The importance of fluid-structure interaction in pipe systems design

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ABSTRACT The current research work aims at analysis of fluid-structure interaction in hydraulic pipe systems induced by pipe degradation, corrosion, seismic or differential pressure actions. The extreme importance of this subject is the occurrence of an abnormal accident in a main pipe water drinking system in the Pumping-Station of Telheiras, from Lisbon Water Supply System, which caused pipe displacements and breaks in some supports. This situation occurred after a valve closing, which lead a significant differential pressure in the pipe system.

To seek the vulnerability of these hydraulic systems (to different typical loads), many case studies were developed by a water hammer and structural model, WANDA 3.53 and SAP2000, respectively, having always the base system of the Pumping-Station of Telheiras, where the accident occurred. These analyses were developed in order to show the possible consequences in terms of displacements, when the system is submitted to different loads and type of supports. The study comprises the analysis of the effect of seismic action in the pipe structure and a pressure differential between the two sides of the valve V59 (upstream and downstream), occurred during the accident. The results of the displacements obtained by the simulations were compared to the values measured by experts.

It is equally emphasized the importance of integrated analysis (fluid-structure interaction), the purpose of supports in water pipe systems, as well as the identical system behaviour for completely different type of actions (i.e. seismic and pressure variation) in the infrastructures design.

Keywords: Fluid-structure interaction, waterhammer, seismic action, safety infrastructure, pipes systems.

1. INTRODUCTION

The current research work aims at the study of instability factors leading to rupture and the safety risk on a hydraulic pressure system that is under subjected to a seismic action, valves’ operation and due to internal corrosion phenomena.

One of the subjects relates to a real case study which refers to the occurrence of an abnormal accident in a main pipe water drinking system in the Pumping-Station of Telheiras, from Lisbon Water Supply System that caused pipe displacements and breaks in some supports.

In general, the hydraulic pipe systems are usually under different types of vulnerabilities. The associated hazards when neglected in the different stages of a design: in the conception phase, implementation and operation (Ramos, 2006; Ramos, 2007), may jeopardize the safety and operation of each system. In the area of fluid-structure interaction, the analysis of various aspects involved in hydraulic pipe systems is confronted with one of the most complex subjects, which in recent decades has been remarkable progresses due to the advent of computers and their evolution, as regards the analysis of transient phenomena.
2. STATE-OF-THE-ART

2.1. Water hammer and structural deformation

Changes in pressure caused by changes in flow induce the appearance of inertia forces that interfere on fluid compressibility and on pipe walls deformation. These variations in flow conditions originated from some voluntary or involuntary disturbance imposed on the flow velocity, such as the operation of hydromechanical equipment installed in the system, mechanical failures of protection and control devices, as well as seismic actions.

According to Tijsseling (1993), the waterhammer appears as one of the most responsible for extreme transient phenomena in pipes systems. The pipe movement due to the occurrence of this phenomenon depends on mechanical properties, supports’ conditions and dynamic forces that act on the fluid, on the pipe wall and on supports.

The transient pressure variations that occur in the flow produce forces and may lead to deformations and displacements in the pipelines, which will interact with the transient hydraulic flow and cause new vibrations or resonance phenomena that can cause, consequently, the collapse of the system. Thus, the interaction between the liquid and pipe wall is noticed through three effect types: the effect of junction, the effect of Poisson and the effect of hydraulic interface.

Fluid-structure interaction in piping systems consists on the transfer of momentum and forces between pipes and the fluid during unsteady fluid-structure conditions. The interaction is evident through pipe-structure vibrations and disturbances in the flow velocity and pressure. The additional resulting in the pipes are transferred to the support mechanisms and may also cause damage in these components. The phenomenon has recently received increased attention because the safety and the reliability concerns in hydraulic and structural systems which transport a scarce and essential good to the life as the water is. It is made particular reference for the pumping-stations of water dinking and drainage systems, hydropower, environmental issues in the event of failures pipe systems, and the questions related to stringent industrial piping design performance guidelines (Tijsseling e Wiggert, 2001).

