Surge Protections: Modeling vs. Design vs. Construction

Jinsheng Huo

Hydraulic transients, also known as pressure surge or water hammer, are the time-varying phenomena that occur when the equilibrium of steady flow in a system is disturbed by a change of flow that occurs over a relatively short time period, such as rapidly closing a valve or loss of power on a pump. Hydraulic transients can introduce large pressures and rapid fluid accelerations into a water distribution system, which can result in pump and device failures, system fatigue or pipe ruptures, and dirty water backflow and intrusion. Thus, surge control is extremely important for the design of hydraulic systems and for water system operation and protection.

To complete surge protection systems, engineering projects typically have three phases (modeling, design, and construction) that might lead to changes in a system. During the modeling phase, the surge problems are identified by the surge modeling programs and alternatives are evaluated and recommended based on the modeling results. Although modeling results provide a good reference on what to do to mitigate potential surge damage, it is sometimes impractical to apply all of these methods. As a result, during the design phase, sound engineering judgments are needed to finalize the engineering design, as well as the consideration of other factors, such as tradeoff between risk and cost, client preferences, etc. The last phase is the construction phase, where uncertainties could be anywhere and anytime. Therefore, it is not uncommon that some engineering design may need to be re-evaluated and revised based on the real field conditions and other factors, such as unavailability or unreliability of specified or alternative equipment, which may be changed during the value engineering or bidding phase.

The surge analysis might be needed to re-evaluate the new conditions and confirm that the revised surge protections can meet the designated requirements. To elaborate why and how the surge protection systems changed during these three phases, the regional Peace River Water Treatment Facility expansion project is presented. Its final surge protection systems include hydropneumatic tanks, bypass valves, surge valves, air valves, etc., as well as operations and maintenance guidelines. The final simulation results indicate that the surge control strategies will provide adequate surge protections to the pumping and pipe systems.

Common methods of surge control include: careful design of the plan and profile of the pumping station and pipeline system; selection of pipes and fittings to withstand the anticipated pressures; identification of proper start-up, operation, and shutdown procedures for the system; and selection and location of the proper control devices to mitigate the adverse effects of surge events. The advantages and disadvantages of the control devices, such as hydropneumatic tanks, air vacuum or release valves, surge anticipation or relief valves, and pump control valves, are also discussed. Furthermore, analysis of a surge protection system for a large pumping system is presented.

Methods

Surge Review

The primary cause of hydraulic transients is start-up or shutdown of pumps, or rapid opening or closing of valves. The analyses of pressures, velocities, and other abnormal behaviors caused by hydraulic transients make it possible to effectively choose various control strategies, such as: 1) selection of pipes and fittings to withstand the anticipated upsurge and downsurge pressures, 2) selection and location of the proper control devices to mitigate adverse effects of pressure transients, and 3) control of start-up, operation, and shutdown procedures to avoid rapid flow changes.

Pumping and piping systems are subject to potential surge problems. However, in practice, sometimes it is impossible to analyze them all due to time and budget constraints. Therefore, empirical guidelines can be used to determine whether a complete transient analysis is required (Jones, G.M.; Sanks, R.L.; Tchobanoglous, G.; and Bosserman, B.E., 2006). Generally speaking, a surge analysis is recommended if a system has one of following cases:

- Pumping system with a total dynamic head (TDH) larger than 14 meters (m) or 50 ft, and a flow greater than 115 cu meters per hour (m^3/h) or 500 gal per minute (gpm).
- Any pressurized pipe with a diameter greater than 200 mm (8 in.) and a length longer than 300 m (1000 ft).
- Any system where column separations can occur, such as systems with knees (points where gradient reduces) or high points, or pressurized pipelines with a more than 100-m (300-ft) steep gradient followed by a long, shallow gradient.

Jinsheng Huo, Ph.D., P.E., BCEE, is capital projects manager with City of Sunrise and is president and chief engineer of JINSHENG HUO in Fort Lauderdale.

