Increasing the quality of water pipe network systems by tracing the vulnerability

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Abstract: - The main objective of this paper is to introduce an emerging theory of vulnerability of water pipe networks and, in particular, its theoretical concepts. It is based on the form of a network and follows a systems approach. The application of the theory is presented using an example of a simple water pipe network. The fundamental contribution of this theory is to enable the design of water pipes networks that are more robust. It can also be used to achieve a more efficient management of water supply systems.

Key-Words: - Water pipe networks, vulnerability, water management, failure, system, quality.

1 Introduction

Traditionally, an analysis of demand and capacities has worked well for most networked systems. However, with increasing complexity of systems and the changing nature of demands, that is no longer sufficient. There is a need to examine the impact of damage to a system. For this purpose, for structural systems a theory of vulnerability has been developed (see for example, [1-4]). This is a theory of structural form and connectivity which is able to identify the vulnerable parts of a structure. The concept of vulnerability is associated with the disproportionateness of the failure consequences in relation to the initial damage. Thus a structure is vulnerable when a small damage demand leads to a disproportionately large structural failure. The action that may cause initial damage can be of any type including human error or even an act of sabotage. These concepts are applicable to many systems [5].

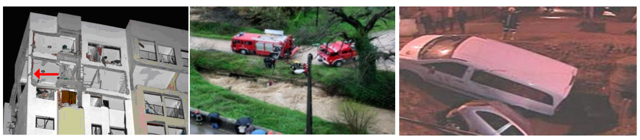
Recent research has lead to the application of the vulnerability concepts to water pipe networks. The purpose of this paper is present this emerging theory of vulnerability of water pipe networks (TVWPN). Much of the previous work on pipe network analysis has been on optimization problems. This shows that maximum flow occurs in a loopless network but such a network is not robust.

There have been some studies that examine the loss of links in a network. For example: [6] presented a scenario-based methodology for ranking the elements of water-supply networks according to the value to the owner; [7] have analyzed the change in nodal heads upon failure of different links. Among the network reliability studies; [8] has computed mechanical reliability by examining source-demand connectivity; [9] predicted the probability of the occurrence of structural failures in water mains; [10] calculated the reliability of a water distribution network using the ratio of the pressure-dependent outflows to the demand values; [11] and [12] examined the vulnerability of water supply systems using fuzzy models. Many of such reliability studies are based on an analysis of failure of either a single element or cut-sets for a given set of operational flows. The theory presented here is fundamentally different in that it focuses on damage events with disproportionate consequences.

The paper is organized as follows. Firstly, the theoretical concepts of TVWPN are identified. Secondly, its application procedure to water pipe networks (WPN) is described. Thirdly, the approach is illustrated through an example. Finally the conclusions are drawn.

2 The basic theoretical concepts of the TVWPN

In the context of this research work, vulnerability has been defined as being the disproportionateness of the failure consequences in relation to the initial damage. This definition is fundamental for the understanding of the TVWPN. A WPN is vulnerable when a small damage demand leads to a disproportionately large WPN failure. Fig. 1 illustrates three recent real Portuguese cases of vulnerable scenarios.



a) Setúbal, 22/11/2007 b) Jamor, 18/02/2008 c) Rio Tinto, 12/01/2010

Fig. 1: Recent vulnerable failure scenarios occurred in Portugal

A key concept in the proposed approach is to consider a system as a set of interacting objects. The objects are arranged in layers and connected together in an appropriate form. At the lowest level, a graph model represents the system in terms of nodes and links. In a WPN system nodes are the joints and links are the pipelines. The basic theoretical concepts of the TVWPN are: WPN leaf cluster, WPN branch cluster, WPN reference cluster, WPN ring, well formedness, nodal connectivity (η), WPN deteriorating event, WPN damage demand (E), relative damage demand (E_r), separateness (γ_r), WPN vulnerability index (φ). These concepts have been defined by making a direct extrapolation from the reciprocal concepts used in the structural vulnerability theory [1-4].

3 Application procedure of the TVWPN

The application of the theory to a WPN consists of two main stages – a clustering process and an unzipping process. The clustering process results in a description of a hierarchical model of the WPN for use in the next stage. The unzipping process results in the identification of failure scenarios.

