INTEGRATION OF GIS WITH HYDRAULIC TRANSIENT MODELING: EXPLORING BENEFITS, APPLICATIONS AND IMPACT ON MODEL SKELETONIZATION

BongSeog Jung[1], **Paul Boulos**[2]

[1]*Tebodin Middle East Ltd., UAE*
[2]*Innovyze Inc., USA*
bjung@tebodinme.ae, paul.boulos@innovyze.com

Abstract

Leveraging a utility's existing GIS is the easiest way to begin the development of a hydraulic model; however, the determining the most appropriate final model structure is important and challenging. Model skeletonization is the typical process of representing a water distribution network model in GIS. Applications include merging series pipes and consolidating parallel pipes into a single hydraulically equivalent pipe with the same carrying capacity, removing pipes less than a specified diameter, and trimming dead end mains. This paper addresses the effects of network model skeletonization on hydraulic transient analysis and includes a discussion of the factors that should impact skeletonization decisions. Case study is presented to illustrate the sensitivity of transient pressure extremes for various levels of skeletonization. It is shown that skeletonization can introduce significant errors in estimating pressure extremes and can overlook water column separation and subsequent collapse at vulnerable locations in the distribution system. This can lead to poor design and operation as well as inadequate protection of water distribution systems and added maintenance costs.

Keywords: GIS, Hydraulic model, Transient Analysis, Skeletonization, Water Distribution Network

1 INTRODUCTION

Advances in information management technology are allowing an increasing number of organizations to integrate traditionally separate information systems and applications. Geographic information systems (GIS) provide, in many cases, a common link between the various types of information. For a water utility, this common link is the utility's drinking water distribution system.

Historically, hydraulic models have been reconstructed every few years and often at much intervals, depending on the need at the time (e.g., a master-planning project or a pipe-sizing study). Reconstructing a hydraulic model was a necessary but time-consuming process. Interfacing with GIS is perhaps the most accurate and effective means of developing hydraulic network models of water distribution systems. These systems will normally contain large data sets of the water maps of the distribution systems with detailed descriptive facility information including node type, location, elevation and type, pipeline connectivity, size, length, material and age, population information, metered use data, and other pertinent data. Because GIS facilities are typically created for use in Automated Mapping/Facilities Management (AM/FM) applications (e.g., distribution system maintenance and management), this format is generally not suitable for construction of hydraulic network models. Common data format problems encountered are inclusion of hydrants, service connections, line valves, tees and crosses. In order to effectively utilize GIS data for hydraulic network modeling, the detailed GIS data must be properly processed and excess information eliminated (Figure 1). The process of representing only selected pipes in the network model is referred to as skeletonization [1].

2 NETWORK SKELETONIZATION METHODOLOGY

Three specialized skeletonization operations are normally required to convert GIS data into a hydraulic model. These are: data reduction (Reduce), merging (Merge), and trimming (Trim) applications (or RMT applications). Data reduction application is the capability to remove excessive pipe segmentation caused by valves, fire hydrants or other data capture processes, by dissolving interior nodes on pipe reaches and combining the associated pipe segments into single pipes. For example, combining all series pipes of similar characteristics (e.g., diameter, material and age) into a single pipe of equivalent length (sum of the length of each individual pipe). Data merging application refers to the capability of replacing parallel pipes and series pipes with a hydraulically equivalent pipe. Data trimming application designates the capability to remove short pipe segments such as dead ends (branching pipes) and hydrant leads. Trimming is carried out on only those pipes possessing at least one node of degree one, where the degree of a node is the number of pipes connecting that node.

It should be recognized that RMT is an iterative process, and the order in which each application is executed may result in distinct network segmentations. Figures 2a-c depict a two-level network reduction application while Figures 3a-c illustrate a two-level network trimming application.