There is no simple way to perform reliable transient analyses due to many complicated factors. Computer modeling is available to analyze surge events; however, it might not always be practical to conduct surge analysis due to the high cost of proprietary surge programs. Therefore, the extent of the analysis should be related to the size and cost of specific project requirements. It is suggested that designers use more than one program to compare results as a check on the surge simulations. Experience shows that different programs might provide significantly different simulation results, although these programs are based on the same or similar principal theories. Two principal equations are:

$$a = \sqrt{\frac{K/\rho}{1 + C(\frac{K}{E})(\frac{D}{e})}} \qquad (1)$$

$$\Delta h = -\frac{a\Delta v}{g} \qquad (2)$$

Where, a is elastic wave speed in water contained in a pipe (m/s, or ft/s), K is the bulk modulus of elasticity of water in (N/m^2, or lb/ft^2), E is modulus of elasticity of pipe material (N/m^2, or lb/ft^2), D is inside pipe diameter in meters (m, or ft), e is the pipe wall thickness (m, or ft), C is a correction factor for type of pipe restraint, ρ is the density of water (kg/m^3, or $slugs/ft^3$), Δh is the change in pressure head (m, or ft), is the change in velocity of water caused by the event (m/s, or ft/s), and g is the acceleration due to gravity (m/s^2, or ft/s^2); Jones, G.M., et al, 2006.

Table 1 shows the typical values for wave speed for water in pipes.

Table 1. Typical Wave Speed in Pipe for Water Containing Dissolved Air

Pipe Material	Wave Speeds	
	m/s	ft/s
Asbestos Cement	820-1200	2700-3900
Copper	1000-1300	3400-4400
Ductile Iron	980-1400	3200-4500
High-Density Polyethylene	180-370	600-1200
Polyvinyl Chloride	300-600	1000-2000
Steel	600-1200	2000-4000

Program developers provide designers a "black box" solution. Designers generally do not exactly know how the computer analysis program solves the complicated surge events. Therefore, designers should not depend solely on computer results; instead, they should use their own judgment to make the reasonable decisions, with help from computer simulations.

Surge Control Methods

Three key elements should be considered when designing a surge protection: 1) identify events that result in surge conditions, 2) evaluate system vulnerability to surges, and 3) consider susceptibility to infiltrations under low pressure (down surge) transients. Surge control strategies are developed according to operational practices that can cause transients, engineering practices that will minimize the impact of transients, and maintenance practices to reduce the likelihood of intrusion when surge occurs.

The commonly used surge control devices and their advantages and disadvantages are shown in Table 2; surge control strategies are shown in Table 3.

Table 2. Commonly Used Surge Control Devices

Control Devices	Advantages	Disadvantages
Pump control valve	Effective in surge protections by controlling pump start-up and shutdown. Can use automatic control system.	Ineffective when power outages happen. Must have auxiliary power source to operate valves if power fails and it might not be effective because it takes time for the power to fully operate.
Hydropneumatic tank	Can be used in control both upsurge and downsurge problems. Commonly used on pumping station discharge header, high points, or "knees" in pipeline.	Requires auxiliary equipment and controls. Requires frequent maintenance; large tanks can be expensive and large space is required at site.
Surge anticipation or relief valves	Effective in reducing upsurge pressures.	Cannot prevent downsurges. Requires drain piping and disposal area to release water
Variable speed pump	Effective in surge protections with gradual changes in flowhead and control of pump start-up and shutdown. Can use automatic control system. Enhance motor life due to infrequent starts.	Little protection from power failure. Variable speed drive for a motor is expensive. Adds complexity, reduces reliability, and requires special training of operation and maintenance workers.
Higher pressure rated piping, valves, and equipment	Simple to implement. Used in small raw sewage pumping stations and force main systems. Lower maintenance cost.	Pipe and other accessories may eventually fatigue due to cyclic surge pressures. In the long term, portions of force main may fail and have to be replaced. Higher capital cost.

Table 3. Commonly Used Surge Control Strategies

Control Strategies	Methods
Start-up	If there are several pumps, start them one at a time at intervals from 4-10 times the critical period $t_c=2L/a$, where t_c is the critical time, L is the length of the pipe, and a is the elastic wave speed. Program a pump-control valve to open slowly (from 4 to 10 times t_c) after the motor starts. Pump motors typically reach full speed within 1 to 2 s. Use a variable-speed drive for each pump ramped up to full speed slowly enough (from 4 to 10 times t_c) to avoid high surges.
Shutdown	Turn pumps off one at a time at intervals from 4 to 10 times t_c. Program a pump-control valve to close slowly (from 4 to 10 times t_c) before the motor is stopped. If pumps are equipped with variable-speed drives, ramp down slowly. Increase the inertia of the motor and pump unit by adding a flywheel so that it coasts to a stop over a longer interval. Add a hydropneumatic tank. The tank is not needed for normal pump shutdown, but if one is installed for other reasons, it would be an effective control.
Slow filling empty pipelines	The initial filling of empty pipeline must be done cautiously with velocities kept below 0.3 mg/s (1 ft/s) with air release valves open to exhaust the air slowly. Avoid full-capacity start-ups until all of the large air bubbles are exhausted. Always include the start-up procedure for empty pipelines in the operation and maintenance manual.

