Journal of Water Supply: Research and Technology—AQUA | 59.1 | 2010

Water supply operation: diagnosis and reliability analysis in a Lisbon pumping system

A. B. Almeida and H. M. Ramos

ABSTRACT

An abnormal accident with no flow in a pumping system occurred with a large displacement of the pipe system. A slow closure of an isolation valve installed in a large suction pipe was the main action. As soon as the valve was closed the 1.6 m diameter pipe moved and the pipe supports were broken, presenting an expansion joint almost fully opened and the main pipe almost broken. This was a critical event that took place in one of the most important pumping stations of the water supply system in Lisbon. In order to avoid future accidents, a detailed analysis was developed as a priority in order to identify the cause of this event. The paper describes the event and the methodology followed in order to fully validate the diagnostic and the proposed chain of events that caused the pipe movement. The process included a careful, *in situ* observation of the system, hydraulic and structural analyses and some site tests. Ironically, the explanation of abnormal events can give the opportunity to better understand the operation of water supply systems. Weak points in the design and in the operation can then be detected and future accidents can also be avoided.

Key words | accidents, corrosion fatigue, hydraulic and structural analysis, pumping system, reliability and safety

A. B. Almeida
H. M. Ramos (corresponding author)
Department of Civil Engineering,
Instituto Superior Técnico (IST),
Technical University of Lisbon (UTL),
Av. Rovisco Pais,
1049-001, Lisbon,
Portugal
E-mail: *hr@civil.ist.utl.pt*

INTRODUCTION

Several components of pressurized pipe systems have to be considered in the modelling of fluid–structure behaviour. The residual structural capacity of water mains can be affected by material deterioration due to environmental and operational conditions, as well as the quality of manufacturing and the type of installation. Fluid transients and vibrations produce the highest pressures in the waterways and associated conduits. They cause critical stresses in the overall hydraulic and mechanical structures and therefore cannot be neglected during the design and exploration stage of each system project. This aspect is independent of the size of the pipes or of the hydromechanic equipment and it is thus recommended for all types of pipe system installation.

Safety and system operation are increasingly important factors to ensure reliable functioning, as well as social and environmental risk minimization. As a result of corrosion cracking, abnormal catastrophic failures can occur induced by unbalanced forces.

Extensive use of numerical simulation for the performance of hydraulic system behaviour occurs nowadays, but can result in a shortage of qualified specialists and engineers (Maricic & Pejovic 2007).

Most of the time, solutions for new installations are well known but the origins or causes of accidents or failures are forgotten or even omitted. Accidents are always a problem for everyone directly involved but they can be very important as a way to provide non-conventional information and a way to identify our lack of knowledge and an incentive to develop new research areas. In fact, a significant part of our technical knowledge is based on errors. Some examples of post-accidents studies are presented in Almeida & Pinto (1986), Almeida (1992) and Almeida & Koelle (1992).

doi: 10.2166/aqua.2010.051

The present paper describes an abnormal accident that occurred in a main water supply pumping system in Lisbon (Portugal), inducing large pipe displacements and putting the installation out of service for repair. This severe accident presented many unexpected characteristics and a systematic research procedure was developed in order to find the causes in order to avoid another similar failure.

BASIC TOOLS OF ANALYSIS

Hydraulic and structural models

The traditional design of pipe systems has been based on guidelines that attempt to provide strength capacity to the system components against expected loads (due to both operational and environmental factors) with a sufficient degree of security.

Any hydraulic system needs to perform complex tasks demanding specific studies and requiring meticulous operation and control procedures. In order to achieve reliable operation of the system, the project needs to be well coordinated and take into consideration several details and possible failure scenarios. Hence, when only a few of these details are overlooked, under-estimated or improperly linked to each other, an increased failure risk can quickly arise (Karney *et al.* 2003).

Up to now, complete software tools rarely take into account all the important parameters or factors that can significantly influence the system response. While in some cases these factors can be neglected, with no loss of significant accuracy, under certain circumstances the error can be unacceptable. Fluids-induced pressure variations along a hydraulic system are a basic design and safety evaluation topic that should not be forgotten.

Waterhammer models have been widely used for prediction of extreme fluid pressure and in the definition of safety and operational rules in order to avoid accidents due to normal or abnormal operations or scenarios. Any disturbance induced in the flow or in the structural boundary is propagated with a wave speed that will strongly influence the dynamic response of the pipeline. Pressure transients in pipe systems are usually described by the well-known fluid conservation equations: the continuity and momentum equations. The basic differential equations of fixed pipes and unsteady pressurized flows can be written as a hyperbolic system of equations (Chaudhry 1987; Wylie & Streeter 1993; Ramos 1995) which can be presented in matrix form as follows (Ramos 1995):

$$\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} = D(U) \qquad (1)$$

yielding the following vectors:

$$U = \begin{bmatrix} H \\ Q \end{bmatrix} \quad F(U) = \begin{bmatrix} \frac{c^2}{gA} Q \\ gAH \end{bmatrix} \quad D(U) = \begin{bmatrix} 0 \\ -\frac{JgA}{Q^2} Q|Q| \end{bmatrix} \qquad (2)$$

where $x =$ distance along the pipe axis (m); t = time(s); $A =$ cross-section flow area (m^2); Q = discharge (m^3 s^{-1}); $H =$ piezometric head (m); J = hydraulic gradient (−); $g =$ gravitational acceleration (m s^{-2}); $c =$ wave speed (m s^{-1}).

In transient flows inducing severe cavitation or water column separation, the presence of free air or vapour modifies the elastic wave speed and, consequently, introduces additional dynamic effects associated with the bubbly flow response. Extreme pressures, even with small duration, can reach excessive values and provoke unsafe operational conditions: the maximum pressure values can cause ruptures in pipes and fittings, while low values can lead to the buckling and collapse of the pipe-wall, as well as air admission and release, or the formation of vapour cavities (water-column separation). Any well-designed, built and operated hydraulic system will be prepared to avoid potential accidents, because the designer has foreseen the most probable threats (risk evaluation) and has taken preventive measures and defined rules against potential damages (risk mitigation).