3.1 Clustering process

The clustering process consists of a progressive formation of *WPN* branch clusters that are tightly connected. It starts at the lowest level by only using primitive clusters (i.e. the pipelines between the adjacent nodes) and finishes, at the highest level, by having the whole *WPN* including the storage tanks. It is a selective process that requires five clustering criteria to decide the next *WPN* branch cluster to be formed at each level of definition. These five clustering criteria, in order, are the following: the minimum total head loss (ΔH_{Tmin}), the maximum damage demand (E_{max}), the maximum nodal connectivity (η_{max}), the maximum distance from a storage tank (D_{ISmax}) and a free choice (F_C).

3.2 Hierarchical model

A hierarchical model is an alternative representation of a WPN but one which is central to the vulnerability approach. However, the WPN elements (i.e. the joints and pipelines) appear in this model according to the quality of the form of the WPN clusters resulting from the previously applied clustering process. The formation of a hierarchical model has to start from the bottom and then it moves up. New WPN branch clusters are formed during the clustering process and the respective primitive clusters used are clearly identified. Simultaneously, the WPN rings that represent these new WPN branch clusters and the clustering criteria used for the candidate selection are also shown. The part of the WPN that appears at the bottom of the

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hierarchical model has better form than the others parts appearing higher up in the hierarchy. This model is used during the next stage (i.e. the unzipping process) of the application of the TVWPN. This idea of using hierarchical model to represent a system was inspired on the biological hierarchical models. This process allows reducing enormously the number of possible failure scenarios (NFC) to analyze that may occur in a WPN. Instead of NFC measured by equation (1), the possible number of NFC using this process is a maximum as the number of branch clusters defined during the clustering process.

$$\sum_{p=1}^{n} A_p^n = \sum_{p=1}^{n} \left[\frac{n!}{(n-p)!}\right] \quad (1)$$

Where,

n is the number of sections (pipes)

A^n_p is the simple combination of the n sections p to p.

3.3 The unzipping process

The unzipping process uses the hierarchical model of a *WPN* as the basis to search for the vulnerable failure scenarios in the *WPN*. The hierarchical model is unzipped from the top to the bottom focusing on all the existing *WPN* branch clusters. Each *WPN* branch is unzipped in turn by introducing deteriorating events until a *WPN* branch cluster or the whole *WPN* becomes totally inoperative. After every deteriorating event, the *WPN* branch cluster changes and, therefore, it becomes necessary to re-cluster and to define a corresponding new hierarchical model of the damaged *WPN* branch cluster. This indicates that the unzipping is an iterative process. An ordered sequence of deteriorating events resulting from this process defines a vulnerable failure scenario.

For the guided search of failure scenarios, the unzipping criteria, in order of application, are the following: a cluster is not the reference cluster (storage tank), N_R; connects directly to the reference cluster, C_D; is a leaf cluster (a pipeline) rather than a *WPN* branch cluster, L_C; has a higher value of head loss, $S_{\Delta H}$; has the smallest damage demand, S_E; was clustered the latest, C_L; free choice, F_C. At this stage of the research, for simplicity, the damage to the reference cluster (storage tank) is not included. If a pipeline connects directly to the storage tank then it is likely that its loss will result in a disproportionate failure consequence. It is possible to identify a deteriorating even in a leaf cluster (i.e. a pipeline) rather than a branch cluster.

3.4 Failure scenarios

Through the unzipping process, several failure scenarios of a *WPN* are identified. Of these, the following are important. Total failure scenario is the one where least effort is required for the whole *WPN* to become inoperative (i.e. there is no water supply to any point). Among the identified failure scenarios with separateness equal to 1, the total failure scenario is the one that has highest value of vulnerability index (φ). Maximum failure scenario is the one that results in maximum damage from the least effort. Among the failure scenarios found, the maximum failure scenario is the one that has the highest value of φ. The maximum failure scenario is related to the most vulnerable part of a *WPN*. Minimum failure scenario is related to the least well formed part of a *WPN* and, in general, corresponds to the last leaf cluster to be clustered in the clustering process. Minimum demand failure scenario is related to the weakest part of a *WPN* to suffer damage. It corresponds to the leaf cluster that has the smallest value of damage demand. An interesting failure scenario is the one in which the designer is specifically interested for local reasons such as sensitivity to particular usage.