From a review of the plan and profile of the pumping station and pipeline system, as well as the operation and maintenance procedures, it is possible to determine where potential hydraulic transient problems may exist and what methods might be taken to control them with the help of computer simulations.

Designers can reduce transient pressure by avoiding knees, high spots, and steep gradients near the pump or along the pipelines (i.e., flatten grade lines). If any of these conditions cannot be avoided, a combination of piping/fitting strength and control strategies can be used to provide adequate protection at reasonable cost. It is recommended to design the surge protections based on advanced surge analyses and simulations.

Surge Analysis Programs

These programs have their advantages and disadvantages. There is no easy way to choose one program over another; ideally, a designer should have access to at least two programs so that the results can be compared and evaluated.

Surge Analysis

Project Description

The Peace River/Manasota Regional Water Supply Authority (Authority) is an independent regional water supply company providing drinking water to Charlotte, DeSoto, Manatee, and Sarasota counties in southwest Florida. A consultant will design and expand the Regional Peace River Water Treatment Facility from 24 mil gal per day (mgd) to 51 mgd. This expansion program included three major pumping stations:

- North Regional High-Service Pumping Stations (NRHSPS) – The North System: Design Flow = 21 mgd, Head = 80 pounds per sq in. (psi)
- South Regional High-Service Pumping Station – The South System: Design Flow = 45 mgd, Head = 80 psi
- River Pumping Station – Design Flow = 90 mgd, Head = 40 psi

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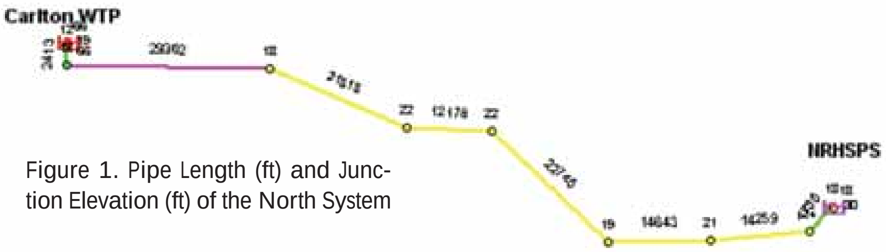

Figure 1. Pipe Length (ft) and Junction Elevation (ft) of the North System

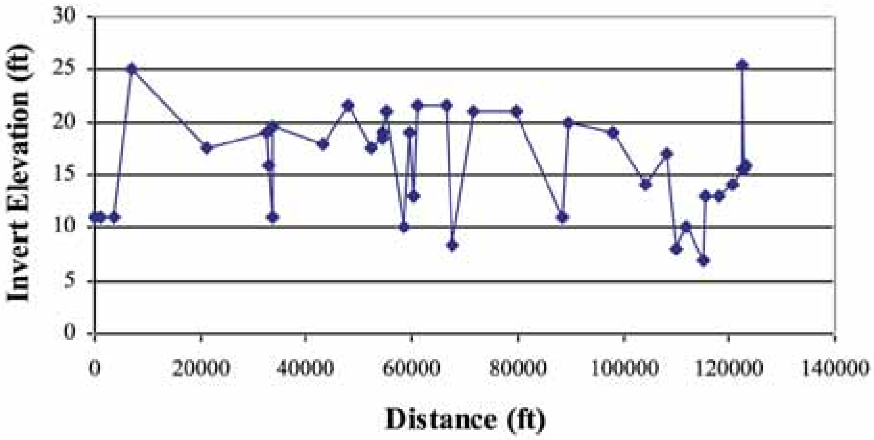

Figure 2. Profile of the North Regional System Transmission Main

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The North System is reviewed as an example; the South System will also be discussed briefly because it changed to an integrated system with the North System during the construction/operation phase.

