Transient Field Monitoring as a Key Driver for Decision Making and Design

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ABSTRACT

Both new sensors and new data processing technologies allow alternate approaches to system assessment, ones that are more strongly based on measured performance and less dependent or *a priori* modeled behaviour. This paper reviews the limitations of conventional design and briefly outlines a possible data-rich approach to design, one that characterizes loading in terms of a more probabilistic or holistic framework. Such an approach is particularly desirable – and likely more suitable – for transient events in truly complex supply and distribution systems. To be ultimately satisfying, it will be necessary to relate the extracted statistical behaviour to key performance issues and to the key variables influencing design.

INTRODUCTION

Design decisions have historically been made largely on the basis of simulation models of the proposed systems that rely on deterministic design loads. Yet as infrastructure ages and grows in size and complexity, our problems often change from whole-scale construction to the need to repair, rehabilitate, or renovate largely existing structures. Of course, system modifications still need to be well considered and selected: as our requirements expand, we must modify existing designs to match our needs, the process changes. Simulation may still play a significant role, but suddenly it becomes essential that we also learn more about what already exists and how this already behaves. Due to advances in sensor technology, we are now in a position where we can now listen to the system more, and get it to "tell us" what must be done. Existing technologies enable us to observe and listen to the system in a nondestructive and non-invasive manner.

In the case of water distribution systems, monitoring pressure transients is one way we can listen to the system. The response of the system to normal operating conditions can tell us how the system may respond to abnormal conditions, and how we might better protect the system from its own response to transient loading. Further, this complimentary approach provides efficient insights into the system behaviour, particularly for highly complex and evolved systems.

The intent of this paper is to explain the shortcoming of the current design practice (especially for transients) and to discuss how field monitoring of existing infrastructure can be used as a driver for decision-making about system modification and re-design. These topics will be explored from the context of transient design and advice on strategic investment in transient protection and monitoring protocols. The paper begins with an overview and critique of the current steady state and transient design practice and then proceeds to propose a more enhanced and approach for transient analysis and design.

CURRENT DESIGN APPROACH

Traditional engineering design has often relied on worst-case design loading; loading which is typically set out by a regulated design code or practice. Research, innovation and technological improvements have made engineering design easier, but the basic theory and design approach has not changed much. Whether or not we are talking about designing a bridge or a water transmission system, the least variable (i.e., the most restricted) aspect of the design comes through the determination of loads. Once a general design has been agreed upon, the detailed design is highly depended on a pre-specified set of loads such as weight, seismic quake, wind, pressure, flow, etc.

The design of a water system, whether it consists of components pertaining to supply, transmission or distribution, has long suffered through the question of what loading is appropriate. Nowhere is this clearer than in North America, where water is treated as a right and where as a result, a water system's required capacity is typically determined by a relatively arbitrary worst-case design load; a load driven by a deterministic assumption. The determination of the worst-case load typically first requires the determination of an average or typical load.

Long term population and industry forecasting is used to predict the size of a future service area, and these extrapolations are then typically multiplied by a per capita or per industry consumption rate. Many different techniques can be used to determine actual consumption rates, and some of these include: analysis of historical data (billing or metering records), similarity comparisons with other municipalities, unit consumption demands, extrapolation from regional models/studies, and small scale surveys of individual and/or industry use. If historical data is scarce, unreliable or not comprehensive, then the most common practice is to apply a standard per capita or per industry consumption. A standard consumption rate in North America may be 300 to 350 liters per capita per day. Even though this approach can rely on historical analysis of data, its ultimate application is purely deterministic. Furthermore, present population census data and/or billing records are fairly reliable, but future ones are inherently probabilistic in nature. They are therefore highly influenced by random future events and factors.

When the service areas are multiplied by the deterministic consumption rates, a rather benign quantity is born: the average day demand (ADD). Unfortunately, in both a historical or non-historical approach for determining ADD, this quantity is always presented as a deterministic value. The ADD methodology for determining baseline design loads is rarely disputed or questioned, and has been continuously used without an associated probability or level of risk. This baseline load directly feeds into all other design loads, including: minimum hour demand (MHD), maximum day demand (MDD) and peak hour demand (PHD). Once cast, it is a combination of these loads that ultimately determines the size of the water system components such as water treatment plants, feedermains, pump stations, reservoirs, and ultimately surge protection. However, these design loads are also by their very nature variable, and therefore the conventional design of a water system is left without any other option than to use a worst-case variation of this load. With the diurnal nature of demand (and therefore pressure), the difference between PHD and MHD can be many fold. Even more troubling is that original design loads are rarely confirmed or monitored post construction and/or operation, and lessons are infrequently learned. As a result, the conservative load based design of water systems has yielded a sleuth of under-used system components that are more difficult and costly to operate. A good example of such components comes in the form of dedicated surge protection equipment, which is designed through the use of computer aided transient analysis.