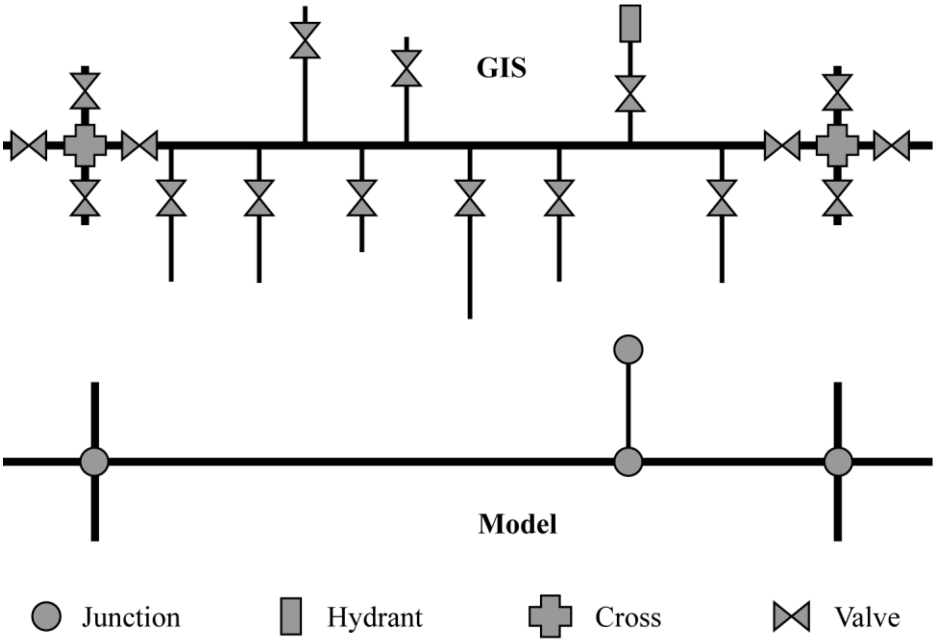

Figure 1. Single pipe GIS and network model representations.

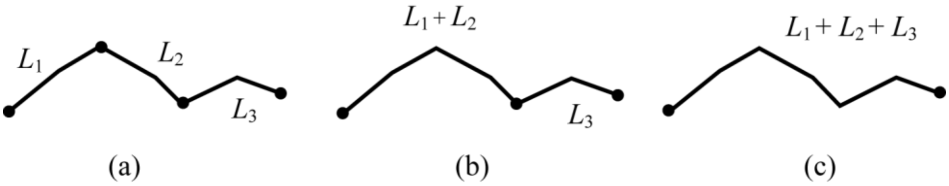

Figure 2. Example two-level reduce application.

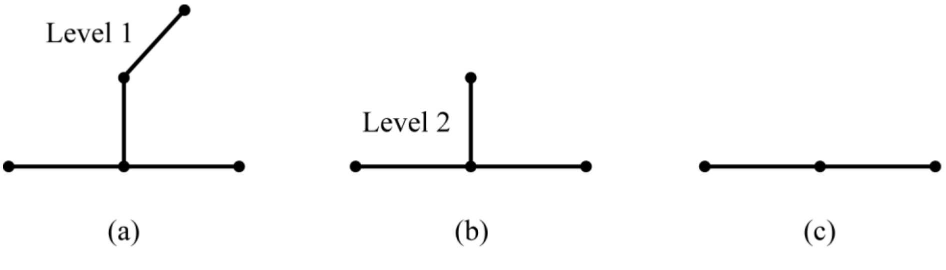

Figure 3. Example two-level trim application.

The data merging application makes use of hydraulic equivalence theory to maintain the hydraulic behavior of the larger, more explicit model. The concept of hydraulic equivalence refers to the idea of defining an equivalent pipe to replace two or more pipes in parallel or two or more pipes connected in series, while preserving hydraulic integrity. The equivalent pipe will produce the same head loss as the pipes it represents and will most likely have a nonstandard diameter.

3 IMPACTS OF SKELETONIZATION FOR TRANSIENT MODELING

Skeletonizing water distribution models offers considerable benefits in terms of computational performance such as a reduction in model complexity, faster model development, and shorter run times. However, such a model reduction process is only applicable under limited conditions as network hydraulic equivalency basis is derived solely from steady state network equilibrium theory. When applied to steady state network analysis, the skeletonized model is able to generate accurate results for flows and pressures. This theory does not hold for surge analysis and should be limited to steady state modeling applications. Network model skeletonization for surge analysis can lead to ineffective design recommendations leaving the system poorly protected and vulnerable to catastrophic failures and external contamination.

To illustrate some of the difficulties inherent in the skeletonization rules discussed in previous section, the following discussion is intended to raise awareness about where these rules might be misleading and could lead to a poor basis of design. After these general concepts, specific cases are presented to illustrate some of these pitfalls in greater detail.

The first is the skeletonization using reduction. Merging series pipes of similar characteristics and dissolving interior nodes could be acceptable in a steady state analysis; however, this process should be more carefully assessed for surge analysis. The approach of re-allocating nodal demands required when dissolving interior nodes during a network reduction application may eventually change the amount and location of demands, which can affect the reflection and dissipation of pressure waves.