During the design stage some hazard scenarios are excluded owing to their very small probability of occurrence, although there is knowledge of some vulnerable aspects in the systems. However, some of them will remain unknown and undetected.

Correct risk management presupposes that, during the system operation, potential risky weak points and factors will have the opportunity to be revealed. The occurrence of an accident can be a consequence of: (i) design/manufacture error or bad system maintenance; (ii) failure of operational management; (iii) failure of risk management;

and (iv) an unknown cause or abnormal situation, needing special expertise and investigation in order to avoid future similar events. The appearance of strong unbalanced transient forces induced by unexpected and non-controlled surges is a typical consequence of an abnormal situation.

The explanation of an unexpected behaviour requires a detailed analysis of complex hydraulic and structural interactions. Several studies on fluid–structure interaction (FSI) are motivated by incidents and accidents in which large displacements, vibrations and failure of pipes, supports or machinery have occurred (Tijsseling & Vardy 2005). For FSI analysis a simplified mathematical model in the time domain (Vardy & Brown 2003, 2004) is presented. This model is valid for the low-frequency transient behaviour of straight lines, thin-walled, linearly elastic effects and prismatic pipes of circular cross-section for a weakly compressible fluid.

Torsion vibration is assumed not to be affected by the fluid and the assumed radial pipe motion is quasi-static, because inertia forces in the radial direction are neglected in both the fluid and the pipe wall. The hoop or circumferential direction stress is then linearly related to the pressure by:

$$\sigma F = \frac{D}{2t} p \tag{3}$$

where D is the inner diameter (m), t is the pipe wall thickness (m) and p the internal pressure (Pa).

The FSI model, first described by Wiggert *et al.* (1987), is solved by the method of characteristics (MOC). It includes a 4-equation model presented as follows:

$$U = \begin{bmatrix} H \\ V \\ \dot{u}_x \\ \sigma_x - \frac{HgvD\rho F}{2t} \end{bmatrix} \quad F(U) = \begin{bmatrix} \frac{c_F^2}{g}(V - 2v\dot{u}_x) \\ gH \\ -\frac{\sigma_x}{\rho_t} + gZ \\ -\rho_t c_t^2 \dot{u}_x \end{bmatrix}$$
$$D(U) \begin{bmatrix} 0 \\ -\frac{f}{2D}(V - \dot{u}_x)|V - \dot{u}_x| \\ -\frac{f}{8t}(V - \dot{u}_x)|V - \dot{u}_x| \\ 0 \end{bmatrix} \tag{4}$$

in which

$$c_F^2 = \left(\rho F\left(\frac{1}{K} + \left(1 - v^2\right)\frac{D}{E_p t}\right)\right) \tag{5}$$

and

$$c_t^2 = \frac{E_p}{\rho_t} \tag{6}$$

are the squares of the fluid and solid wave speeds, respectively, V is the cross-sectional averaged fluid velocity (m s^{-1}), p the pressure (Pa), E_p the Young's modulus of the pipe material (Pa), c wave speed (with subscripts: F for the fluid, t for the pipe (m s^{-1})), ν Poisson ratio, t pipe wall thickness (m), D inner diameter (m), ρ mass density (kg m^{-3}), σ normal stress (Pa), K the fluid bulk modulus (Pa) and $\dot{u}$ is the structural velocity (m s^{-1}).

These Equations (4) allow for the calculation of four dependent variables such as axial fluid velocity, fluid piezometric head, pipe axial stress and velocity as a function of two independent variables: space, x, and time, t. They are extended waterhammer and beam equations describing the coupled vibration of the fluid and the pipe behaviour which have to be solved numerically.

Typical mechanical actions

The physical mechanisms that lead to the understanding and explanation of the unexpected structural behaviour of water mains are often very complex, involving several important factors (Rajani & Kleiner 2001): (i) pipe structural properties, the material type behaviour, the pipe-soil interaction, and the quality of the installation; (ii) internal loads due to operational pressure and unbalanced actions and external loads due to soil overburden, traffic loads, temperature variation loads; and (iii) material deterioration due to largely external and internal chemical, biochemical, electrochemical and environmental reactions. The structural behaviour of buried pipes is fairly well understood except for issues such as how the material deterioration affects the structural behaviour and the final performance. Most pipes and accessories, such as valves, joints, convergences or divergences are predominantly of metallic material. The damage to cast iron is often represented by a corrosion pit that will grow with time and eventually lead to a water main break. The physical adjacent environment of a pipe has a significant impact on the deterioration rate. Factors that accelerate corrosion of metallic pipes are stray electrical currents, soil characteristics, such as moisture content, chemical and microbiological content, electrical resistivity, aeration or redox potential. The interior of a metal pipe may be subject to tuberculation, erosion and crevice corrosion resulting in a reduced effective inside diameter, as well as a breeding ground for bacteria. The water in pipes can affect the internal corrosion through its chemical properties: for example, pH, dissolved oxygen, free chlorine residual, alkalinity, as well as temperature and microbiological activity.

Pipe breakage is likely to occur when the environmental and operational stresses act upon pipes, accessories and supports whose structural integrity has been compromised by stability, resistance, corrosion, degradation, inadequate installation or manufacturing defects. There are studies about the type of breakage in pipes which can be split into four categories (O'Day *et al.* 1986): (1) circumferential breaks, caused by longitudinal stresses; (2) longitudinal breaks, caused by transverse stresses (hoop stress); (3) split bell, caused by transverse stresses on the pipe joints; and (4) holes due to corrosion effect.

The contribution of the internal pressure in the longitudinal stress, even small, may increase the risk of circumferential breaks when occurring simultaneously with one or more of the other sources of stresses, such as thermal contraction, bending stress due to soil differential movements or inadequate trench and bedding practices. Longitudinal breaks due to transverse stresses are typically the result of hoop stress by the pressure inside the pipe, ring stress by cover loads of soil or traffic.

The pipe safety factor (FOS) is the ratio between the residual tensile (flexural) strength and the admissible or allowable stress. Regulation advises the designer of water mains to adopt a FOS of 2.5 for tensile and flexural stresses. However, over time, corrosion pits develop randomly and diminish the FOS of a pipe. Internal pressure produces uniform circumferential tension across the wall, while external loads may produce bending stress in longitudinal and circumferential directions.