CONVENTIONAL TRANSIENT ANALYSIS AND DESIGN

The field of hydraulic transients has long been considered as a ‘black box’ of a topic. The traditional and true expertise in this field has often been limited, and its importance is only now gaining widespread traction in standard water transmission and distribution systems. The increased requirement for the considerations of transients in design has quickly brought the need for engineers to develop this expertise in order to be able to compete. At the same time, the advances in, and acceptance of computer modelling has never been higher. With these two driving factors, the field of transient analysis has quickly progressed to the development of an unwritten design strategy: the worst-case design using the aid of a computer model.

A transient analysis of a water system requires the understanding of the system characteristics; an understanding that is nowadays always summarized within a comprehensive steady-state computer model. It is the combination of this steady-state hydraulic model and the previously discussed deterministic design loads that drives the decision making and design process for water systems. The proliferation of hydraulic modelling arose from the need to ‘predict’ the future without intruding on, or risking the performance of, a real life system. The advances in research and in technology have spawned a whole branch of hydraulics which is simply referred to as modelling. Whether or not we are talking about models for asset management, master planning, computational fluid dynamics, transient analysis or system optimization, the purpose of any model is still only to mimic nature through mathematics and to be able to do it in a non-intrusive manner. Every model should have its own purpose and goal, and nowhere is this clearer than in hydraulic transient modelling. However, this important purpose is quickly fading because the scale and complexity of the models is rapidly increasing and because the industry is quickly shifting towards rehabilitation and optimization of existing infrastructure.

A standard transient analysis typically relies on a previously constructed steady state model that contains all system characteristics pertaining to pipes, elevations and boundary conditions. This is probably the most overlooked point in a standard transient analysis. Given the traditional deterministic nature of the steady-state model outputs, the subsequent transient model inputs are themselves assumed to be deterministic. Very little thought is actually given to the uncertainties and variability of steady-state modelling parameters such as roughness, leakage, demand, etc. Uncertainty in water distribution system parameters is usually ignored and the most likely parameter value is selected and used in the analysis and design (Grayman, 2005). The best one can hope is that the steady state model has been calibrated or at least partially calibrated for a current design year.

All transient modelling packages solve a set of two governing non-linear partial differential equations. The two most accepted and used procedures for solving the equations are referred to as the method of characteristics (MOC) and the wave characteristics method (WCM). Depending on the code, the steady-state model might have to be simplified in order to reduce the run-time of the transient model simulation. For example, a boundary intensive WCM solution typically require orders of magnitude fewer calculations and is often much quicker in solving large systems with many pipe lengths and nodes (Wood et al, 2005). This type of transient analysis approach relies on the pure belief that computer power can overcome anything, and often leads to individuals performing detailed transient analysis on asset management models in excess of 30,000 links and nodes. The ultimate question comes down to whether or not the results are believable and or realistic when it comes to actual field conditions.

The model simplification process is typically referred to as skeletonization for surge purposes; the rules for which are relatively unclear and often contradictory of the general hydraulic equivalency theory. Skeletonization can be performed manually or through the aid of computer algorithms, however this theory is predicted based on steady state equilibrium and does not consider the implications of pressure wave interactions throughout the system and at important boundary conditions (Jung et al., 2007). Once the steady state model for the surge analysis is finalized, assumptions and estimates on several key transient related parameters have to be made. These may relate to: pump run times, pump and motor inertias, acoustic wavespeeds, vapour pressures, valve characteristics, etc. These parameters are often uncertain and are also used as surrogates for other more variable non-modelled parameters such as air content, actual energy dissipation, sediment content, etc. Even if all all of the system characteristics and parameters are determined and/or assumed, the final question for a transient analysis still comes down to what to design the system for and at what load?

