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**WATER HAMMER AND COLUMN SEPARATION DUE TO ACCIDENTAL
SIMULTANEOUS CLOSURE OF CONTROL VALVES IN A LARGE SCALE TWO-
PHASE FLOW EXPERIMENTAL TEST RIG**

Anton Bergant
Litostroj Power d.o.o.
Ljubljana, Slovenia

Jos M.C. van 't Westende
Deltares
Delft, The Netherlands

Tiit Koppel
Tallinn University of Technology
Tallinn, Estonia

Janez Gale
Litostroj Power d.o.o.
Ljubljana, Slovenia

Qingzhi Hou
TU Eindhoven
Eindhoven, The Netherlands

Zoltan Pandula
TU Budapest
Budapest, Hungary

Arris S. Tijsseling
TU Eindhoven
Eindhoven, The Netherlands

ABSTRACT

A large-scale pipeline test rig at Deltares, Delft, The Netherlands has been used for filling and emptying experiments. Tests have been conducted in a horizontal 250 mm diameter PVC pipe of 258 m length with control valves at the downstream and upstream ends. This paper investigates the accidental simultaneous closure of two automatic control valves during initial testing of the test rig. The simultaneous closure of both valves has induced upsurge and downsurge at the same time. Large water hammer and column separation have caused failure of pipe supports and leakage at pipe joints. The incident was caused by a fault in an electronic conversion box due to power failure. Afterwards the downstream end automatic valve has been modified to a manually operated valve to avoid the accidental simultaneous closure of the valves. The accidental transient event has been fully recorded with pressures, flow rates and water levels. The measurements of the accident are presented, analyzed and discussed in detail. Photographs show the damages to the system.

Keywords: pipeline test rig, water hammer, column separation, fluid-structure interaction, accident

INTRODUCTION

Filling and emptying of pipelines is common in many hydraulic applications, such as water distribution, hydropower, sewage and cooling, conveyance of storm-water flows during intense rainfall, fire fighting systems and oil transport through long pipelines. Rapid filling and emptying of the piping system may be considered as a specific case in which both vaporous and gaseous cavities may be present. During filling or drainage part of the pipeline is filled with liquid and part of it is filled with gas (or vapour), while in between the pipeline is filled with a mixture of both. Undesired transients may occur and lead to pipe rupture due to overpressures, pipe collapse due to vacuum conditions, and entrapped gas pockets preventing complete filling or drainage. Design engineers should be able to predict fluid transient events in systems and take measures to keep transient loads within the prescribed limits. The modelling of filling and emptying of piping systems is a relatively complex task and different pipe configurations with many types of initial and boundary conditions may lead to a wide variety of solutions [1-6]. Developers and users of computational codes need full-scale data with which to compare their theoretical models. Unfortunately such data are limited and available only for special cases [3-4, 7].

Here, a large-scale pipeline test rig at Deltares, Delft, The Netherlands has been used for filling and emptying experiments [8]. Previously the test rig had been designed and used for classical two-phase flow experiments. Pipeline filling and emptying experiments have been conducted in a modified horizontal 250 mm diameter PVC pipe of 258 m length with control valves at the downstream and upstream ends. This paper investigates the accidental simultaneous closure of two automatic control butterfly-type valves during initial testing of the test rig. Luckily the accidental transient event has been fully

recorded including measurements of pressures along the PVC pipe test section and flow rates in the system, and photographs show the damages to the pipeline test rig. The automatic control valve signals, flow rates at the downstream and upstream ends of the test PVC pipe section, and pressures at six locations along the test section during the accident are presented, analyzed and discussed in detail. Modifications to the test rig are presented and lessons learned from the accidental event are addressed.