The North System consists of four variable speed pumps with a firm capacity of 21 mgd and discharge head of 80 psi. The design condition of each pump is 7 mgd, 80 psi, or about 5840 gpm, 185 ft. The main transmission line is 23 mi of 42-in. thin-wall (3/16-in.) steel pipe. It conveys finished potable water at the plant to the North Regional Transmission System, primarily pumping to ground storage located at Sarasota County's T. Mabry Carlton Jr. Water Treatment Plant (Carlton WTP). This pump was designed to pump 21 mgd flow with a minimum of 20 psi residual pressure at the end of the 42-in. diameter pipeline, in accordance with the Authority's water supply contract.

Hydraulic Modeling

It is necessary to run the hydraulic modeling first to determine the starting point before a surge event happens. As shown, the hydraulic modeling of the NRHSPS system is completed to: 1) confirm the design of pumping and piping systems, and 2) determine the starting point for the following surge analysis:

1. Discharge pressure for Sarasota County at the Carlton WTP is set at 20 psi (about 47 ft). The pipeline terminates at a future ground storage reservoir.
2. The North Regional Transmission Line is a 122,000-ft (38.71-km), 42-in. steel pipe. A roughness factor of C = 120 was used.
3. With three pumps running and one standby, the simulated operating condition for each pump running is 5,758 gpm, 189 ft, according to the simulation results. The hydraulic system is shown in Figure 1.

For hydraulic modeling, a lower C-value needs to be selected to be conservative. However, for surge analysis, it is opposite—the higher the C-valve is, the more conservative the modeling result is.

Surge Analysis: Settings

1. *Pressure Wave Speed* – The wave speed varies from 340 m/s (1,115 ft/s) to 1,438 m/s (4,718 ft/s) for thin-wall plastic pipes to thick steel pipes. The North Regional Transmission System has thin steel pipes. A pressure wave speed of 1,000 m/s (3,280 ft/s) is calculated using Equation (1).
2. *Critical Time Period* – The equation (tc = 2*L/a = 2*122,000 ft / 3,280 ft/s ≈ 75 s) means a valve closed in any shorter time produces the maximum pressure head rise at the valve, where pressure rise is reduced if the valve is closed in a longer time interval.
3. *Liquid Properties* – Because the pumped fluid in the system is drinking water, a temperature of 20 °C (68 °F) and a specific gravity of 1.0 are assumed.
4. *Vapor Pressure* – For drinking water systems at typical temperatures and pressures, an approximate vapor pressure of –10.0 m (–14.2 psi, –32.8 ft) is used. If the system's elevation is significantly different from sea level, the vapor pressure should be adjusted according to published references.
5. *Elevations* – Extremely important in hydraulic transient modeling. Therefore, defining the profile of a pipeline is a key requirement prior to undertaking any hydraulic transient analysis. The piping profile, as shown in Figure 2, is built based on the record drawings.