If a pipe is uniformly loaded and supported along its length, then circumferential stress can be more important than axial stress (Ahammed & Melchers 1994; Rajani *et al.* 2000; Rajani & Kleiner 2001). The circumferential bending stress in a pipe wall (due to external loads) is in addition to the tensile circumferential h-1oop stress produced by internal fluid pressure (Table 1).

$$\sigma_\theta = \text{Hoop or circumferential stress} = \sigma_F + \sigma_S + \sigma_L + \sigma_V \tag{7}$$

In a similar way, the axial stress flow can be presented (Sadiq *et al.* 2004):

$$\sigma_X = \text{axial stress} = \sigma_T + (\sigma_F + \sigma_S + \sigma_L + \sigma_V)\nu_p \tag{8}$$

Corrosion actions

The loss of pipe wall thickness (or in other hydromechanical equipment) due to corrosion can be of localized type or of a continuous type as happened during the early stages of uncoated CI pipes (Sadiq *et al.* 2004). For a CI pipe continuous corrosion is a self-inhibiting process, reducing the corrosion rate over time.

Rajani *et al.* (2000) proposed a two-phase corrosion model (in the first phase a rapid exponential pit growth and in the second a slow linear growth) to accommodate this self-inhibiting process. As this is a complicated process and there is a lack of data over time, prediction of pit depth, in the first 15–20 years of a pipe life, should be considered highly uncertain.

Table 1 | Stresses acting on pipe systems

Stress type	Model
Thermal, σ_T	$-E_P\alpha_P\Delta T$
Internal fluid pressure, σ_F	$\frac{\nu_p}{2}p\left(\frac{D}{t}-1\right)$
Vehicular or traffic load, σ_V	$\frac{3K_m I_c C_t F E_P t D}{L(E_P t^3 + 3K_d p D^3)}$
Soil or earth load, σ_S	$\frac{3K_m \gamma B_d^2 C_d E_P t D}{E_P t^3 + 3K_d p D^3}$
Frost load, σ_L	$f_{frost}\ \sigma_S$

Where E_P = pipe material elastic modulus, α_P = thermal expansion coefficient of pipe, ΔT = maximum likely temperature difference between water and surrounding ground, ν_P = pipe material Poisson's ratio, p = internal pipe pressure, D = nominal pipe diameter, t = pipe wall thickness, K_m = bending moment coefficient, I_c = impact factor, C_t = surface load coefficient, C_d = calculation coefficient, F = wheel load traffic, L = pipe effective length, K_d = deflection coefficient, γ = unit weight of soil, B_d = width of ditch, f_{frost} = frost load multiple.

Considering a two-phase corrosion model, in Equations (7) and (8) the wall thickness is replaced by a residual wall:

$$d_T = a + bc\,e^{-cT} \quad (9)$$

where d_T = pit depth at time T; a = final pitting rate constant (typically 0.009 mm/year); b = pitting depth scaling constant (typically 6.27 mm); c = corrosion rate inhibition factor (typically 0.14 year^{-1}).

Following Sadiq *et al.* (2004), it is obvious that, as time passes, the pipe wall thickness decreases, implicitly reducing the FOS.

SYSTEM DESCRIPTION

General layout

The water supply system between Castelo de Bode dam reservoir and Lisbon city has a length of 2,100 km. The drinking water is transported by different sub-systems with a capacity of 240,000 m^3/day. The Portuguese Water Company of Lisbon area (EPAL) supplies water for about 3 million people over a total area of 7,000 km^2 divided into different district meter areas which are characterized by different topographic zones (Figure 1).

Telheiras is the most important pumping-station and there are reservoirs located in the superior zone (Figure 2), which supplies some of the water to Lisbon, as well as to the nearby cities of Sintra and Amadora.

The pumping system comprises three sets of parallel pumps (3 for superior zone (3 × 800 m^{3}h^{-1}) + 3 for Amadora (3 × 900 m^{3}h^{-1}) + 4 pumps for Sintra (4 × 1280 m^{3}h^{-1} and H = 120 m)), which are fed by a large reservoir of water through two steel pipes (D = 1.0 m), identified by CRE and CRD in Figure 3. These pipes are connected to the horizontal main CPC steel pipe (D = 1.6 m) placed on concrete supports with axis at level 117.60. This pipe is connected to the pumps (Figure 3) and is also connected to another pipe (D = 1.0 m) with axis at level 126.62. This CPC pipe has two isolating butterfly valves (identified by V58 and V59) and a third valve is placed at the upper pipe (V53).

Valves V58 and V59 can isolate three pipe branches: (i) branch D connected to the three pumps for the superior zone; (ii) intermediate branch connected to Amadora