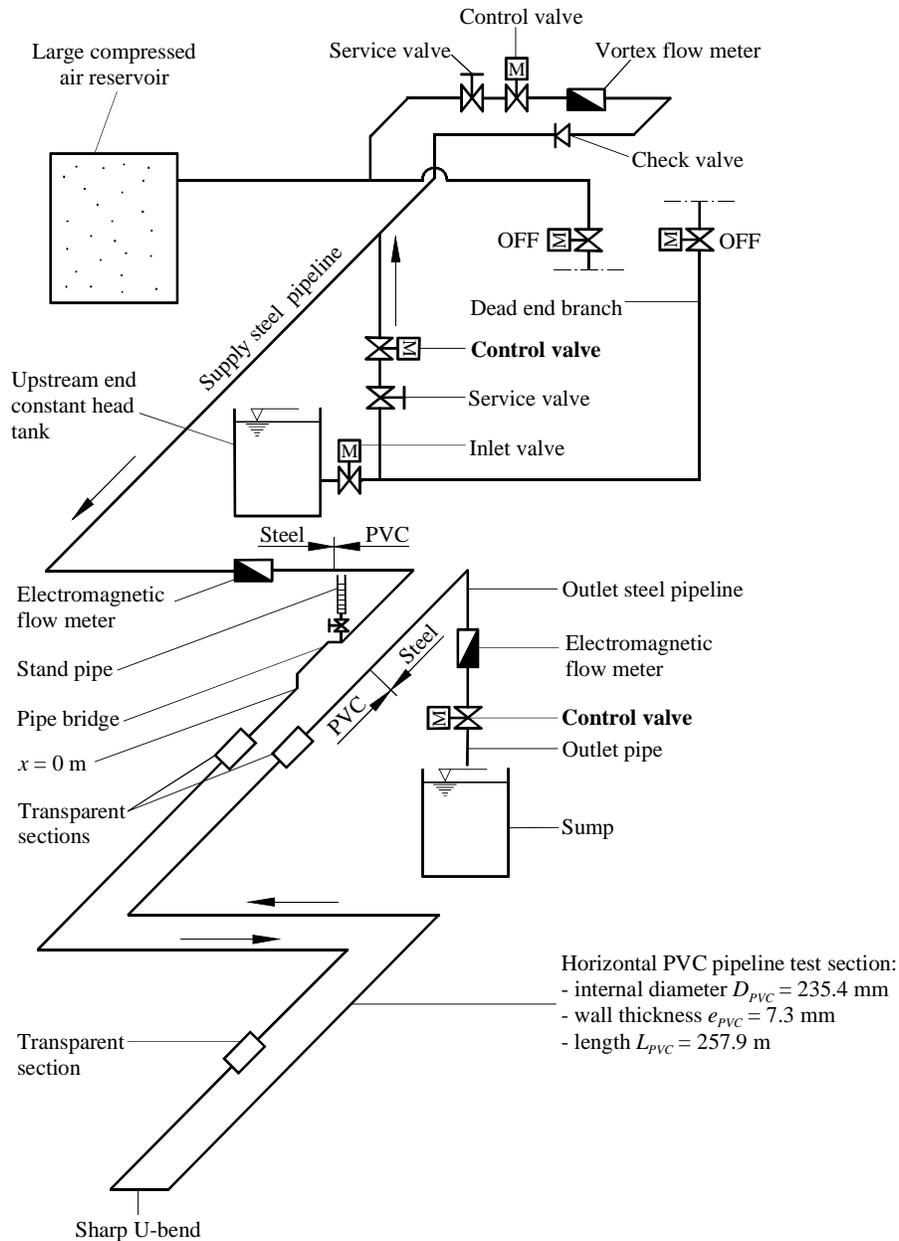


Figure 1: Dynamic two-phase flow test rig at Deltares, The Netherlands.