2.2. Protection devices against the waterhammer

A pumping system design should take into account the effects of waterhammer, especially those motivated by the sudden interruption in the operation of the pumps. The waterhammer analyse can indicate the need to provide protection devices against this phenomenon. Sometimes these devices can be released through changing velocity values during a steady flow, avoiding the high points of the pipeline profile and considering pumping-groups with variable rotational speed (Almeida, 1981; Ramos et al., 2000).

![Figure 1 – Typical examples of protection devices against waterhammer: (a) air vessel; (b) bypass; (c) air valve.](image)

The protection devices against the waterhammer effects should limit the values of the depression and overpressure caused by this phenomenon, being some of these equipments: flywheels, air vessels, surge
tanks, unidirectional tanks, bypass, relief valves and air valves (Figure 1). The selection of one or more protection devices should result based on analysis of a number of alternatives that should elect the best possible solution to be adopted, considered from the point of view of efficiency, economy, maintenance and operation.

2.3. Design of pipelines
The water main system constitutes an essential part of lifelines of urban cities, as all public and private infrastructure which support the human’s activities. They are so important that their existence and their good operation had so many implications in the politic, as economic level to be able to satisfy the human life quality, in terms of gas, water and electricity distribution and other fluids, dams preservation, phone, radio, radar and net communications and roads. Pipe systems need special attention in terms of hydraulic-structural analysis, because their destruction or damage could bring serial consequences in human lives, as well as in social and environment issues (Pereira and Ferreira, 2003). The design of water pipe systems is a complex process that involves the calculus of dynamics conditions of the flow and the structure, which are not so much as a simple determination of the economic diameter and the pipe capacity. The protection of quality life and environmental is and will be always an important factor in the decision of new Civil Engineering projects (Tullis, 1989).

2.4. Deterioration mechanisms
According to Fontinha and Salta (2007) the metallic components performance used in the construction, such as water mains design is specially conditioned by the corrosion of metal that constitutes the pipes and hydromechanical equipment. So, the corrosion is looked as the major cause of degradation of these materials, leading to the lack of service (e.g., collapse, breaks, reduction of capacity, infiltrations), and sometimes the deterioration of the surrounding environment (e.g., water consumes contamination), leading to the loss material and modification of the mechanical and aesthetic properties (Figure 2).

![Figure 2 – Different types of corrosion/erosion (source: http://www.aquaambiente.com).](http://www.aquaambiente.com)

It is important to alert that there are factors which contribute to accelerate or to origin the pathologies of corrosion, such as an inadequate selection of pipe material or defies existent in the design or during the construction/assemblage. The metallic components are subjected to many corrosion problems that affect their performance needing an adequate selection for the type of pipe material for each case, to define the correct anti-corrosion protection, to present an adequate configuration (minimizing interstices, settlement accumulation zones), to prevent assembly failures and type of uses and to carry out periodic maintenance inspections (of cleaning and covering repair) (Fontinha, 2007).

2.5. Hydraulic systems rehabilitation
In developed countries, most of water main systems were designed and implemented several years ago. Now a days, the management entities confronts with problems of an efficient operational maintenance and
reliance to balance the water main in quantity and quality satisfaction of all consumers (Grilo and Covas, 2008).

The degradation of water infra-structures and respective hydromechanical equipments (since the source caption to consumers) is a natural process and inevitable and, as well the difference components gets the end of their life, the lack of volume (physicals) of water grows up, the occurrence of breaks and the water mains interruption is more frequent and the maintenance’s costs systems starts to increase (Borda d’Água et al., 2008). Suddenly the management entities are confronted with the need of rehabilitation actions. It may define rehabilitation as some physical intervention that extends useful life of an existing system, improving hydraulic performance, structural and quality of water. Within the rehabilitation area there are many types of intervention, such as, renovation, replacement and reinforcement.

2.6. Earthquakes
The evaluation of seismic action in water mains can be carry out by direct damages analyses, that are related with interruption of water supply after the earthquake, or by indirect damages, resulted of some lack of operation system for a long period, with social consequences, economic and environment in the affected areas (Silva, 2002).