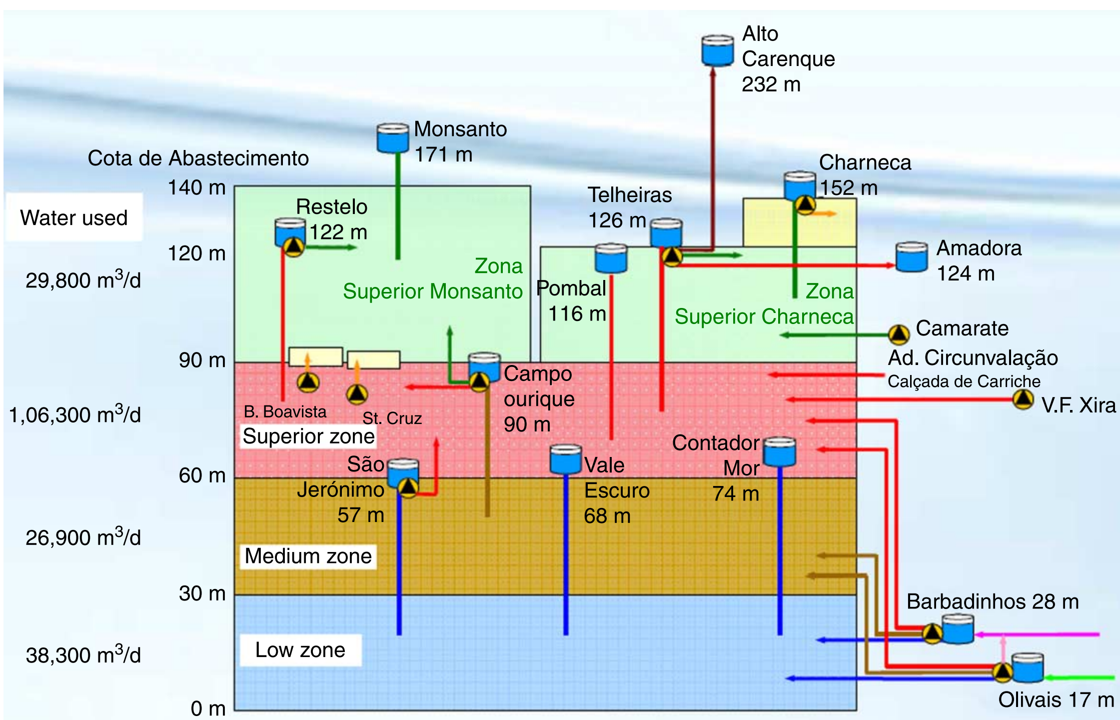

Figure 1 | Scheme of different supply reservoirs in Lisbon city (adapted from www.epal.pt/).

pumping system; and (iii) branch E connected to Sintra pumping system. Between valve V53 and the opposite CPC pipe D end, there are several elastic joints (Figure 3). This main pipe is vertically supported by steel plates which are embedded in concrete blocks but small movements along the axis are allowed.

Ten pipes ($D = 0.4$ m) link the main pipe to the suction side of the pumps. A bypass ($D = 0.4$ m) connects the high pressure pipe for Sintra ($D = 1.0$ m) and the CPC main pipe. This pipe has an isolating valve (valve VBP) that is permanently closed. All pumps have a non-return valve and the reverse flow from Sintra pipe is also avoided by means of a non-return valve VR. Figure 4 shows some detailed views of the Telheiras pumping-station.

The accident description

Just before the accident, the system operating conditions were as follows (Figure 3):

- *Valves*: V53 – closed; V58 – opened; V59 – opened; V8 – opened; V12 – opened; VBP – closed
- *Pumps*: Lisbon superior zone – two pumps operating (780 + 820 $m^3 h^{-1}$); Amadora – three pumps (900 + 1,030 + 900 $m^3 h^{-1}$); Sintra – out of service
- Reservoir level = 129.00.

Owing to a routine maintenance procedure and the need to fully isolate the Sintra pumps in order to replace a component, they were put out of service and, after that, valve V59 began to be closed (by hand and under equal pressures) for pipe branch E isolation. It was the first time in 20 years that this kind of operation was done. After 15 min valve V59 was closed. Suddenly in the final instants of the hand manoeuvre, the CPC pipe and valve V59 also moved (0.065 m) towards valve V58. Joint JP2 opened almost completely (0.07 m) and pipe branch E moved 0.015 m in the opposite direction (Figure 5). Several displacements were detected in the pipe system at the

Figure 2 | Telheiras reservoir in the uptown Lisbon zone.

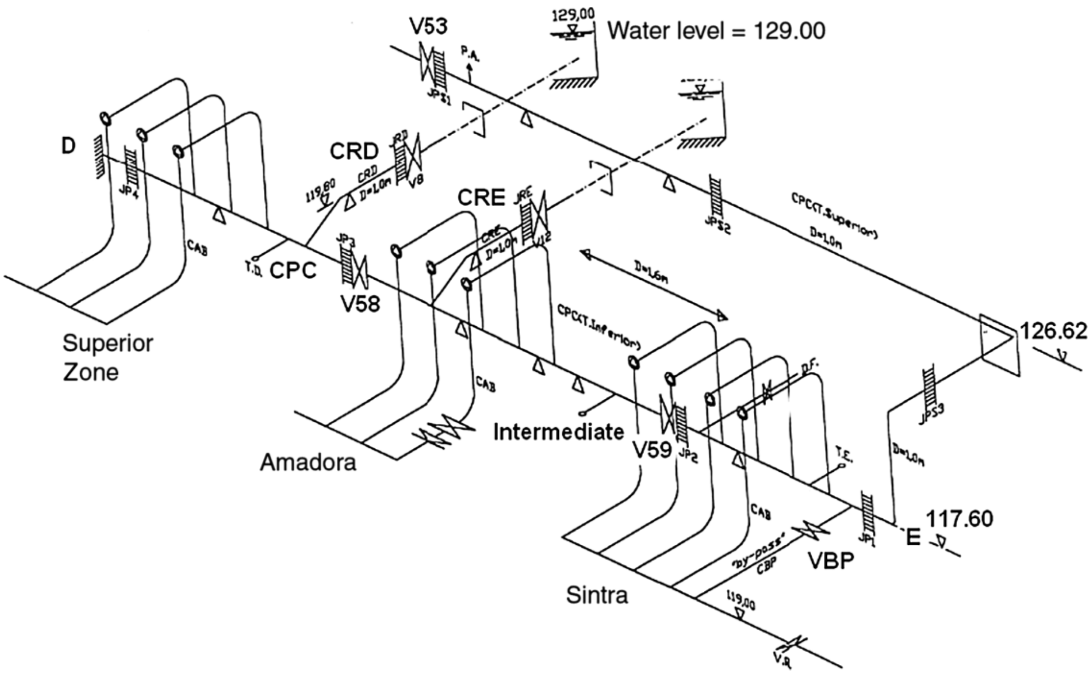

Figure 3 | Pumping-station layout.

pumping station including pipe CRE and pipe CRD and the pipes connecting the pumps (Figure 6). In Figure 7 the rupture in some concrete blocks of the pipe support is visible.

After the accident, valve V59 was slowly opened and the system remained without any more movement.

DIAGNOSIS ANALYSIS

After the accident, a careful *in situ* inspection was made and all components of the pumping station were checked. During this procedure it was found that valve VBP (bypass)

Figure 4 | Views of Telheiras pumping-station: the concrete roof of the water reservoirs, the pump suction pipes, the water level inside the reservoirs, the CPC pipe, the bypass pipe and valve V59.