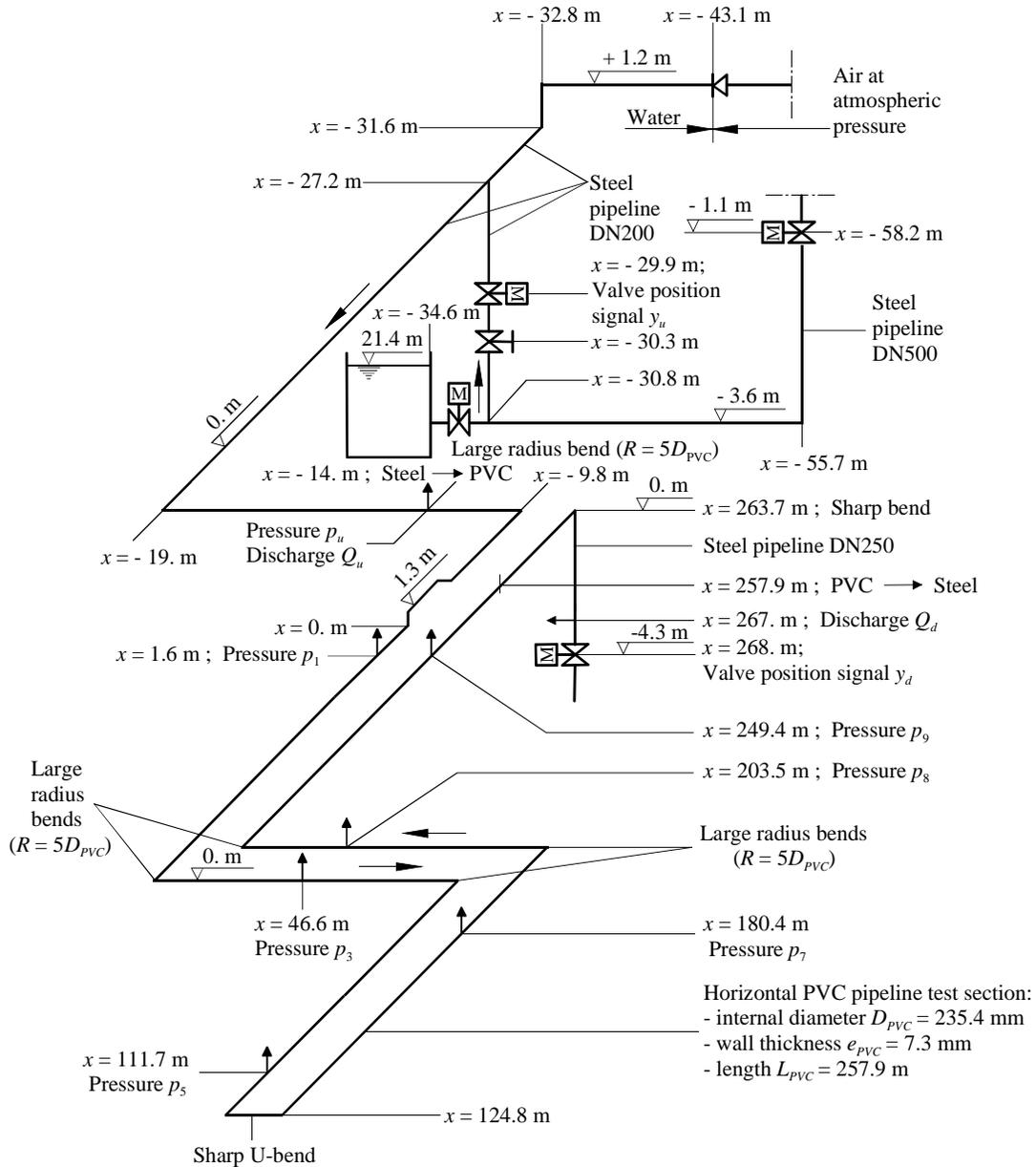


Figure 2: Layout of dynamic instruments in water supply steel pipe system and PVC pipe test section for influential quantities during accidental event.

TEST RIG

The dynamic two-phase flow test rig at Deltares, Delft, The Netherlands has been used for pipeline filling and emptying experiments. Due to the limited capacities of water tank and compressed-air reservoir the original industrial size 250 mm nominal diameter horizontal PVC pipeline test section was shortened from 600 m to 258 m. The water was supplied from a 25 m constant head tank through a supply steel pipeline and PVC pipe bridge to the PVC pipe test section (see Fig. 1). The compressed-air reservoir (volume of about 70 m^3) provided the

air plug for a controlled rapid emptying of the test section. This section describes the layout of the test rig during the commissioning period in which the accident happened. During trial and error tests the liquid flow in the system was regulated by automatically operated control valves at the upstream-end constant-head tank and at the outlet of the PVC pipe test section. The modified layout after the accident will be described later on.

The water-supply steel pipeline comprised inlet and service valves, an automatically operated DN150 butterfly valve, steel

pipe sections (of 200 mm nominal diameter), and electromagnetic flow meter connected to the PVC supply pipe at its downstream end. The stand pipe and the pipe bridge served for a better control of the inflow conditions. The horizontal PVC pipe test section consisted of straight pipes, four large diameter bends (of radius $5 \times D_{PVC}$, where D_{PVC} = PVC pipe nominal diameter), one sharp U-bend and three transparent sections used for flow visualization. It should be noted that due to space and time limitations the sharp U-bend was mounted to connect the shortened (from 600 m to 258 m) PVC pipeline. Because the experiments were planned without any anticipated large water hammer events, the sharp U-bend was acceptable. The bend was clamped with two metal supports which partially (friction) allowed axial movement and five metal axial restraints (small steel columns) which prevented movement in horizontal direction. The restraints were calculated to be sufficient for the planned experiments. The PVC pipeline outlet was connected to a 250 nominal diameter steel pipeline that diverted water into the sump. The outlet steel pipeline comprised horizontal and vertical sections, electromagnetic flow meter and an automatically-operated DN150 butterfly valve. The compressed-air supply piping system consisted of 300 mm nominal diameter steel pipe sections, service and control valves, vortex flow meter and an undamped swing-type check valve that prevented backflow of water into the air supply line.

INSTRUMENTATION

The instruments used in the pipeline emptying and filling measurements have been carefully selected (accuracy, frequency response) and calibrated prior to and after the dynamic measurements. The sampling frequency for each continuously measured quantity during the trial and error tests was $f_s = 20$ Hz. The following quantities were recorded continuously during the commissioning period:

- valve-position signals to automatically operated control valves at the upstream-end constant-head tank and at the outlet of the PVC pipe test section, and to a control valve in the air supply line (for the upstream valve the voltage supplied by the computer was recorded; for the downstream valve the current to the valve was recorded)
- air pressure in the large compressed-air reservoir and at the control valve
- air temperature at the control valve
- water pressure at the electromagnetic flow meter at the upstream end of the PVC test section
- water pressures along the PVC pipe test section (at inlet; at app. 1/5, 2/5, 7/10 and 3/4 of the PVC pipe length measured from the inlet; at outlet)
- water temperatures along the PVC pipe test section (at inlet; at app. 1/5 of the PVC pipe length; at outlet)
- air flow rate (vortex flow meter in the compressed-air supply line)
- water flow rates (2 electromagnetic flow meters: at inlet and at outlet of the PVC pipe test section)