4 An example

In order to illustrate the application of the *TVWPN*, the *WPN* shown in Fig. 2 is used as an example. It is formed by 6 pipelines, 6 joints and 1 storage tank. It is kept simple for the ease of explanation of the procedure.

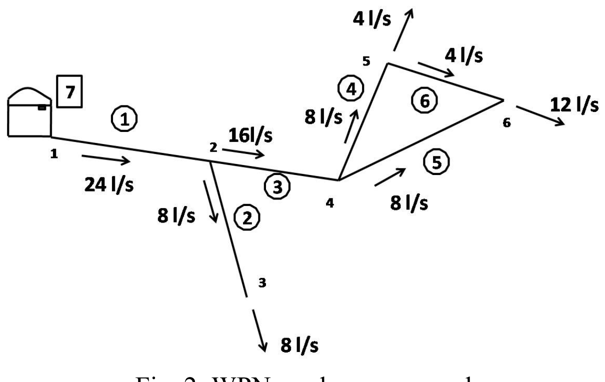

Fig. 2: WPN used as an example

The material for all the pipelines is polyvinyl chloride (PVC) with 0.01 mm roughness and 6 kgf×cm^{-2} (~ 0.6 MPa) service pressure is assumed. The relevant geometric (pipe's length and diameter) and hydraulic (flow and head loss) data of the *WPN* is presented in Table 1. The flow and the head loss values result from the hydraulic design of the *WPN*.

Table 1: Geometric and hydraulic data of the WPN

Leaf cluster	Joints	Length (m)	Flow ($L.s^{-1}$)	Diameter (mm)	Head loss (m)
1	1 ; 2	500	24	200	1.68
2	2 ; 3	600	8	125	2.67
3	2 ; 4	400	16	160	1.89
4	4 ; 5	300	8	125	1.33
5	4 ; 6	500	8	125	2.22
6	5 ; 6	400	4	110	0.94

Meanwhile, Fig. 3 shows schematically the clustering process, step by step, of the *WPN* of Fig. 2 in which black and grey lines represent leaf and branch clusters respectively.

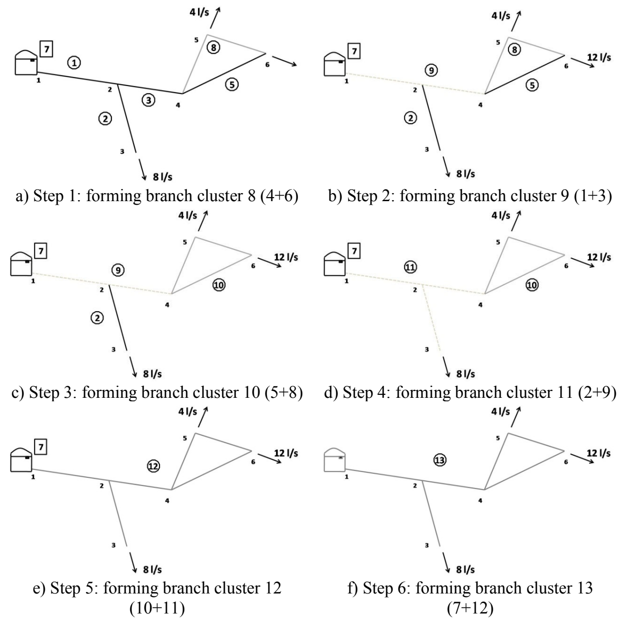

Fig. 3: Clustering process of the WPN (example)

Based on the information obtained during the clustering process, the hierarchical model of the WPN used as an example is defined (Fig. 4).

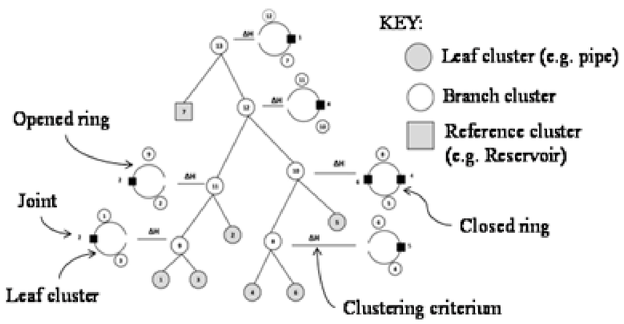

Fig. 4: Hierarchical model of the WPN (example)

As it was stated above during the unzipping process each *WPN* branch (see Fig. 4) is unzipped in turn by introducing deteriorating events until that *WPN* branch cluster or the whole *WPN* becomes totally inoperative.