It is known that water supply systems, sewers, gas and fuel networks are usually made by buried pipeline systems. One of the principal characteristic of theses systems that extend for very large areas is standing to the random earthquake occurrence such as in space, time and intensity. This kind of structures can suffer damages caused by earthquake waves or caused by permanent ground displacements such as, geologic fails, liquefaction, or slips/slides (Bento, 2000).

Pipelines systems, buried or superficial, continuous or not (fragmented by branches), are important components of lifelines. Their design and implantation rarely obey to performance earthquake conditions. By this omission many damages are being demonstrated in lifelines during the earthquake, as for San Francisco (California, 1906), San Fernando (California, 1971), Northridge (Los Angeles, 1994), Kobe (Japan, 1995), Izmit (Turkey, 1999) and Chi-Chi (Taiwan, 1999) (cited by Proença, 2000), earthquakes. Figure 4 shows several damages in water pipes during one São Francisco earthquake.

3. COMPUTATIONAL MODELLING
3.1. Hydraulic components
It is advisable to use computational modelling in all phases of a design (previous studies, viability studies, projects for tender, final project, and during exploitation – operation and maintenance), just to know the highest and minimum pressure and their evolution in time and along the hydraulic circuit. Only this way it is
possible to specified the control procedures in terms of dynamic effects that may occur (e.g., pressure and velocity variations) and what is the best way to control themselves (Almeida, 1981; Ramos, 2003, 2004, 2006; Covas e Ramos, 2006). The hydraulic modelling is based on the following equations derived from Navier-Stokes equations:

Dynamic equation: \[ \frac{\partial Q}{\partial t} + gA \frac{\partial H}{\partial x} + RQ \frac{\partial |Q|}{\partial x} = 0 \] (1)

Continuous Equation: \[ \frac{\partial H}{\partial t} + \frac{\epsilon^2}{gA} \frac{\partial Q}{\partial x} = 0 \] (2)

It is important to refer that in equations (1) and (2) there is no analytical solution known, but by using the Method of characteristics (model WANDA Engineering 3.53) they can be converted into equations with total derivatives and be used more efficiently.

3.2. Structural components

Physical phenomenon behind structural problems are based in the same Navier-Stockes equation and consequently in the same conservation principles as the hydraulic component adding the specific structural variables (Covas and Ramos, 2006; Tijsseling and Wiggert, 2001). In general, it is only possible to obtain analytical solutions for relatively simple situations, for example, with basic geometric shapes, and particular cases of boundary conditions. The method of finite elements gets the solution by minimizing the functional energy in each element. This solution is based on the virtual work principle, which establishes that if one particle is on balance by a system of forces, so for any motion the virtual work is zero, this is the aim of the basic conservation principle of total mechanical energy of continuous systems (Tijsseling, 1993; Tijsseling and Wiggert, 2001; Lemos, 2005).

Conservative equation of total energy:

\[ \Pi = \frac{1}{2} \int_{\Omega} \sigma^T \epsilon dV - \int_{\Omega} d^T b dV - \int_{\Gamma} d^T q dV \] (3)

where \( \sigma \) and \( \epsilon \) are vectors of stress and strain components in every point, \( d \) is the vector of displacements in the same points, \( b \) the vector of force in each element per unit of volume, and \( q \) the vector of tension applied in the control volume surface. The method of finite elements is the method used in SAP2000, which supported the structural calculus in this research work.

4. CASE STUDIE

4.1. Modulation of a seismic action in the water pipe system

In modulation to seismic action it was considered the regulation spectral answer of earthquake Type 1, soil Type II, zone A and a damping coefficient of 5%. The described test matches to a seismic analysis to the pipelines system inside the Telheiras Pumping-Station (Figure 5).
To take into account a seismic analysis of the effect of water inside the pipelines was necessary to add into pipe elements a distribute loads per meter. The only loads that account for this analysis are the pipeline’s and water’s weights, for the reason that this pipes are above the ground.