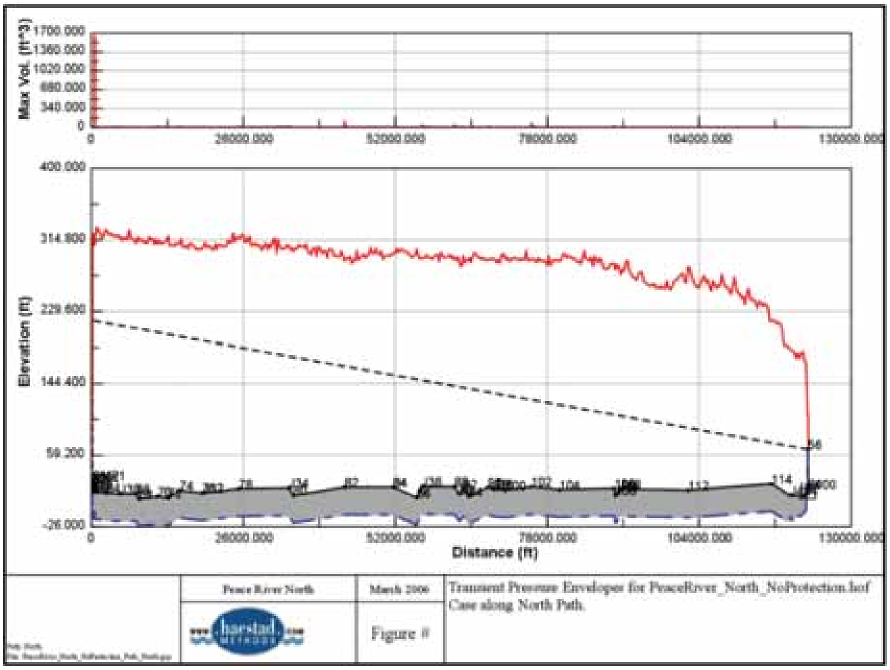

Figure 3. Surge Analysis of the North System Without Surge Protections

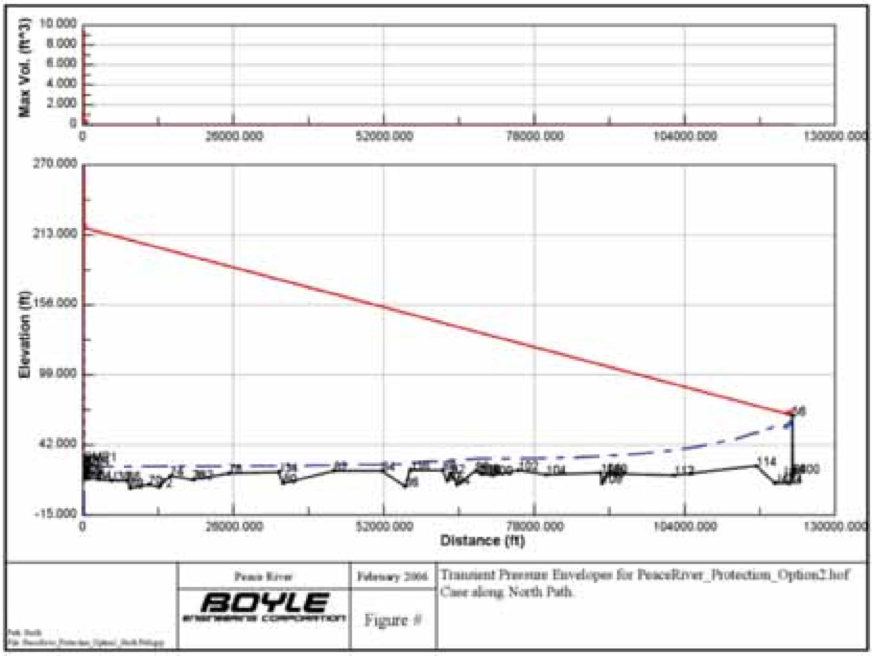

Figure 4. Surge Analysis of the North System with Recommend Protections

Modeling of Surge Protection Systems

The hydraulic modeling and surge analysis of the North System is completed and corresponding surge control strategies and equipment are recommended based on the modeling results. The surge analysis of the existing system without surge protections is illustrated in Figure 3.

Figure 3 shows that:

- There are serious downsurge problems, as highlighted with the gray color under the pipelines. The most serious consequence of downsurge is column separation, which must always be avoided. Column separation occurs if water is boiling and forming large air pockets when external air pressure drops below the saturated vapor pressure at a certain temperature.
- There are also air pocket problems, which is also likely to occur at knees. When air pockets collapse, two or more liquid columns can

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collide at extremely high speed, which can cause enormous forces and damages; the first and second highest point and the discharge point from pumps will be considered. It should be noted that air pocket problems commonly are the key reasons for downsurge/upsurge problems. The corresponding control strategies and equipment are similar as previously discussed.

- Various control methods for preventing column separation include, but are not limited to: 1) adding flywheels to the pumps sized to prevent the column separation, 2) installing pneumatic tanks (air chambers), and 3) adding air vacuum or release valves.

Theoretically, adding flywheels to the pumps is an option to prevent column separation and downsurge pressures by extending the pump shut-off time, especially when there is a power outage; however, the mechanical flywheel might not be practical in reality. Some pump manufacturers hesitate to use flywheels because of potential adverse effects on the pump performance (for example, reduced efficiency).

A hydropneumatic tank is selected to provide the required surge protection, especially for downsurge, which is modeled at Junction J28 (pump discharge point). According to record drawings, a 6-in. air combination valve is also installed at Junction 60 (flow meter), which has the highest elevation (25 ft). Figure 4 shows the results of the surge analysis without proposed surge protections.