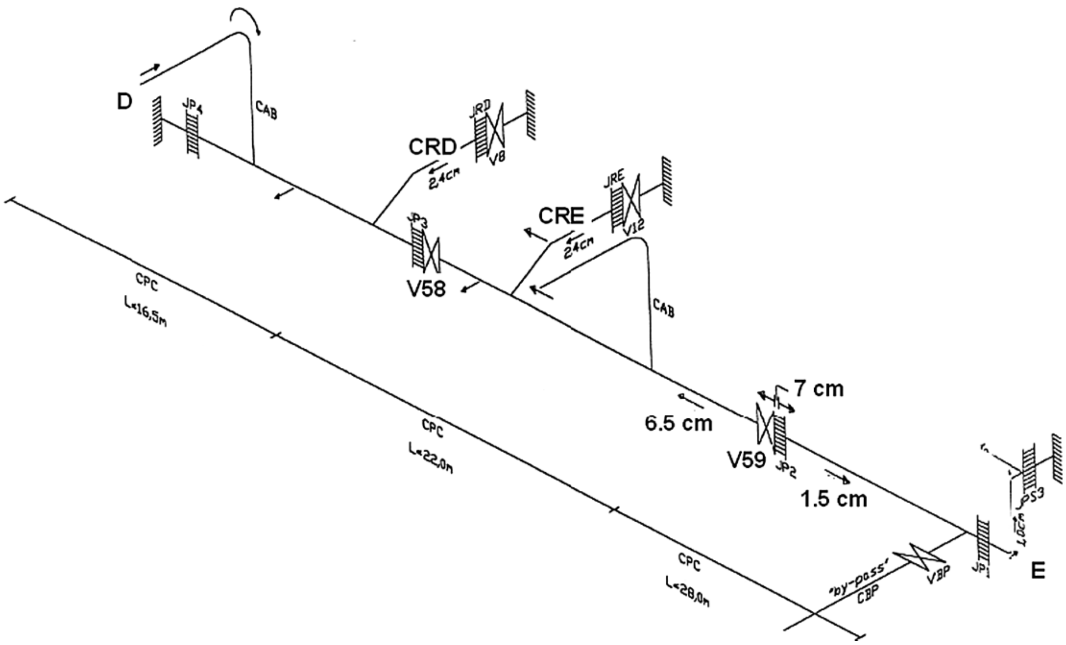

Figure 5 | General pipe displacements due to the accident.

was slightly corroded (a very small leakage was noticed) and the non-return valve was not isolating well enough.

Based on this inspection and on the pipe displacements, a preliminary conceptual analysis was developed. Several possibilities were considered and one of them was selected as the most probable for the identification of the accident causes. Figure 8 shows the evolution of the analysis developed in order to find and identify the main causes of this accident. It was necessary to make compatible the non-operating conditions and the possible action forces with the pipe displacements and the differential pressure in the system.

Figure 6 | Visualization of different displacements in the pumping-station.

Figure 7 | Visualization of support blocks rupture.

A basic diagnostic was considered as a reference framework for this research:

- *in-situ observation:* for data collection and to pay attention to operator description
- *preliminary diagnostic:* existence of differential pressure due to an unbalanced force at V59 as a fact
- *analysis:* bypass and valve inspections leading to the finding of the corrosion in the valve VBP body (Figure 9).

Hence, a preliminary brief explanation of the event was suggested:

– Valve VBP was leaking because of the differential pressure on both sides of it; high pressure at the bypass connected to the compression pipe for Sintra and lower pressure at the main CPC pipe of the pumping-station.

– As a result of the valve V59 closure, the CPC pipe had two isolated branches: one branch between valve V59 and valve V57, receiving the high pressure leakage flux through the small hole in valve VBP from the bypass pipe; and the other branch between valve V59 and pipe end D, connected to the large water reservoir at 139 level.

– The leakage through valve VBP makes possible a pressure transfer across it and increases the internal pressure between valves V59 and V53 during the valve manoeuvre.

As a result of this situation an unbalanced force suddenly acted on valve V59 after its closure and the pipe system moved.

The corrosion in valve VBP (Figure 9) may be due to different circumstances. In fact, the water in the bypass had not moved for a long time, developing slime layers close to the valve, which may have induced the creation of an anaerobic environment and favourable microbiological activity. Under anaerobic conditions, with the presence of sulphates and organic content in the bulk water, the reduction of sulphates to sulphides by facultative anaerobic microorganisms, such as *Desulfovibrio desulfuricans*, could take place, with iron sulphide deposition which attacked the valve surface. After the development of ‘weak’ zones and small ‘holes’, the significant pressure difference between the two faces of the valve body or the valve nave possibly resulted in water leak movement. Another possibility consists of local chemical corrosion of the valve associated with water quality problems; namely a high dissolved oxygen concentration, a significant electrical conductivity of the fluid and high concentrations of chlorides and/or nitrates and/or sulfates. All these factors contribute to chemical corrosion, the most important being, perhaps, the dissolved oxygen content (aerobic condition). The local hydrodynamic conditions created after the existence of a hole in the valve body may have accelerated the corrosion process.

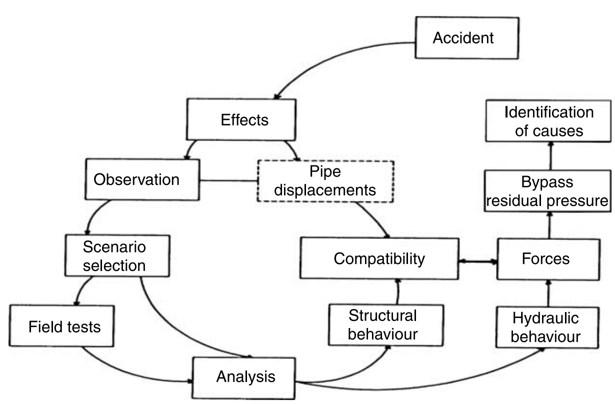

Figure 8 | Procedure for the identification of accident causes.

Figure 9 | Valve VBP corroded.