Related with supports’ conditions (see details in Almeida and Ramos, 2007), the CPC Inferior pipeline, CRD and CRE can have axial movements with the exception of the pipe connection nodes of CRE and CRD to CPC Inferior, where only it is restrict to vertical movement, and CPC Superior pipeline can moved in its axis direction, except in pipe connection node of d=1 m with CPC Superior, which only allows the rotation.

The absolute displacements in valve V59, such as many points of the pipeline are registered in Table 1. Observing this table, it is evident that exists a major and a minor value for the same direction movements which is due to the fact of seismic action is an enveloping efforts resulting actions in two directions, being the minor and the major values match with the sense earthquake force in that direction.

<table>
<thead>
<tr>
<th>Node of valve V59</th>
<th>Pipe and Water weights+Seismic combination</th>
<th>U_x (cm)</th>
<th>U_y (cm)</th>
<th>U_z (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max.</td>
<td>10.9583</td>
<td>0.0076</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>-10.8436</td>
<td>-0.0078</td>
</tr>
</tbody>
</table>

The positive and negative signs of displacements presented in Table 1, only represents the fact that these displacements can or cannot turn out into positive direction global axes system. The U_x correspond to the movement in direction X, the U_y in direction Y and U_z describes the movement in direction Z.

For the observation of all displacements the valve V59 reveals to be the conditioning section of the system. Valuing the displacements obtained in this node, it is visible that the axial movement in CPC pipeline is about 11 cm, value a little superior than the value obtained in the accident by closing the valve when an unbalanced force is observed (8 cm). This aspect is due to the fact that during the occurrence of an earthquake, all the structural components (i.e., pipes and supports) are integrated involved with the hydraulic component. In an isolated analysis of the hydraulic component, only the fluid compressibility and the deformation of the pipe walls may interact, bringing significant pressure waves that propagate along the hydraulic system which can induce, also, pipe displacements.
4.2. Differential pressure action modelling in valve V59

In this topic it is simulated, inside the Pumping-Station of Telheiras, the difference of pressure between the valve V59 occurred during the accident and the development of comparisons between the results of displacements obtained by simulation, according to the hydraulic and structural analysis, with the values verified in situ (Figure 6).

![Figure 6 – Damage in supports (Almeida and Ramos, 2007).](image)

In structural simulation analysis it was added the effect of water in the system, such as loads per linear pipe length, in the direction of pipe axis, where their action directions can change between different pipes branches, since the load will always be considered to increases the pressure in valve V59. Then the loads are the pipeline weight, the water weight and the pressure differential (Figure 7).

![Figure 7 – Pipeline system in Pumping –Station of Telheiras and momentum diagrams due to differential pressure combination.](image)

The Table 2 shows the movement occurred in the valve V59 (10 cm), a value a little superior then the observed one after the accident.

<table>
<thead>
<tr>
<th>Node of valve V59</th>
<th>Pipe and Water weights+Dif.pressure</th>
<th>Ux (cm)</th>
<th>Uy (cm)</th>
<th>Uz (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-10.312</td>
<td>-0.007</td>
<td>-0.2106</td>
</tr>
</tbody>
</table>

**Table 2 – Displacements in the valve V59.**

**Conclusions about the simulations**

Concluded several simulations it is important to mention that the introduction of pressure forces in valve V59 (differential pressure tests) demonstrated that the force of about 765 kN, obtained by hydraulic simulation and introduced in structural simulation, that results a final displacement a little superior than the observed, is not relevant, because the structural model considers the supports effects while the hydraulic model did not.

Hence, it is emphasized the important to have good correlation of an interaction fluid-structure analysis with measurements (in situ, after the accident) to give confidence about the results.

Another important factor, resulted from the interpretation of the results, is the fact that the system simulation based on a seismic combination and on a closure of a valve (completely different type of actions) had an identical answer (similar effects) originating significant displacements in the support of the valve. In this case,
this similar effect verified in Table 3, corresponded to the differential pressure surge and the seismic combination.

Table 3 – Comparison of displacements obtained for differential pressure at valve V59 and the seismic combination.