The second is the merging application. To minimize the number of pipes in the model, series and parallel pipes are commonly replaced by a single hydraulically equivalent pipe with the same carrying capacity of the original pipes. This holds true for steady state analysis with virtually no effect on the results. However, the hydraulically equivalent pipe neglects the interaction of wave reflections and transmissions in the series and parallel pipes and often attenuates or magnifies the original surge response. For example, series pipes with area reduction can significantly increase the magnitude of the surge pressure [2]; however, the hydraulically equivalent pipe cannot represent the increase in surge pressure. Any difference in the pipe size, material and thickness, valves, orifices, accumulators, and other system elements provide unique transient characteristics. The influences of these discontinuities in pipelines create pressure wave reflections and refractions, and have a significant influence on both the magnitude and the phase of a rapid pressure pulse during a transient event. For example, pipe material doesn’t play any role in steady state analysis (it affects only the pipe roughness coefficient); however, the material elasticity directly affects the wave speed and significantly influences the magnitude of a surge and the phase of its wave. Similarly, it is not conservative to use the equivalent pipe with the assumption that the parallel pipe configuration can alleviate water hammer. Karney and McInnis [3] have shown that surge response can be more severe in a looped system than in a single pipeline. Depending on the system characteristics, the looped system may not attenuate a surge pressure and, in fact, can often make the surge response worse.

The last one is the trimming process: Since a dead end main does not play an important role in steady state analysis and the demand is shifted to the last remaining node to preserve the total system demand, branch trimming is widely applied to skeletonize a large model. Although branch trimming has no effect on steady state flows and pressures, it can have a significant effect on surge analysis. First, the elastic behavior of a dead end will be neglected in the trimming process and the corresponding wave reflection cannot be represented. Second, in a very different mechanistic way for open ends or connections to reservoirs where a pressure is negatively reflected, a dead end reflects a pressure wave positively, which means that it will experience the doubling of a surge pressure. Therefore, dead ends constitute some of the most vulnerable locations for objectionable pressures and should be carefully considered in a surge analysis. Additionally, trimming a dead end neglects the impact of its ground elevation, which if sufficiently high may cause cavitation under a transient event.

In summary, the traditional rules of steady-state model skeletonization ignore the complex interaction of transient pressure waves in the different pipe properties and characteristics of a water distribution system. The hydraulic equivalency theory used in model skeletonization and derived from steady state network equilibrium, is not applicable to surge analysis. At pipe junctions and dead ends, wave reflections and transmissions occur, which often magnify or attenuate the surge waves. Conducting a surge analysis with a skeletonized model may not be conservative and may not be suitable for estimating transient pressure extremes in a distribution network system. These observations were confirmed by a number of researchers. Martin [4] warned that oversimplified models will surely introduce some error. Boulos et al. [5] and Wood et al. [6 and 7] discouraged the use of highly skeletonized models for surge analysis of water distribution piping systems. As pointed out by Jung et al. [8], the water hammer response in water distribution systems is strongly sensitive to system-specific characteristics, and any careless generalization and simplification could easily lead to incorrect results and inadequate surge protection.

4 CASE STUDY

The purpose of the case analyzed is to verify the rules of skeletonization and compare the surge analysis results between the original and skeletonized models. In order to illustrate some of the pitfalls of skeletonization for surge analysis on a larger more complex system, the rules of model skeletonization are applied to an actual water distribution network shown in Figure 4. This system comprises 1639 junctions, 2088 pipes, 23 wells, 23 pumps and one storage tank. The identity of the corresponding water utility is withheld due to security concerns. Figure 5 shows the skeletonized model after trimming dead end pipes and replacing series pipes with hydraulically equivalent pipes while conserving total system demand. The skeletonized network is reduced to 1134 pipes and 685 junctions and meets the EPA IDSE network model requirements [9]. For this example, transient is initiated from pump trips initiated at 5 s. Figure 6 presents the transient head profiles at junction 242 before and after skeletonization. As shown in the figure, the transient results for the skeletonized model are much less severe than those of the original system. It should be noted that because of satisfying hydraulic equivalency principle, both the original and skeletonized models produce the same steady hydraulic equilibrium condition (66.6 m) for the initial 5 s period; however, the maximum surge heads before and after skeletonization are 153.1 m and 84.7 m, respectively. This shows that the maximum surge head of the original model is 81% higher that that of the skeletonized model. This exercise also demonstrates some limitation of the EPA IDSE hydraulic model requirements for transient analysis. For example, the IDSE requirements neglect the importance of both dead ends and high elevation points in the distribution system that can have a severe effect on pressure surges.