From the simulation results, it can be concluded that:

- The selected hydropneumatic tank is a 3600-ft^3 bladder tank with an inlet diameter of 24 in. and a preset pressure of 50-ft H_2O.
- With recommended surge protections, it will reduce upsurge and downsurge pressures significantly.

Ideally, negative pressure should be eliminated under any condition; however, modeling results indicate that the theoretical size of a hydropneumatic tank to eliminate native downsurge is impractically large. The allowable negative pressure will be discussed.

During the modeling phase, the North and South systems are designed to operate separately. These two systems have two interconnections, but both connections are defaulted as "closed."

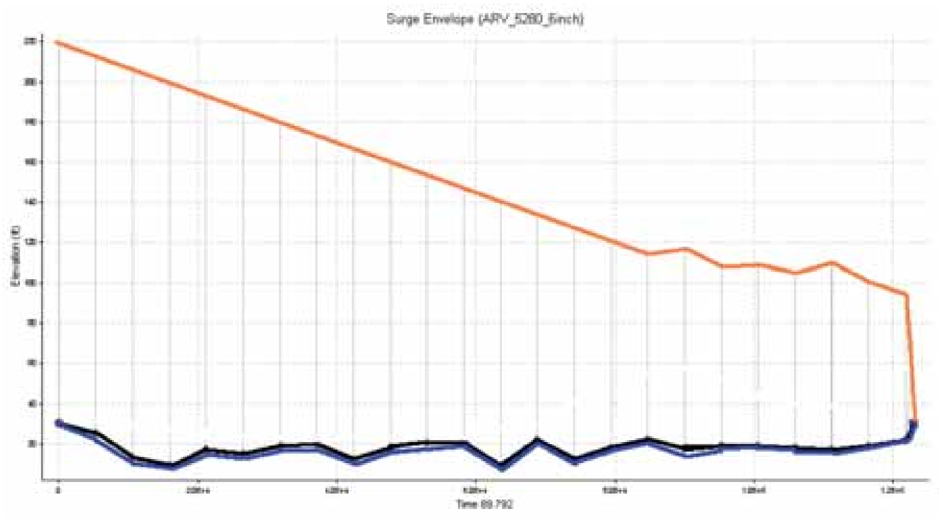

Figure 5. Surge Analysis of the North Regional High-Service Pumping Stations System With Recommend Surge Protections

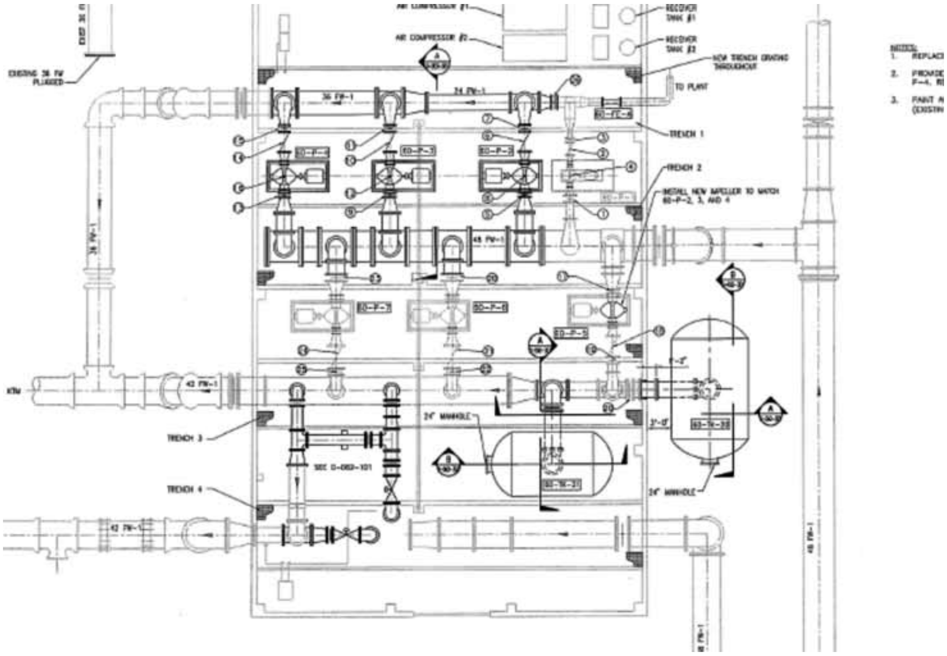

Figure 6. Recommended Surge Protections for the North and South System During the Design Phase

Design of Surge Protection Systems

Although modeling results provide a good guidance to designers on the selection of surge control devices, the indicated selections and sizes of devices may be impractical to construct. As a result, during the design phase, sound engineering judgment is needed.