- void fractions (more accurately: detection of the presence of water) along the PVC pipe test section (at inlet; at app. 1/2 of the PVC pipe length; at outlet)

- water levels along the PVC pipe test section (at inlet; at app. 1/5, 2/5, 7/10 and 3/4 of the PVC pipe length; at outlet)

The accident occurred during steady flow trial and error tests by unintentional closure of the automatically operated control valves at the upstream-end constant-head tank and at the outlet of the PVC pipe test section (see Fig. 1). It has been found afterwards that void fraction and water level remained nearly constant during the accidental event (no void, pipe full of water) and these will not be considered in this paper. The air supply line was at atmospheric pressure during the accident. The quantities that significantly changed were the automatically operated butterfly valve position signals, water pressures and water flow rates. The layout of the instruments that recorded these dynamic quantities is depicted in Fig. 2.

Water pressures were measured by strain-gauge type absolute-pressure transducers ($U_x = \pm 0.3\%$). The uncertainty in a measurement U_x is expressed as a root-sum-square combination of bias and precision error [9]. The uncertainty in the measured water flow rates was $U_x = \pm 2\%$.

ACCIDENTAL CLOSURE OF CONTROL VALVES

Before the accident

The experiments in the test rig had been ongoing for four working days when the accident occurred. At the end of the third working day, after successful completion of the first series of pipeline filling experiments, it was decided to equip the motorized upstream butterfly control valve with an automatic pressure-control function. This computer-supported function with input from the upstream pressure transducer was available at that time but not yet in operation. By inclusion of this function the research group would benefit from the very nice option to put a constant pressure set-point as upstream boundary condition. This was one of the important parameters for the planned second series of pipe emptying experiments.

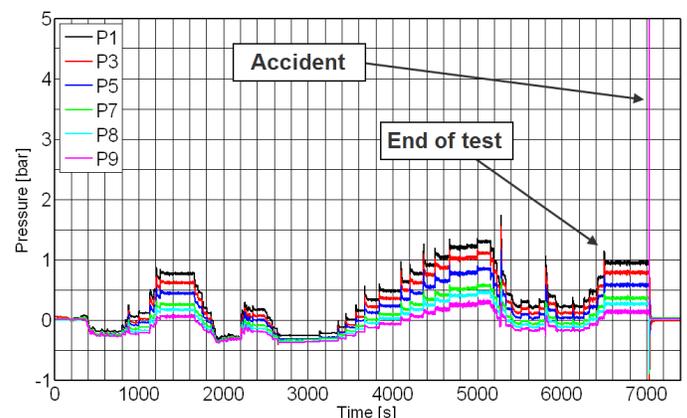


Figure 3: Pressure history at different positions along the PVC pipeline during testing and accident.

The performance of the newly installed upstream-end automatic pressure-control valve needed to be tested. For this reason the researchers started with gradually changing the pressure set-point on the control panel (up and down) thereby waiting for the initiated transient to damp out into steady state flow in the PVC pipeline (Figure 3). At all times during the testing the group focused on stability and reliability of the automatic upstream-valve performance. Because the experimental test rig was designed for two-phase flow experiments, and not for water hammer tests, the pressure jumps during all tests were moderate and there was no speak of any significant pressure surge (Fig. 3). As the pressure set-point testing was not part of the experimental programme, the

sampling rate was reduced to 20 Hz, which was sufficient for its purpose, and - as it turned out later - it was just high enough to catch the unintentional water-hammer accident. It turned out that the performance of the upstream-end automatic control-valve was reliable and stable. The testing successfully ended after 6500 seconds and then the team members were gathered in the control room to discuss new settings for the second series of experimental measurements (all authors were present except the last co-author). The second series concerned controlled emptying of the PVC pipeline; therefore, the flow rate through the piping system of about 145 litres per second was maintained and not interrupted. Figure 3 indicates that the accident happened approximately after 7000 seconds of testing.