RESEARCH PROCESS

Field analysis of the damaged zone

The research process had the main purpose of demonstrating that the basic diagnostic of the accident was consistent with the pipe effects (displacement data). In Figure 10 the hydraulic system directly involved in the accident is presented.

The first component comprised the analysis of the pipe system associated with the pumping-station and field observations related to the accident:

- Sintra pumps during the shutdown induced a residual high head (pressure) between the non-return valve VR and the valve VBP – the average head measured at the valve was 248 m imposed by the manometric head of the Sintra system.
- The simplified hydraulic system involved directly in the dynamic effects associated with the valve closure (V59) is represented in Figure 10.

A simplified structural representation is defined essentially based on the pipe branch where V59 is installed. Figure 11 shows a schematic representation

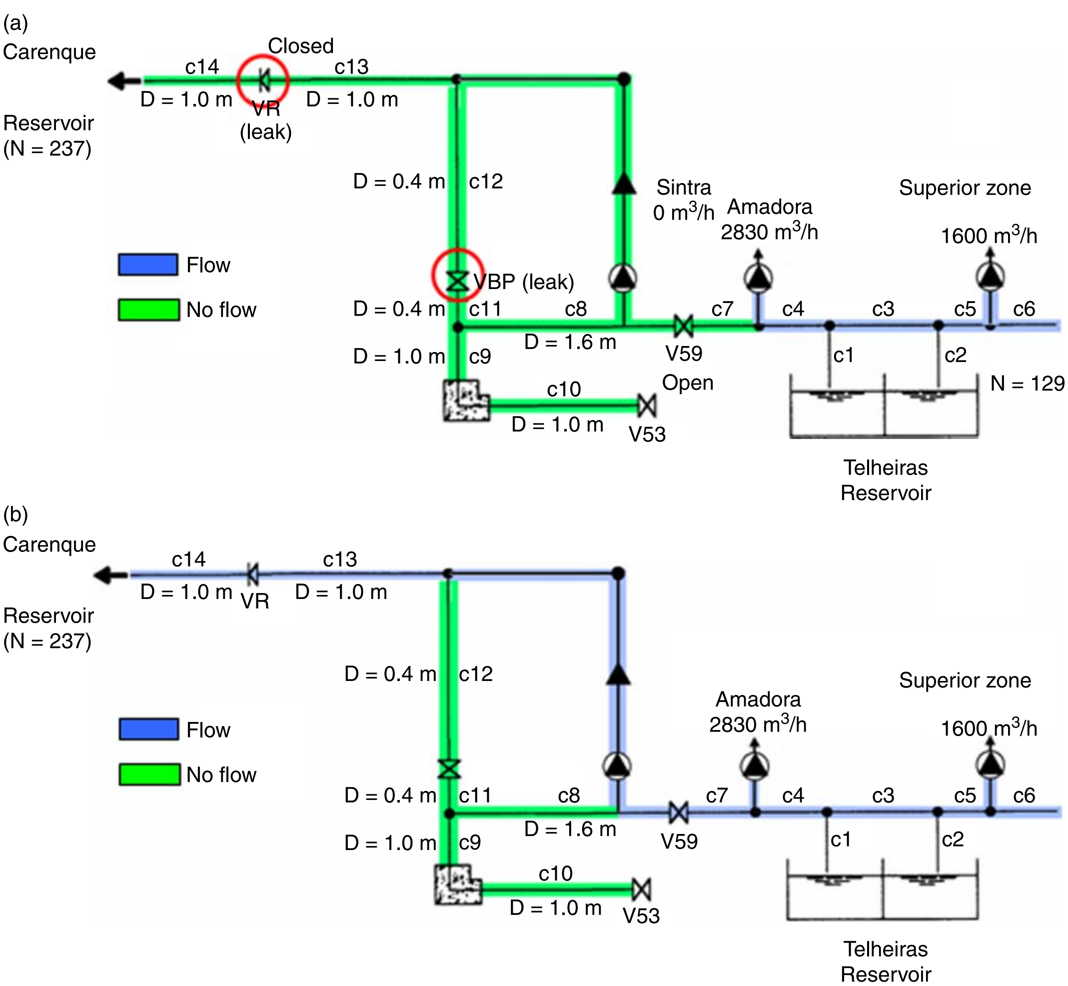

Figure 10 | Simplified hydraulic system (a) for normal operation and (b) before the accident.

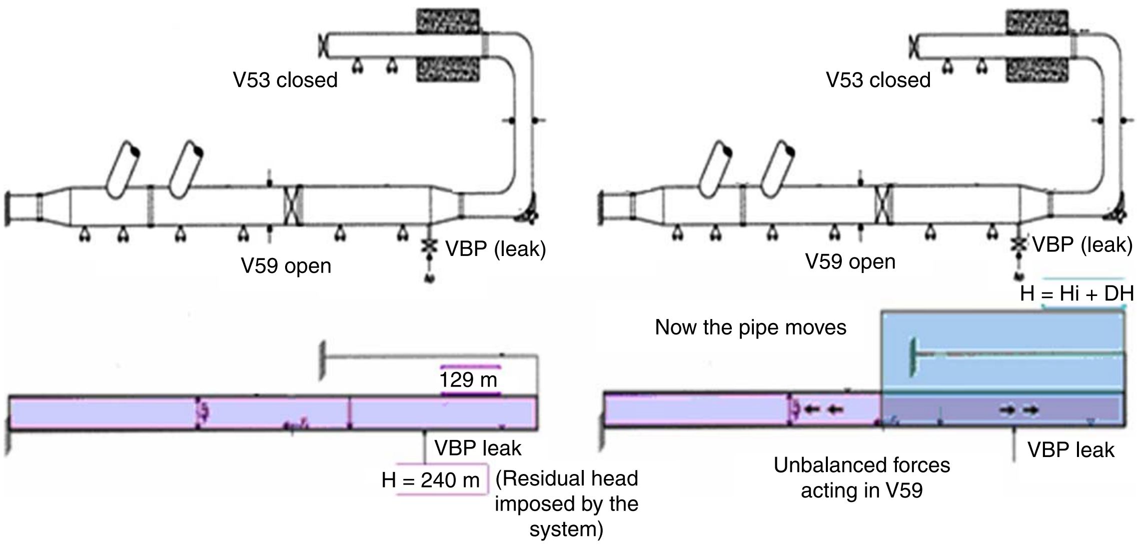

Figure 11 | Pipe branch of V59 and VBP (a) for normal operation and (b) before the accident.

of the unbalanced pressure head on both sides of the valve body due to the effect of an induced leak in the VBP valve.