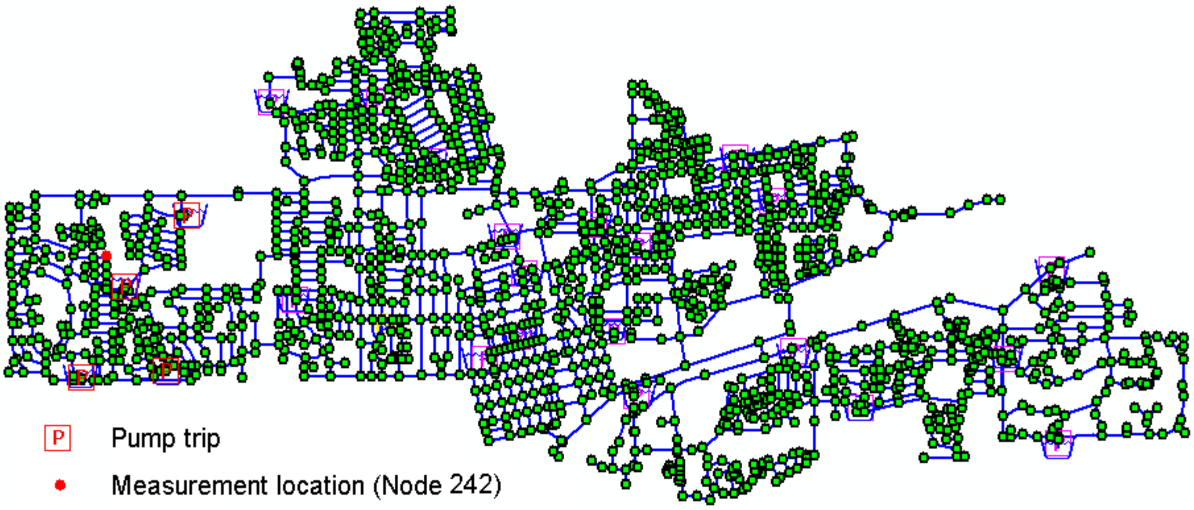

Figure 4. A network system before skeletonization.

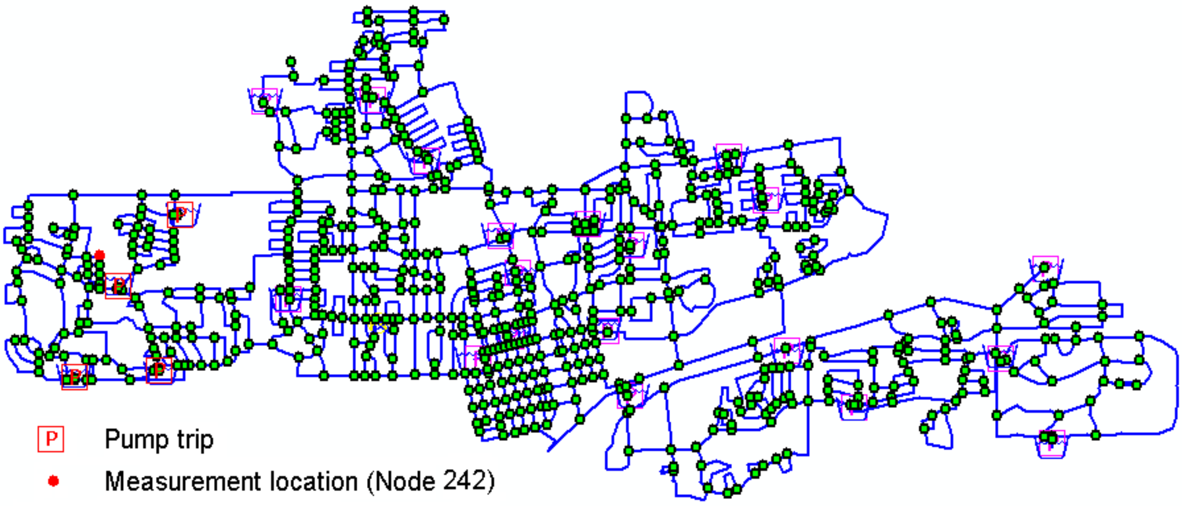

Figure 5. A network system after skeletonization.