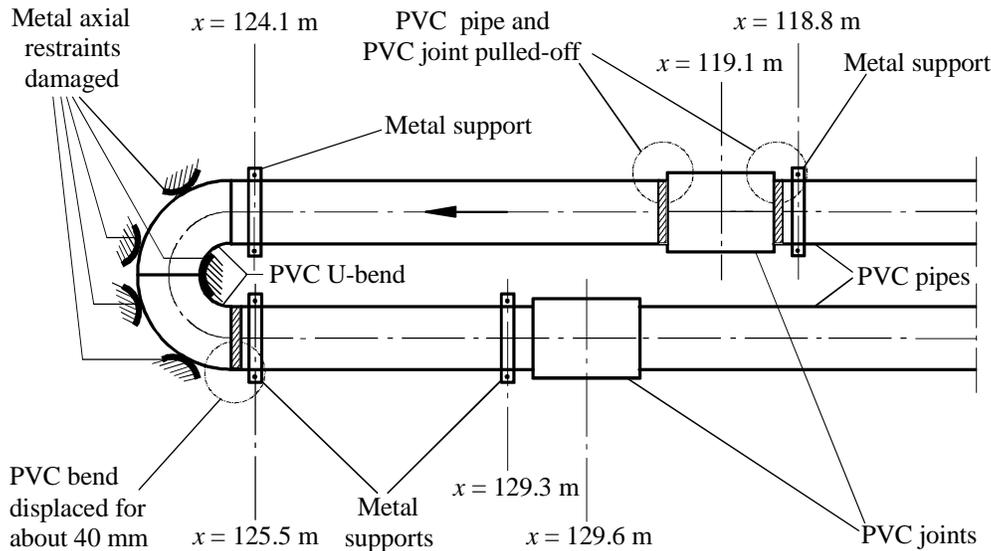


Figure 4: Overview of damages at the sharp U-bend of the PVC pipeline test section.



a) Damaged PVC pipe joint at distance $x = 119.1$ m.



b) Damaged PVC U-bend at distance $x = 125.5$ m.

Figure 5: Damages at the sharp U- bend of the PVC pipeline test section.

The accident event and its consequences

As stated, the validation of the automatic control-valve took almost two hours, the performance of the upstream-end automatic valve was satisfactory, the flow rate in the system was constant, and the team was discussing about how to start with a new series of experiments when the accident happened. At a certain moment the team heard a loud noise, but, at the first instant, it was not clear what was going on. The complete pipeline was over 300 metres long and only a small part of the pipeline was under visual inspection of the control room. The recordings appearing on the display (in the control room) were a little unclear as they showed that the upstream automatic control-valve was fully opened and the downstream-end valve signal was somehow instantaneously interrupted. However, the measurements clearly showed that the upstream and downstream discharges were decreasing to zero and this was an indication that simultaneous closure of the two automatic-control butterfly type valves could have occurred. The team members went out of the control room for visual inspection of the piping system. Then they realized that an accident had happened, and an immediate decision was taken to manually close the upstream service valve (Fig. 1). An inspection of the piping system showed leakages (one very large) and damages on the piping system at two distinct locations: (1) at the sharp

U-bend ($x \sim 125$ metres; see Figs. 4 and 5) and (2) at the outlet side of the horizontal PVC pipeline test section ($x \sim 260$ metres; see Figs. 6 and 7).

(1) *Description of damages at the sharp U-bend (Figs. 4 and 5):* The U-bend was clamped with two metal supports at $x = 124.1$ m and $x = 125.5$ m and five metal axial restraints (steel hollow cylinders bolted to the concrete floor) which prevented movement in horizontal direction. During the accident, the forces on the supports were so large that four metal axial restraints were pushed away while the fifth axial restraint got entirely loose and fell away from the U-bend (screws were cut-off at the floor plane). Photograph Fig. 5b shows a damaged metal axial restraint (bolting screws were partly pulled-out and the steel column was inclined). The downstream joint of the PVC U-bend at $x = 125.2$ m displaced for about 40 mm and a small leakage was observed here. The axial movement of the U-bend resulted also in the partial opening of the PVC pipe in the joint at the distance $x = 119.1$ m (Fig. 5a). This was possible because the metal support at 124.1 m enabled axial displacement of the PVC pipe for 35 mm. However, no leakage was detected at this joint. No visible damages were detected at the metal supports (brackets) at $x = 118.8$ m and upstream, and at the metal supports at $x = 125.5$ m and downstream.