A document provided by a manufacturer of surge tanks shows that pipe systems will be tested and qualified in terms of their ability to withstand a certain "negative pressure." If there is no further explanation, it means that it is an atmospheric test: atmospheric pressure air outside the pipe, with cyclical pressure drop inside. In practice, pipes are usually buried, and the external pressure is different from atmospheric pressure. The North Regional Transmission Main is a 42-in. steel pipe with a 3/16-in. wall thickness. The theoretical design standard to prevent buckling of this pipe is a negative pressure of -5 psi. For selection of the surge control system, a design goal of -2 psi is used, with a safety factor of 2.5.

To do this, use of hydropneumatic tanks could be avoided by considering that the existing 42-in. transmission has roughly one 6-in. air valve every half mi and adding one 18-in. pump bypass line. The results indicate that the pressure in the pipeline will not fall below –2 psi (-

4.62 ft) if 6-in. fast-acting air valves are installed every mi (not even every half mi). The modeling results are shown in Figure 5.

After evaluation of the surge simulation results, the recommended surge protections for the NRHSPS are: 1) add four 6-in. quick-response combination air valves at four pump discharge lines, 2) upgrade the combination air valve next to the flow meters to a 6-in. air valve, 3) use pump control valves instead of regular weighted check valves, 4) add one 18-in. surge anticipation and relief valve, and 5) add a 18-in. pump bypass line.

For the South System, the recommended surge protections are: 1) add five 6-in. quick response combination air valves at pump discharge lines, 2) upgrade the air valves next to the flow meters to 6-in. combination air valves, 3) use pump control valves instead of regular weighted check valves, 4) add one 18-in. surge relief valve, 5) add a 18-in. pump bypass line, and 6) use two hydropneumatic tanks at Node 116 at the pump discharge manifold, with a total volume of 2500 ft^3.

For the River Pumping Station, the recommended surge protections are: 1) add 6-in. quick-response combination air valve at pump discharge line, 2) add or replace the 6-in. combination air valves next to where the flow meter is, at the local high point, 3) use pump control valves instead of regular weighted check valves, and 4) add one 24-in. surge anticipation and relief valve to release high-pressure backflow water to the Peace River.

For the Recycle Pumping Station, the recommended surge protections are: 1) add 6-in. quick-response combination air valve at pump discharge line, 2) add or replace the 6-in. air combination valves next to where the flow meter is, at the local high point, 3) use pump control valves instead of regular weighted check valves, and 4) add one 18-in. surge anticipation and relief valve to release high-pressure backflow water to the wet well.

Construction of Surge Protection Systems

The last phase of implementation is the construction phase, where various details and needs to coordinate with related construction will become apparent. Therefore, it is not uncommon that some engineering designs may need to be re-evaluated and revised based on field conditions and other factors, such as unavailability or unreliability of specified or alternative equipment. Based on final adjustment or constraints on equipment, the surge analysis may need to be updated to reevaluate the new conditions and verify that the finalized surge protections can meet the designated requirements.