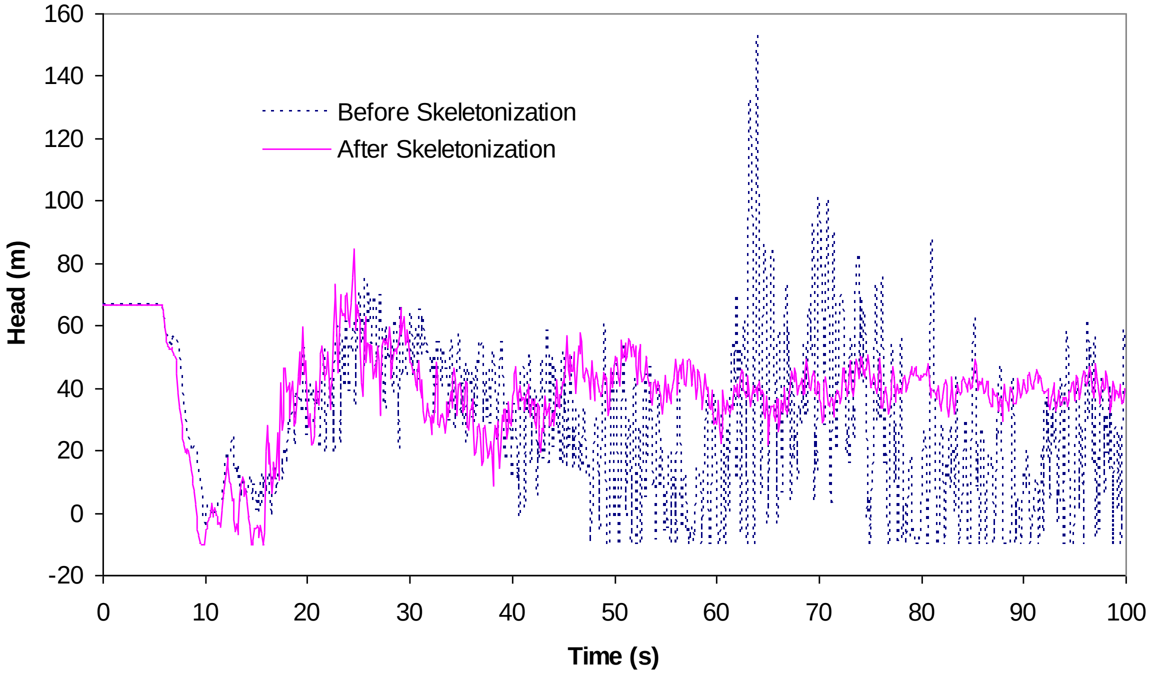

Figure 6. Pump trip transient results at node 242

5 CONCLUSION

The integration with GIS is the most accurate and effective means of developing hydraulic network models of water distribution systems. The representation of water distribution network mode needs a process of model skeletonization and this skeletonization should be carefully accessed on the hydraulic modeling purpose and application, especially for hydraulic transient analysis.

Water distribution systems rarely operate in steady-state conditions and their behavior under transient conditions must be properly assessed to avoid catastrophic system failures and unnecessary leakage and contamination, and ensure safe, reliable operation. Comprehensive surge modeling is required to help predict objectionable transient pressures and help prioritize control and preventive strategies. Traditionally, surge modeling has focused on analyzing large diameter transmission mains with few or no branches and loops. Skeletonization techniques derived from hydraulic equivalency theory were used to reduce the size and complexity of these systems and generate smaller skeletonized models. However, skeletonization can affect the surge results of distribution system model in various ways. Distribution systems respond differently than transmission lines because of branches and loops, and excessive pressure surges can be present in distribution piping. The rules of skeletonization ignore the inherent problem of interaction of surge waves in the different components and pipe properties of a water distribution system. At pipe junctions and dead-end branches, wave reflections and transmissions occur, which often magnify or attenuate the impinging surge waves. The wave speed is also a function of the pipe material, diameter, and thickness. Finally, oversimplified models can overlook the dangerous effects of liquid column separation and subsequent collapse on system integrity. A surge analysis can be used to accurately determine the extent of transient pressure extremes but only with properly defined representative models.

AUTHOR INFORMATION

Bong Seog Jung Discipline Specialist, Middle East Ltd, bjung@tebodinme.ae
He has BS and MS degrees in environmental engineering from Pusan National University in Pusan, South Korea, and a PhD in civil engineering from the University of Toronto in Ontario, Canada. He has more than 15 years of experience in water distribution engineering and has written more than 40 engineering articles.

Paul Boulos President, Innovyze Inc., paul.boulos@innovyze.com
He has BS, MS and PhD degrees in civil engineering from the University of Kentucky in Lexington, USA and an MBA from Harvard University in Cambridge, USA. He has more than 30 years of experience in water distribution engineering and has written more than 200 engineering articles, reports and books.

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