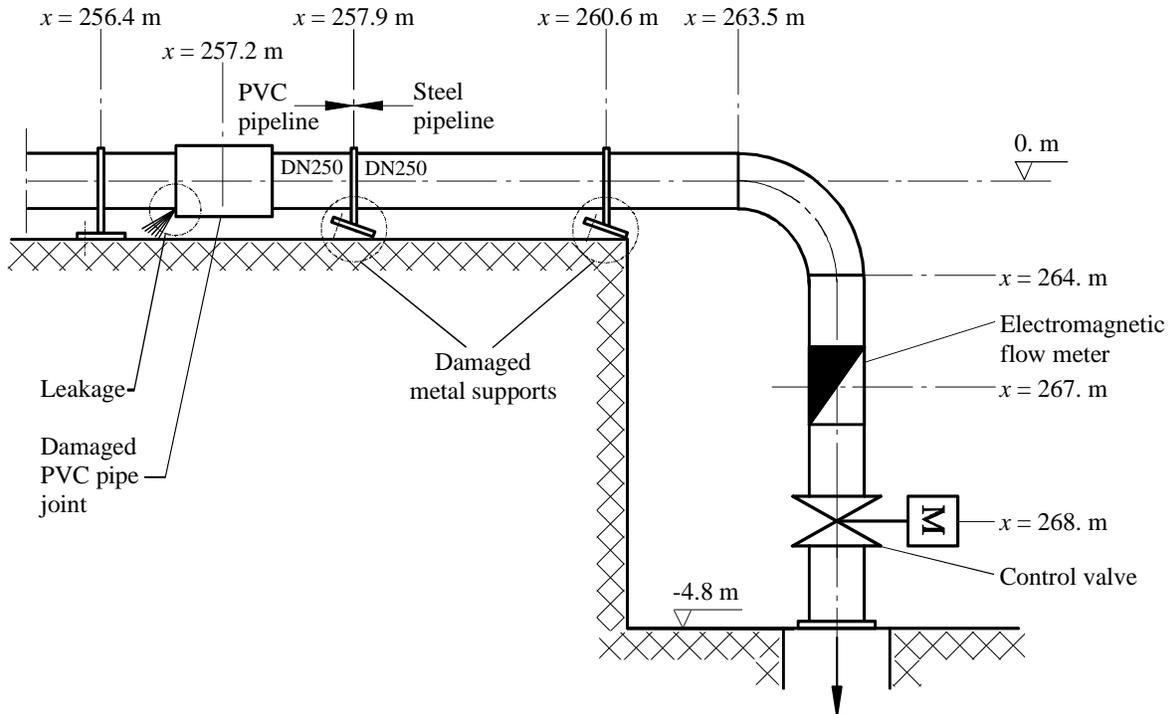


Figure 6: Overview of damages at the outlet of the horizontal PVC pipeline test section.



a) Leakage from damaged PVC pipe joint at distance $x = 257.2$ m.

b) Damaged metal anchor at distance $x = 260.6$ m.

Figure 7: Damages at the outlet side of the horizontal PVC pipeline test section.

(2) *Description of damages at the outlet side of the horizontal PVC pipeline test section (Figs. 6 and 7):* The PVC pipeline was located on the balcony of the laboratory (first floor) and a steel pipe section with sharp downward 90° elbow was used to divert water into the sump (ground floor). The connection between PVC and steel pipeline was at $x = 257.9$ m, and the downward elbow was at position $x = 263.5$ m. The vertical part of the steel pipeline was supported by a steel structure and was free to move in the horizontal plane and in vertical direction (up). The horizontal part of the steel pipeline was clamped with two metal supports at $x = 257.9$ m and $x = 260.6$ m. When the pressure upsurge was travelling through the downward elbow, the steel pipeline was lifted-up and away from the PVC pipeline. The steel pipe itself was undamaged but the metal supports were deformed as it is evident from Figs. 6 and 7. Figure 7 shows that some of the bolts anchoring the metal supports (brackets at $x = 257.9$ m and $x = 260.6$ m) to the concrete floor were damaged. Then the PVC pipe joint at $x = 257.2$ m opened and a large water leakage occurred (Fig. 7a). The pipeline upstream of the undamaged metal support at $x = 256.4$ m was left intact up to the metal support at $x = 125.5$ m (Fig. 4). No damages were detected at the electromagnetic flow meter and the control valve.

Brief analysis of the event was made at the spot confirming that the accidental simultaneous closure of two automatic-control butterfly-type valves had happened. It was found that the incident had been caused by a fault in an electronic conversion box due to power failure. Afterwards the downstream-end automatic valve was modified to a manually operated valve so to avoid a further unintentional simultaneous closure of the valves. The damaged piping system was repaired the very same day and the decision to continue with the experimental programme was accepted. The next morning, on

the fifth working day, the pipeline test rig was in operation again and the group was able to proceed with the planned experiments.

Analysis of the accident

Before the accident, the DN150 upstream-end automatic valve was opened 75% and the DN150 downstream-end automatic valve was opened 100% and these settings corresponded to an initial flow rate in the piping system of $Q = 0.145$ m³/s with an upstream gauge pressure of $p_u = 1.01$ bar. Figure 8 shows the position signals y of the automatically operated control valves together with the upstream and downstream flow rates Q during the accidental event. The position signals were wired from computer via a volt-current converter to the control-valve actuators. The position signal of the downstream control valve y_d was set to a constant value (full opening) whereas the position signal of the upstream control valve y_u was controlled by computer in order to maintain a desired upstream pressure p_u set-point. The observed signals in Fig. 8a were taken as follows: (1) y_u was captured between the computer and volt-current converter and (2) y_d was captured between the volt-current converter and the valve actuator. A sudden drop of the signal y_d to -25% occurred at a test time of about 7030.2 seconds (see Fig. 8a). Because both control valves were wired to the same volt-current converter this time can be considered as the time at which the control valves started to close. However, the position signal y_u of the upstream control valve shows adjustment of the valve opening to its maximal opening at a time of about 7033 seconds (see Fig. 8a). This difference is because the position signal y_u was taken in between the computer and the volt-current converter.