Along the pipe several support blocks are installed, which do not limit the axial pipe movement. The dynamic behaviour is governed by axial and lateral waves in the pipe walls and by pressure waves in the fluid. Strong fluid–pipe forces occur at the pipe closed ends, namely at V59.

Simulation analysis

In order to better understand the phenomena that occurred during the accident, several simulation analyses were developed

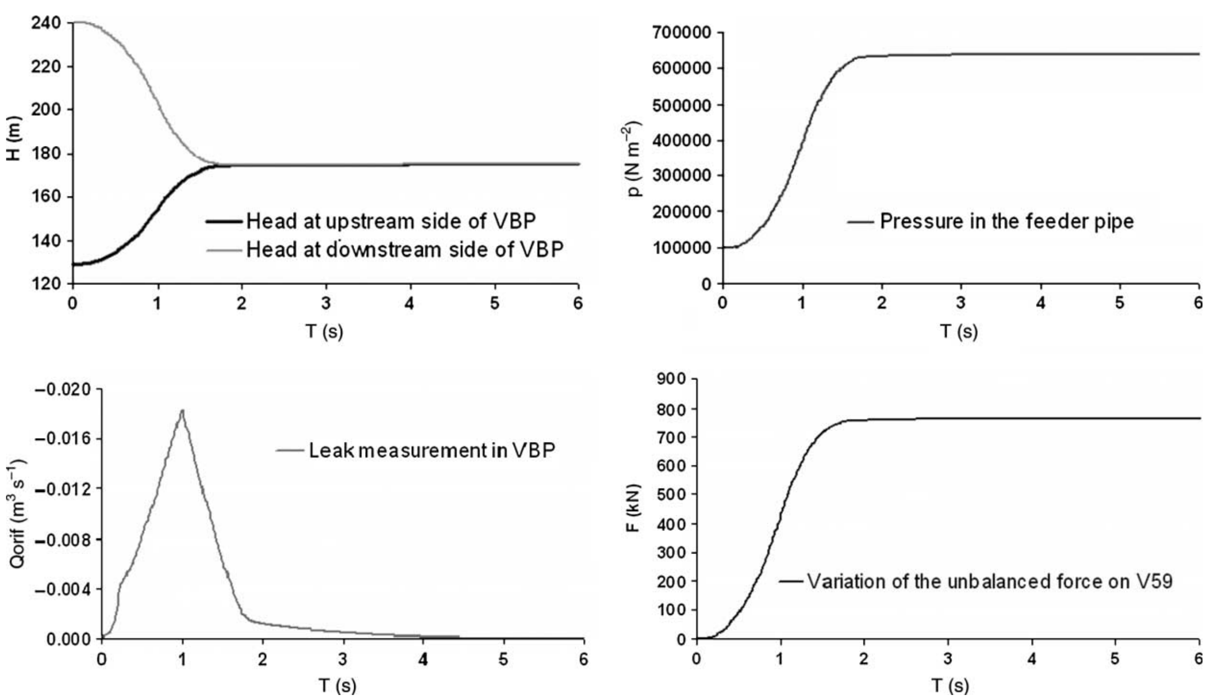

Figure 12 | Unbalanced head and respective force at V59.

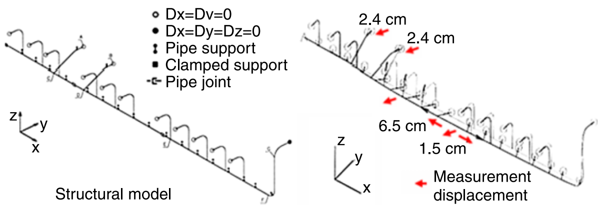

Figure 13 | Structural model and pipe displacements.

for different scenarios and flow conditions. A separate analysis related to hydraulic and structural responses is presented herein.

Regarding the hydraulic analysis, the rising of the transient unbalanced force acting in the system was verified using an elastic model based on the method of characteristics. The pressure transient analysis associated with the valve V59 closure and the CPC pipe pressure variation due to the VBP leakage (a small orifice as estimated from the valve inspection) were simulated. According to this analysis the dynamic net unbalanced force was estimated (765 kN) as presented in Figure 12.

The structural analysis showed the main effects of the induced unbalanced force on the pipe system: the CPC pipe movement of 0.065 m in valve V59 towards valve V58, the joint JP2 opening (0.07 m) and the pipe branch E movement of 0.015 m in the opposite direction (see Figure 5), as well as several other displacements observed (Figure 6). Hence, the analyses were based on: (i) force/displacement compatibility; (ii) linear analysis; and (iii) 3-D structural analysis.

Due to the unbalanced interior pressure value in valve V59, as shown in Figure 12, by using a hydraulic mathematical flow dynamic model it was possible to simulate the effect of a leakage occurrence in VBP and the induced force of 765 kN, which was responsible for the system motion.

Based on a simplified analysis, the pipe contraction value due to the Poisson effect for the interior pressure head of 176 m in the pipe branch can be estimated as 0.015 m,

$$\left(\Delta L_1 = \frac{\nu L p D}{2 E_p t}\right),$$

where $\upsilon = 0{,}4$ the steel Poisson coefficient, L is the pipe length between fixed supports, p the interior pressure in the pipe branch, D the internal diameter value, E the pipe elasticity modulus and t the pipe thickness.

Another pipe extension is noted due to installed forces in the closed valve. Therefore, in the other pipe branch there is a pipe extension of 0.065 m by traction induced by the pressure in the valve flange,

$$\left(\Delta L_2 = \frac{LF}{(\pi D E t)}\right)$$

neglecting temperature effects.