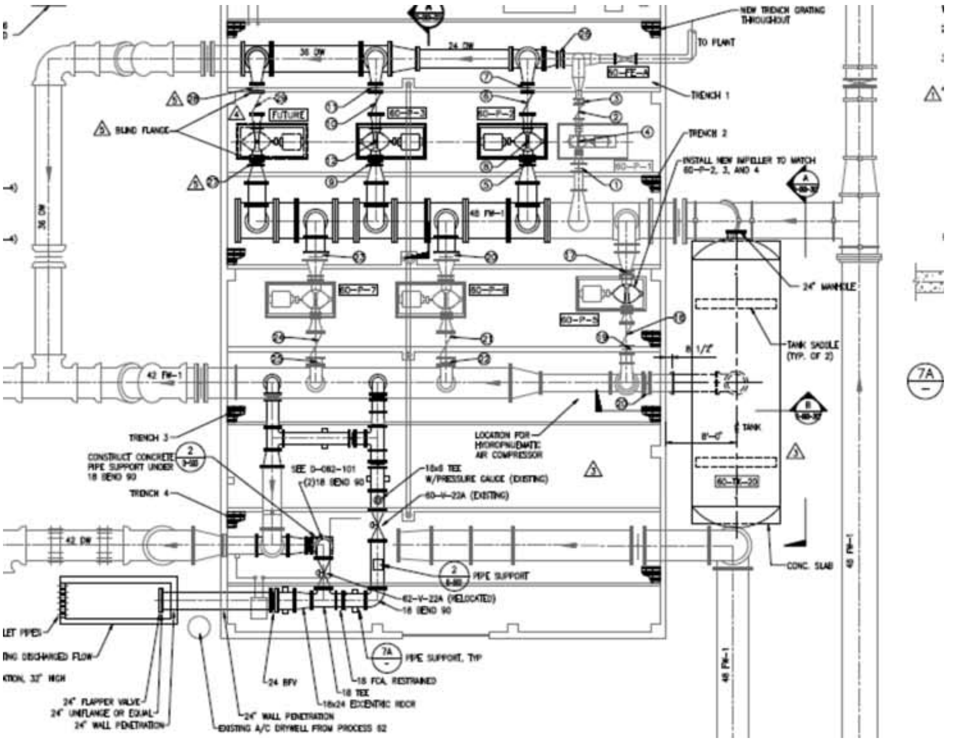

Figure 7. Recommended Surge Protections for the North and South System During the Construction Phase

Two major changes occurred during the construction phase:

- It was decided to interconnect the North and South system discharge piping to function as one system to improve reliability and provide backup systems. This change was made in consideration of existing piping, system reliability, compatibility of North and South system operating pressures, common ground storage tanks, and proximity.
- Due to indoor space limitation and construction feasibility, the two indoor smaller hydropneumatic tanks established in the design phase were revised to one large tank and moved out to the closest location outside the pump building.

The revised configuration was re-evaluated and confirmed by the modeling results.

Other minor changes are mainly to originally specified equipment:

- The surge valve manufacturer was changed during value engineering. These surge valves require positive pressurized water source to close the valves.
- The hydropneumatic tank was changed from a bladder to nonbladder tank using an air compressor due to vender experience and cost concerns.

Figures 6 and 7 compare the as-designed versus as-constructed configuration of the North and South pumping system.

Conclusions

Commonly used surge control strategies were presented, including: 1) redesign of the plan and profile of the pumping station and pipeline system, 2) selection of pipes and fittings to withstand the anticipated pressures, 3) identification of proper start-up, operation, and shutdown procedures for the system, and 4) selection and location of the proper control devices to mitigate the adverse effects of surge events. The advantages and disadvantages of the control devices, such as hydropneumatic tanks, air valves, surge valves, and pump control valves, were also discussed.

To complete the surge protection systems, typical engineering projects have three phases: modeling, design, and construction. During the modeling phase, the surge problems are identified by the surge modeling programs and several alternatives are evaluated and recommended based on the modeling results. To avoid overdependence on "black box" software, independent analyses using three differ-

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ent programs were conducted to verify the simulation results.

Although modeling results provide a good guidance of selecting a surge control device and strategy, it is sometimes impractical to apply all of these methods. As a result, during the design phase, sound engineering judgment is needed to finalize design details.

The last phase is the construction phase, where various details and the need to coordinate with related construction will become apparent. Therefore, it is not uncommon that the design details will need to be re-evaluated and revised based on field conditions and other factors, such as unavailability or unreliability of specified or alternative equipment. The surge analysis might be needed to re-evaluate the new conditions and confirm that the revised surge protections can meet the designated requirements.

To illustrate why and how the surge protection systems changed during these three phases, the 51-mgd Regional Peace River Water Treatment Facility expansion project was presented. Obviously, the pipelines and pumping systems serving public water supplies are critical and no failures are acceptable; plus, effectiveness of surge control cannot be tested. Therefore, reliable surge analysis and protection system are needed and redundant surge control systems are also recommended. The final surge protection systems as constructed include hydropneumatic tanks, bypass valves, surge valves, air valves, etc., as well as operations and maintenance guidelines. The final simulation results indicate that the surge control strategies will provide adequate surge protections to various pumping systems and large-capacity transmission mains.

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