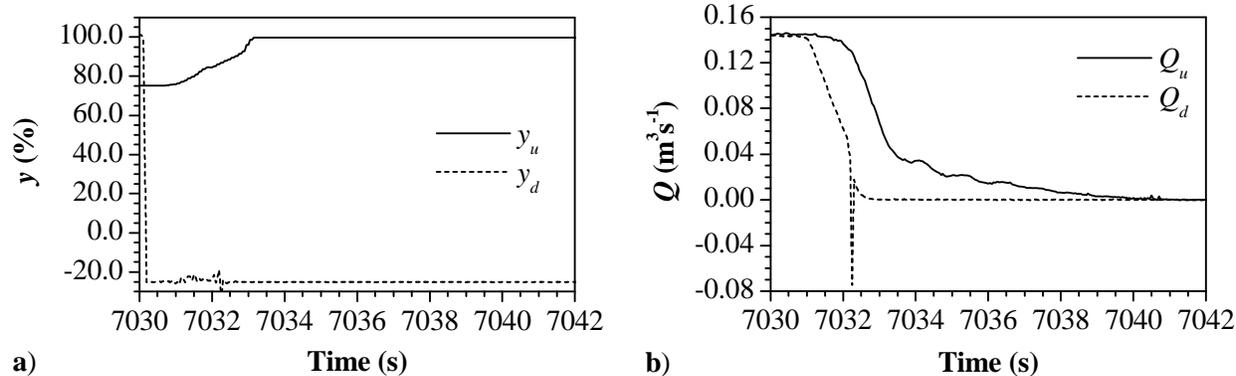


Figure 8: Automatically-operated control valve position signals (y) and water flow rates (Q) during the accidental event.

The consequent change of upstream and downstream flow rates is even more peculiar (Fig. 8b). The downstream flow meter detects the first change of Q_d at time of 7030.7 seconds and the flow is stopped at time of 7033 seconds. The upstream flow meter detects the first change of Q_u at the time of 7031.5 seconds and the flow is stopped at the time of 7041 seconds. The different timing of flow changes may be attributed to different responses of the valve actuators to the accidental loss of the signal and to different flow conditions (boundary conditions). It should be noted that the distance between the upstream control valve and the upstream flow meter was about 16 metres with a pipe branch in between, whereas the distance between the downstream control valve and the downstream flow meter was only one metre (Figs. 1 and 2).

Figure 9 shows pressure histories at different positions along the PVC pipeline. From these graphs one can deduce that there were two major pressure waves in the accident: the pressure upsurge that was travelling in the upstream direction from the control valve at the outlet of the pipeline and the pressure downsurge that was travelling in the downstream direction from the control valve at the upstream end tank. Based on these recordings one may conclude that such pressures are possible only if both valves were closed almost simultaneously. The pressure upsurge travelling upstream caused damage to the piping system at various locations. Upsurge and downsurge were superimposed when they met and this is evident from the figures. Figures 9a to 9c show that pressure peak was cut-off at 5 bar. This is because experiments with expected maximal pressures well below 5 bar were performed (the set maximum for the recorded pressure signal). Extrapolation of the gradient of the rising and dropping pressure gives a rough estimate of the maximal pressure p_0 close to the outlet of the PVC pipe of about 7.5 bar (Fig. 2); however, the Joukowsky pressure rise [10] in the PVC pipeline based on the initial flow rate would be approximately 10 bar. The difference between estimated actual maximal pressure and the rough theoretical estimation is attributed to the large deformations and leakages and not to viscoelastic damping. It is worth to mention here that the PVC part of the experimental test rig was designed to withstand a

maximal pressure of 7.5 bar. Figures 9d and 9e indicate intense transient vaporous cavitation zones along an extended length of the PVC pipeline.

We may conclude that the incident was caused by a fault in an electronic conversion box due to power failure and this led to the actual closure of both automatic control valves as it is clear from the flow rate (Fig. 8b) and pressure traces (Fig. 9). The short power failure damaged the volt-current converter which sent signals to the valve actuators. Both valve actuators were motorized and 1 mA converter output corresponded to closed positions of the valves (the current converter box should always supply a current in the range 1 mA to 5 mA). Immediately after the accident a technician measured an output at the converter of 0 mA, indicating that the current converter box had broken down. This confirmed that in the case of loss of signal the valves close.

CONCLUSIONS

A large-scale pipeline test rig at Deltares, Delft, The Netherlands has been used for filling and emptying experiments. The test rig is a horizontal 250 mm diameter PVC pipe of 258 m length with control valves at its downstream and upstream ends. An accidental simultaneous closure of two automatic-control butterfly-type valves occurred during initial testing of the test rig. Fortunately, the unintentional transient event has been fully recorded including measurements of pressures along the PVC pipe test section, flow rates and valve positions. Photographs of damages to the pipeline tell their own story. The accidental closure of both control valves induced a large upsurge at the downstream end and a downsurge at the upstream end. The large pressure rise due to the closure of the downstream-end control valve caused failure of pipe supports and leakage at pipe joints. The incident was caused by a fault in an electronic conversion box due to power failure. Afterwards the downstream-end automatic valve has been modified to a manually operated valve so to avoid future accidental simultaneous closures of valves.