<table>
<thead>
<tr>
<th>Node of valve V59</th>
<th>$U_x$ (cm)</th>
<th>$U_y$ (cm)</th>
<th>$U_z$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe and Water weights+Dif.pressure</td>
<td>-10,312</td>
<td>-0,007</td>
<td>-0,2106</td>
</tr>
<tr>
<td>Pipe and Water weights+Seismic combination + Seismic combination</td>
<td>Max. 10,9583</td>
<td>0,0076</td>
<td>-0,1965</td>
</tr>
<tr>
<td></td>
<td>Min. -10,8436</td>
<td>-0,0078</td>
<td>-0,2123</td>
</tr>
</tbody>
</table>

It is important to say that in this case, it was also developed a sensitive analysis for the supports conditions, with the interest to prevent from consequences that might occur, in terms of possible displacements. After that, it was concluded that, in terms of supports restrictions, other pipes can be exposed to possible breaks. This analysis can relate the importance of a correct design for all supports as well as the fluid-structure interaction, such as, showing what can happen if some supports leaves their normal functions, resulting problems in new pipes. After these tests, other simulations were been into account, such as seismic action in a simplifying system, where only exists the CPC Inferior pipeline and CRE and CRD pipelines, where all the conclusions were quite similar as the seismic combination tests.

5. GUIDELINES FOR DESIGN

In this chapter appeals the designers about the considerations/criteria to pay attention in the design of pipe systems under transient pressure conditions, especially when the fluid-structure interaction can be quite important.

For the pipes’ design attention should be given to the effect of waterhammer on loads introduced by this phenomenon, as well as its influence in efforts, fatigue of the pipe material and in the dynamic behaviour of the system as a whole.

According with Lemmens and Gresnigt (2001) the pipe systems, especially those installed over the ground, during the occurrence of transients phenomena (waterhammer effect) are under relevant dynamic forces. When these forces are associated with displacements of the system creates an important fluid-structure interaction, which means that the liquid and pipe should be analysed together and the mechanism of interconnection has to be reported (Figure 8).

A pipeline system satisfies all the requirements of design and security when the values respect the imposed ones by the Limit-States.

The Portuguese Structural Regulation - Regulamento de Segurança e Ações para Estruturas de Edifícios e Pontes defines that a Limit-State is a state beyond which the pipeline no longer satisfies the design requirements. Categories of Limit-States are Serviceability Limit-State, Ultimate Limit-State, Fatigue Limit-State and Accidental Limit-State. In several design standards, the Fatigue Limit-State and the Accidental Limit-State are grouped under the heading of Ultimate Limit-States.
CONCLUSIONS AND RECOMMENDATIONS

When the pipe systems are not well supported/anchored may suffer significant displacements due to differential pressures, the occurrence of earthquakes leading to the collapse of the system. On the other hand, these displacements generate pressure waves (i.e., fluid-structure interaction) too, which is always linked to dynamic phenomena that can put at risk the safety and the operation of these infrastructures. An important aspect on the effect of fluid-structure interaction is the type of support system. If the support is rigid in terms of displacements do not allow large displacements, but in return it is generating high stresses on the pipe walls. In relation to support flexible, when a phenomenon like the waterhammer that propagates throughout the hydraulic system occurs unchained displacements in the system and then induces high pressures. The effects of a differential pressure or seismic action, many of which are often neglected in the pipe systems design, could endanger water mains or drainage strategic infrastructures that implicate interruption of water supply for urban densely populated areas. The actions due to degradation of the pipe/supports material that compose the fluid transport systems, the occurrence of earthquakes or the...
change in pressure can have similar effects, inducing high levels of vulnerability, which must be considered from the earliest stages of any Civil Engineering project. It is recommended in design phases and system exploration, the integrated and detailed analysis of unconventional dynamic effects in order to be guaranteed the best solutions in terms of safety and operation of each fluid transport system. Thus in the design, operation, maintenance and exploitation of hydraulic pipe systems should always be considered strategies for monitoring and diagnosis analyses, including the occurrence of transient flows, from possible scenarios associated with different operating conditions and earthquakes, if the local is placed in a seismic zone, as well as the design of the adequate distribution of supports/anchorages along the conveyance system.

7. BIBLIOGRAPHY


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