Sensitivity Analysis of Topological Subgraphs within Water Distribution Systems

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Abstract

This paper presents a novel data analysis methodology for determining the approximate location of a leak/burst within a District Metered Area (DMA). This methodology is based on Statistical Process Control (SPC) and it is encapsulated in a Leakage Location System (LLS) that automatically processes the night-time data recorded, with a one minute frequency, by the DMA’s pressure loggers. The LLS was field tested and verified on a large number of real-life DMAs with both real and engineered leak/burst events (i.e., simulated by opening fire hydrants). The selected DMAs have varying sizes and different characteristics (e.g., industrial/urban/rural, pressure-managed/gravity-fed, etc.). These DMAs were monitored for a period of approximately 4 months and 132 engineered events simulating leaks/bursts ranging between 1% and 40% of the average DMAs’ inflow were carried out. The results obtained illustrate that the LLS enables obtaining substantially reduced operational costs by significantly reducing the leaks/bursts search area and reducing the number of unnecessary leak/burst repairs. The results obtained also illustrate that the LLS has the potential to enable water companies to: (a) improve customer service through more proactive and informed communications and reduction of the number/duration of supply interruptions and poor pressure situations, (b) realise a wide range of sustainability and environmental type benefits by saving large amounts of water, reducing energy requirements for pumping, consumption of chemicals for water treatment and hence the carbon footprint and (c) reduce the social costs associated with the disruption of traffic and business, the reduced fire-fighting capabilities and the potential of pollutant ingress through cracks.

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1. Introduction

Sensitivity analysis plays an important role in hydraulic system engineering. Sensitivities are first order estimates of the change of the state variables (flows, heads) with respect to different kind of parameter changes. Consequently, sensitivity analysis can be used for example for hydraulic model calibration [1]. The calculation of the sensitivities is normally a computationally costly procedure since it involves the inversion of the Schur Complement of the Jacobian matrix of the system equations of the Global Gradient Algorithm [2]. In this paper a new method is proposed that enables the calculation of the analytically exact sensitivities for a smaller subset of nodes. It will be proven that these sensitivities are equivalent with those that results from the inversion of the full system matrix. In terms of time saving, this is a very important result.

In a previous paper the Graph Matrix Partitioning Algorithm (GMPA) was introduced [3]. It was shown that the hydraulic steady-state calculation of large complex pipe networks can be split into a local and a global solution. Whereas the global solution includes solving a nonlinear system of equations the local solution consists of simple linear calculations. The basic idea of this method was the observation that supply networks commonly include a number of tree-like subgraphs (e.g. the large number of subsystems representing the secondary distribution and house connection pipes) that can be treated separately in a more efficient manner. The nodes of these subsystems often carry important information about withdrawals and cannot be removed without losing accuracy. With the GMPA exact accuracy (where the solution is completely identical to the full solution of the hydraulic equations) is maintained while reducing the size of the system to be solved by magnitude.

In this paper the basic idea of the GMPA is used for the derivation of the sensitivity matrix of the global topological minor subgraph. The development is based on the two assumptions that, first, the graph theoretical forest has been removed from the system and, second, that only Demand Driven Analysis (DDA) is considered.

In [3] the topological minor subgraph of a network graph that consists of supernodes and superlinks was introduced. Whereas the set of supernodes is a real subset of the original set of nodes, the superlinks replace the series of original links between the two supernodes. Fig. 1 shows the network graph of an example system (left) and its topological minor (right). The supernodes are the reference node R (by definition) and nodes a and b. The identification of the supernodes is simple for the network core: all nodes with nodal degree > 2. The superlinks consist of the paths between the supernodes. For example, in Fig. 1, superlink s2 replaces the original links 2, 3 and 4. If for each superlink one arbitrary link has to be chosen as so called internal tree chord, the links can be subdivided into the internal tree chord and an arbitrary number of internal tree links.
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