Fig. 5 shows this process of searching for vulnerable failure scenarios of the *WPN* used as an example. Branch clusters 13, 11, 10, 9 and 8 are unzipped. Each branch cluster has represented the respective extended reference cluster (when it is necessary) which means the effect of the rest of the *WPN* on that branch cluster.

The failure scenario found for each branch cluster is presented. Branch cluster 12 is very similar to branch cluster thus it is not included in Fig. 5.

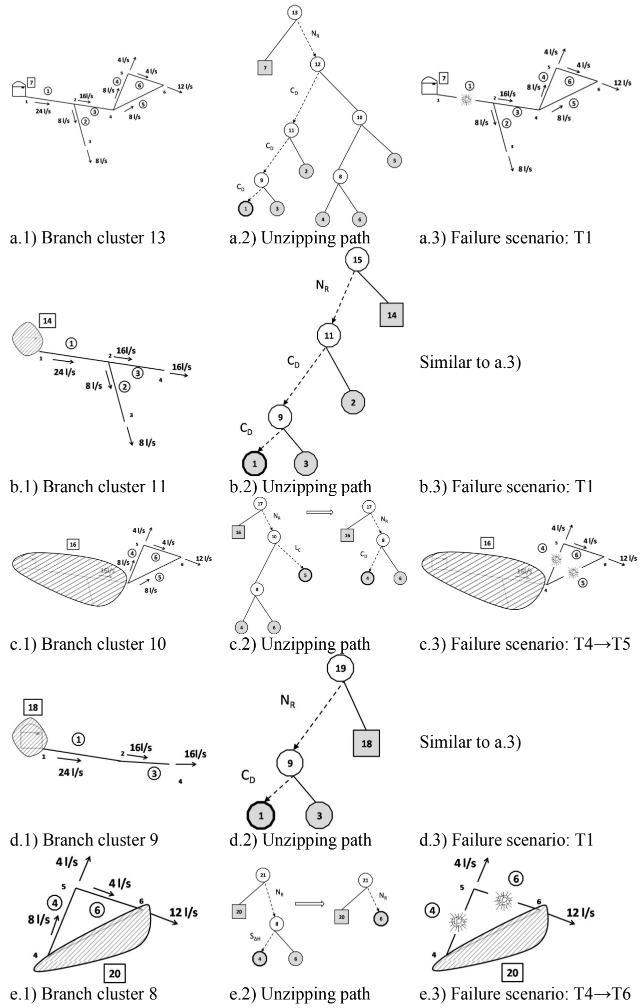

Fig. 5: Unzipping process of the WPN (example)

Table 2 summarizes the results of the unzipping process showing the vulnerable parameters associated to each failure scenario.

Table 2: Failure scenarios obtained through the unzipping process of the WPN (example)

Failure scenario	γ_r^-	E_R	φ
T1	1	0.167	6
T5 →T4	0.419	0.333	1.257
T4 →T6	0.212	0.333	0.636

Finally, based on this information it is possible to identify the vulnerable failure scenarios of the *WPN* used as an example which are:

- the total failure scenario and maximum failure scenarios are to damage pipe nº 1 (T1);
- the minimum failure scenario is to damage pipe nº 2 (T2);
- the minimum demand failure scenario is to damage one of the pipes of the *WPN* used as an example (T1, T2, T3, T4, T5 or T6), since they have the same value of E (6 kgf×cm^{-2}).

5 Conclusions

A theory of vulnerability of water pipe networks has been presented. Its main purpose is to identify the most vulnerable parts of a water pipe network and thus indirectly to increase the robustness of this kind of system and its quality.

The well formedness is a key theoretical concept of this theory. It is based on the connectivity and the quality of the pipelines in a network. The analysis progresses by clustering pipelines according to their well formedness until the whole network is one single cluster. A guided search through the unzipping of different clusters leads to a set of vulnerable failure scenarios.

The application of the theory has been illustrated through a simple water supply system. The results obtained for the example are the expected ones. However, the potential of this theory lies in the identification of inherent weaknesses in a real water pipe network. Further work is in progress to account for different type of damage and consequences and thus manage risks due to failure scenarios not identified by the classical theories.

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