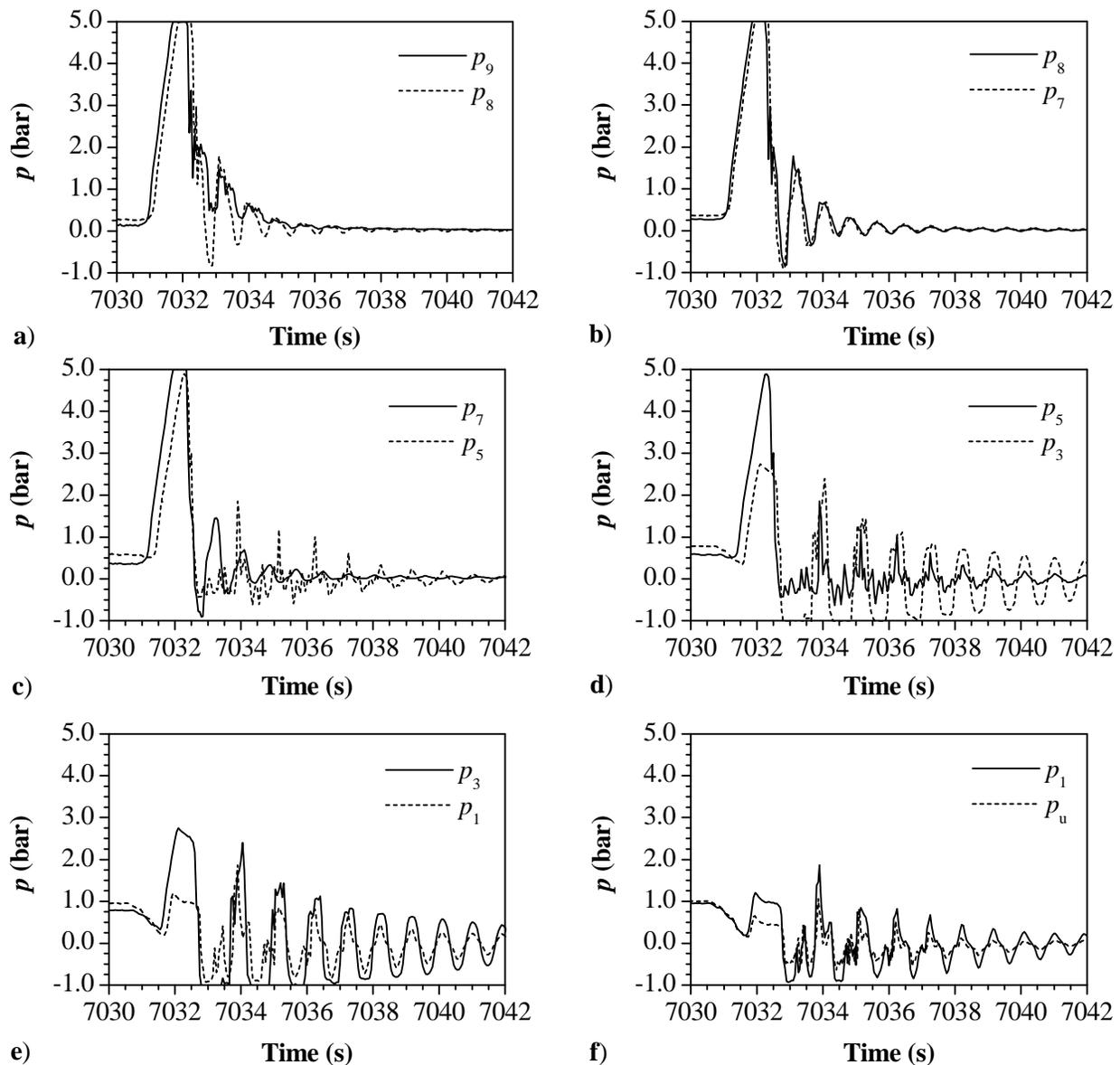


Figure 9: Gauge pressures in water pipeline during the accidental event.

What do we learn from the accident?

- 1) Even under controlled laboratory circumstances accidents may happen (here: power failure and consequent closure of two automatic control valves).
- 2) Large axial pipe motion can damage the pipe joints.
- 3) In the case of a water hammer accident it is virtually impossible to anchor pipes and bends sufficiently rigid.
- 4) PVC pipes themselves can withstand high transient pressures, but the joints will fail.
- 5) Full records of accidents (i.e. measured data, photographic records and many witnesses) are rare and reported here as an illustration to pipeline engineers.
- 6) Assessment of the maximum anchor forces from the measured pressure histories (not presented in this paper).
- 7) Assessment of the strength of PVC pipes and joints (not presented in this paper).

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NOMENCLATURE

D	=	pipe diameter
e	=	pipe wall thickness
f_s	=	sampling frequency
L	=	length
p	=	pressure
Q	=	discharge (flow rate)
R	=	radius
U_x	=	uncertainty in a measurement
x	=	axial distance
y	=	valve position signal

Subscripts

d	=	downstream end
PVC	=	PVC pipeline
S	=	steel pipeline
u	=	upstream end

Abbreviations

DN	=	nominal diameter
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