A 3D simulation model was also used in the analysis which allows observation of forces and displacements associated with each node (Figure 13). In the pipe structural response (3-D pipe analysis) the main forces are considered as well as the characteristics of the pipe supports. By comparing the pipe displacements obtained by the linear analysis in the computer simulation with those obtained in the field it was possible to calculate the corresponding acting force in the system (850 kN). The magnitude of the acting forces obtained by the hydraulic (765 kN) and structural (850 kN) analysis are rather close and it can be concluded that this seems to confirm the accident diagnostic.

CONCLUSIONS

Unfortunately accidents/incidents can be very useful events for progress in engineering, since with them the public, management, researchers, designers and engineers can better realize what is crucial in the design of infrastructures. Researchers are faced with uncertainty and risk concepts which are an important challenge because something was wrong and the facts are real. However, a solved accident/incident, which makes a positive contribution to a better knowledge of system behaviour, provides more confidence than a complex new design without any feedback from the system response.

The investigation of this specific case which identified the causes of the accident makes it possible to make some remarks:

(i) A simple operation, such as a closure of a valve, with no flow condition, can induce a severe disturbance in a system 20 years old without any problems detected before, leading to a quick pressurization of the supplier pipe, when the valve V59 was almost closed.

(ii) Too much confidence in a system without any problem diagnosed can induce a strong opposition to understanding the real causes associated with abnormal and dangerous situations that may occur in any type of pipe system; the bypass valve presented the existence of corrosion and was non-operational for 20 years.

(iii) Consulting experience and knowledge need to be supported by an objective proof based on technical evidence and, if possible, on detailed analysis and comparison with real data.

(iv) Computer simulation, when based on an integrated methodology and a research strategy, is a good tool for engineers and researchers: in this particular case, experimental tests, hydraulic and structural computer analysis were necessary to explain and to convince the experts.

(v) The lack of protection against water corrosion attack (e.g. double valve and routine valve inspection, operation and maintenance) was the first cause of the abnormal system behaviour.

(vi) The analysis demonstrated that the valve leakage was enough to produce a fast and effective unbalanced force; the structural investigation shows that the pipe displacements and the force intensity were of the order of that measured *in situ* and estimated; the main non-return valve was leaking, the joint near valve V59 had a construction error – the specification was to place it on the opposite side of the valve.

ACKNOWLEDGEMENTS

The authors acknowledge the Lisbon Water Company (EPAL) for the support given to this work. The authors also wish to thank FCT through the projects PPCDT/ECM/58375/2004, PTDC/ECM/65731/2006, PTDC/ECM/64821/2006 and PTDC/ECM/68694/2006 (partly supported by funding under the European Commission – FEDER).

REFERENCES

Ahammed, M. & Melchers, R. E. 1994 Reliability of underground pipelines subject to corrosion. *J. Transp. Eng–ASCE* **120**(6), 989–1002.

Almeida, A. B. 1992 Accidents and incidents. A harmful powerful way to develop expertise on pressure transients, *Proceedings of IARH Meeting on Hydraulic Transients in Water Column Separation*, Valencia. Fluid Mechanics Group, Univ. Politecnica de Valencia, pp. 279–400.

Almeida, A. B. & Koelle, E. 1992 *Fluid Transients in Pipe Networks*. C.M.P. Elsevier, Southampton.

Almeida, A. B. & Pinto, A. A. 1986 A special case of transient forces on pipeline supports due to waterhammer effects. *Proceedings of the 5th International Conference on Pressure Surges*, Hanover, BHRA, paper B2, pp. 27–35.

Chaudhry, M. H. 1987 *Applied Hydraulic Transients*, 2nd edition. Van Nostrand Reinhold Company, New York.

Karney, B., Gajic, A. & Pejovic, S. 2003 Case studies: our experience in hydraulic transients and vibrations. *Proceedings of the International Conference on CSHS03*, Belgrade, 29 September–1 October 2003.

Maricic, T. & Pejovic, S. 2007 Standardization as Prevention of Fatigue Cracking of Hydraulic Turbine-Generator Shaft. In: *Electrical Power Conference, 2007, EPC 2007, IEEE Canada* pp. 103–110.

O'Day, D.K., Weiss, R., Chiavari, S. & Blair, D. 1986 *Water Main Evaluation for Rehabilitation/replacement*. AWWA Research Foundation, Denver, Colorado, and US-EPA, Cincinnati, Ohio.

Rajani, B. B. & Kleiner, Y. 2001 Comprehensive review of structural deterioration of water mains: physical based models. *Urban Water* **3**(3), 151–164.

Rajani, B., Makar, J., McDonald, S., Zhan, C., Kuraoka, S., Jen, C.-K. & Veins, M. 2000 *Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life*. American Water Works Association Research Foundation, Denver, Colorado.

Ramos, H. 1995 *Simulation and Control of Hydrotransients at Small Hydroelectric Power Plants*. PhD thesis, Technical University of Lisbon, Portugal (in Portuguese).

Sadiq, R., Rajani, B. & Kleiner, Y. 2004 Probabilistic risk analysis of corrosion associated failures in cast iron water mains. *Reliab. Eng. Syst. Safe.* **86**, 1–10.

Tijsseling, A. S. & Vardy, A. E. 2005 Twenty years of FSI experiments in Dundee. In: Bathe, K. J. (ed.) *Proceedings of the Third MIT Conference on Computational Fluid and Solid Mechanics*. MIT, Boston, Massachusetts, pp. 1014–1017.

Vardy, A. E. & Brown, J. M. B. 2003 Transient turbulent friction in smooth pipe flows. *J. Sound Vib.* **259**(5), 1011–1036.

Vardy, A. E. & Brown, J. M. B. 2004 Transient turbulent friction in fully rough pipe flows. *J. Sound Vib.* **270**, 233–257.

Wiggert, D. C., Hatfield, F. J. & Stuckenbruck, S. 1987 Analysis of liquid and structural transients by the method of characteristics. *J. Fluid. Eng–Trans. ASME* **109**(2), 161–165.

Wylie, E. & Streeter, V. 1993 *Fluid Transients in Systems*. Prentice Hall, Englewood Cliffs, New Jersey.

First received 13 June 2008; accepted in revised form 29 September 2009