment defect (FAD)](image)

According SINTAP, safety coefficient is determined by the distance between the points curve interpolation and evaluation (A) is said to ensure the work of the material, the greater the stress values that remain in the comfort zone full, the material is still working normally [19].

However the pipe has reached the safety threshold is said to be destroyed, then \( f(L_r, k_r) = 0 \), where \( L_r \) respectively \( k_r \) loads acting on the material and the stress intensity factor is not dimensions are defined as follows:

\[
L_r = \frac{\sigma_{\text{max}}}{R} = \frac{2\sigma_{\text{max}}}{\sigma_u + \sigma_f},
\]

\[
k_r = \frac{K_{\rho}}{K_{\rho,c}},
\]

Where:
- \( L_r \) - load parameter;
- \( k_r \) - stress intensity factor;
- \( \sigma_f \) - stress the critical;
- \( \sigma_u \) - ultimate stress;
- \( K_{\rho} \), - intensity factor stress of notch;
- \( K_{\rho,c} \) - critical notch intensity factor stress;
- \( R \) - head loss factor.

When on pipe defects appear semi-elliptical corrosion, the ability of a material fault is often measured by volume method with characteristic quantities are effective distance and effective stress. By volume method, effective stress distribution around corrosive stain volume is divided into 3 regions (figure 4).

Region I increased elastic stress to maximum stress value then the value drops smallest stress gradient (zone II).

Region III breaking stress decreases linearly in logarithmic graph.
Stress distribution along defect root

\[ \log(\sigma_{yy}(rr)) \]

Geometrical defect

\[ K_p = \sigma_{eff} \sqrt{2\pi X_{eff}} \]

Fracture process Zone

Figure 2. Chart characteristic stress distribution around the notch \[20\]

The effective stress is considered to be distributed over the entire volume:

\[ \sigma_{eff} = \frac{1}{X_{eff}} \int_{0}^{X_{eff}} \sigma_{yy}(r)(1-r\chi(r))dr, \quad (8) \]

Therefore, the stress intensity factor of defect is identified: \[ K_p = \sigma_{eff} \sqrt{2\pi X_{eff}}, \quad (9) \]

Where:
- \( \sigma_{eff}, X_{eff} \) - stress effective, distance effective;
- \( K_p \) - intensity factor stress of notch;
- \( \sigma_{yy} \) - stress the critical and destructive.

4. Results

4.1 Modeling application

Modeling applications for water distribution systems of Binh Thanh Phu Nhuan district-Ho Chi Minh City with a total capacity of 1849 m\(^3\)/day. The system has four main pipelines, water taken from two locations as shown in figure 4. The total length of the network 23639.84 m, consists of 55 nodes and 78 pipes, medium pressure network from 30-60m.
4.2 Simulate surge due to closing the valve on the network

Application of theoretical simulations surge after the valve associated with Water Hammer V8i Bentley software [21], researchers build scenarios closed valve on the main pipe (4 scenarios) and branch pipe (3 scenarios) as Figure 4. The simulation results (figure 5) shows the distribution of pressure on the network of 4 case closed valve on the pipe D500, D700, D450 and D150, the pressure is concentrated in the darker color areas then decrease in the surrounding area (Lighter colors). However, when transmitted to the pressure surge is larger than the steady value of the pipe operation.

Figure 3. Simulation of pressure wave propagation on network

Figure 4. Graph the pressure distribution on the network after closing the valve

On the main pipes, after the valve from 2000m to 5000m pressure head magnitude approximately 1MPa (table 2). Because at the beginning of a high pressure network should close the valve FCV-1 has
high pressure (2.5 MPa) but the area affected by the small pressure waves caused by connecting two larger diameter pipe (D900 and D1000) the pressure is dispersed. When closing the valve on the main line at (5) with surge wave is the widest spread because this is the pipe pooled from two main lines of (4) and (3). However, for the branch lines, the water hammer only spread local impact on the brand pipe which have closing the valve and not spread to the main line (figure 5), the diameter of the branch pipes is smaller than the main pipes so when the pressure wave is transmitted to 50-70% removed.

Usually when closing the valve, the greatest surge appears just after valve and decreases with the length of the pipe, however, the valve FCV-7 closing, the biggest pressure in the D150 by this pipe directly into the connection main (4) and the magnitude of the diameter of the pipe is only 30% its connect.

Table 2. The simulation results of water hammer behind the valve

| Closing valve location | The main pipe | The branch pipe |
|------------------------|---------------|-----------------|
| FCV-1 D500             | 10            | 2.5             | 5482 |
| FCV-3 D450             | 8             | 1.42            | 2464 |
| FCV-4 D900             | 16            | 2               | 4150 |
| FCV-7 D700             | 14            | 3.18            | 3952 |
| FCV-2 D150             | 5             | 0.86            | 127  |
| FCV-5 D150             | 5             | 1.09            | 1400 |
| FCV-6 D150             | 5             | 0.55            | 482  |

4.3 Assessment of pressure pipe durability

When the high pressure head, the level of impact higher on pipe material, so in this paper will evaluate the stability of the two largest bearing pipe is D500 (P_{max} = 2.5MPa) and D150 (P_{max} = 3.18 MPa) when closed valve FCV-1 and FCV-7.

Materials pipe in networks are gray cast iron with mechanical characteristics as follows:

Table 3. The mechanical of grey cast iron

| E (GPa) | \(\sigma_y\) (MPa) | \(\sigma_u\) (MPa) | A (%) | H_E (GPa) | F (GPa) | \(K_{p,c}\) |
|---------|------------------|------------------|------|-----------|---------|----------|
| 180000  | 300              | 420              | 10   | 0.035     | 7050    | 14.9     |

Assuming defect geometry is semi-elliptical corrosion shape with depth of notch by 50% thickness pipe and length corrosion marks 10 times the depth. The outer diameter is 170mm and 532mm, thickness pipe is 5.6 mm and 8.6 mm respectively, applied ABAQUS 6.10 software for analyzing finite element mesh area corrosion traces appear, from which curves determine the relationship between the effective stress and effective distance of the defects.

Figure 5. Analyzing traces of the defect
Figure 6. The effective stress on the pipe a) - D150, b) - D500

The effective stress is \( \sigma_{\text{eff}} = \frac{P_{\text{max}} \times D}{2t} \)

maximum loads and intensity stress is defined respectively

equation (8) and (9), determine durability pipe on the FAD (figure 7) shows the water pressure surge
acting on the wall reached the limit bearing of materials.

Table 4. Rating of working pressure and safety factor

| Pipe   | \( P_{\text{max}} \) | \( \sigma_{\text{max}} \) | \( L_e \) | \( k_e \) | SF     |
|--------|-----------------|-----------------|--------|--------|--------|
| D150   | 3.18            | 49.82            | 0.14   | 0.69   | 0.704  |
| D500   | 2.5             | 74.83            | 0.21   | 1.02   | 1.042  |

Overall, diameter 500mm what have semi-elliptical corrosion defect on the wall will not withstand when the valve closing generated the magnitude pressure surge 2.5 MPa.

Figure 7. Assessment of pressure pipe durability

5. Conclusion
Water pressure surge after closing the valve has greater value than the working pressure of the pipe, so the risk of leaking water supply pipes will increase over time work. Studies have looked at specific cases to estimate the effects of pressure wave propagation after the valve. Besides, the application of standards in pipeline corrosion pipe distribution system shows ability busted pipe after the valve completely may occur during closing valves on the main pipe. Apply pressure surge simulation models in the pipeline are a useful tool to localize leaks more precisely, at the same time as the basic.
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