Unlike steady state loading that is in the form of system demand and therefore supply, transient loads (or events) arise in different forms through different sources and it is therefore very difficult to consider all potential risks. Nevertheless, a power failure event that impacts the flow conditions has often (but not always) been found to be the most consequential of all transient events. Power failures must be considered inevitable over the long life of water transmission and distribution system because they are by their very nature unpredictable events. Thus the consideration of a power failure precludes a more direct avoidance of its occurrence and substitutes as a worst-case surrogate for potentially less damaging routine or non-routine pump and valve operations. Nevertheless, power failures can occur at almost any operating condition, for which the variables may include: the magnitude of the system demand and/or flow, the water level in reservoirs and tanks, the number of pump stations operating, the number of pumps operating per pump station, and the status of dedicated surge protection equipment. As systems and their representative models increase in size and complexity, the number of design scenarios that arise from these numerous variables quickly becomes overwhelming. As a result, a computer model aided transient analysis may typically consider a combination of scenarios based on the following options (or variables): global system power failure *or* local pump station power failure, PHD *or* MHD (i.e., reservoir/tank filling), and current *or* future year (and system layout).

These design options lead to eight distinct scenarios and therefore to eight possible design loads. The design year and system demand typically determines how many pump stations and individuals pumps would operate during such a scenario, and therefore determine the conditions during which the surrogate power failure event will occur. The ultimate surge protection recommendations and design are then made on the worst-case level of risk from the scenarios considered. To get to this ultimate design load, several predictions and assumptions were made on steady state system demand, system characteristics, steady state system parameters, transient parameters and transient events. Since real systems contain many unrepresented dissipation mechanisms, this approach can lead to conservative and overdesigned systems which are rarely monitored or learned from. In the end, a transient analysis using numerical modelling is only as good as its model inputs; inputs which are truly not deterministic and therefore highly variable.

Conventional detailed design is often thought of as relatively restrictive in that the decisions made at this stage have significantly less impact that those made earlier on in the process. Nevertheless, a detailed design that is driven by deterministic or worst-case loads can also have a significant impact on future cost and performance a system. The deterministic design of water transmission and distribution systems and the subsequent worst-case load design for transient conditions have a potential to significantly increase the long term cost through inadequate, inefficient and/or highly conservative components. Furthermore, these designs are rarely, if ever confirmed or monitored. Instead, a surrogate in the form of computer aided hydraulic modelling is seen as the optimal solution for design and rehabilitation. With the complexity of the systems and their respective hydraulic models increasing, a new and complimentary approach for transient analysis and design of existing water system components is needed. The most logical base for the new approach is to learn from actual system evolution, and to use this knowledge to determine future level of risk.

Case Study. In order to explain the proposed potential for such a methodology, it is probably best to present actual results and examples of where computer models are either inadequate, conservative or cases in which they can be complimented with non-intrusive field work. This section proceeds to show some results from two different water supply, transmission and distribution systems in North America, from now on referred to as System A and System B. The only system we have space to consider here is a large and growing municipality with a current population in excess of a million. The water is treated from a surface water source and distributed along a vast significant distance using a separated transmission and distribution pipe network. The transmission system carries the water from one pump station to another, and each pump station also distributes the water locally. The detailed hydraulic model for the system contains tens of thousands of links broken down and isolated into a number of pressure zones. A typical pressure zone may have between 1000 and 3000 links. The model is partially calibrated for the current year and is also expanded for a future planning year.

High frequency pressure transducers capable of recording between -14.7 psi (10 m H_20) and 250 psi (175 m H_20) were installed at key locations within these two systems: including water treatments plants, low lift pump stations, high lift pump stations and system high points. The pressure transducers are complimented by smart data loggers that can record at different frequencies, thereby allowing the user to decide on the quantity of data recorded. Furthermore, the data loggers are capable of only recording transient events based on a set of pre-defined user statistics such as absolute pressure deviation and mean standard deviation. The pressure transducers were installed at different locations for durations varying between 1 month and in excess of 13 months. During the recorded period a wide variety of transient events were recorded, including those caused by power failures, routine pump switches, pump trips, pipe breaks, equipment calibration, valve operation, and planned field tests. The planned field tests were used to establish a baseline and to validate the subsequent transient modelling that was geared for future development and expansion. The field tests typically only consisted of single pump trips or pump changes in order to minimize the risk and stress on the systems. Figures 1 and 2 shows a typical result comparing a field recording event to a numerical simulation study; the agreement between the two is typical but unimpressive.

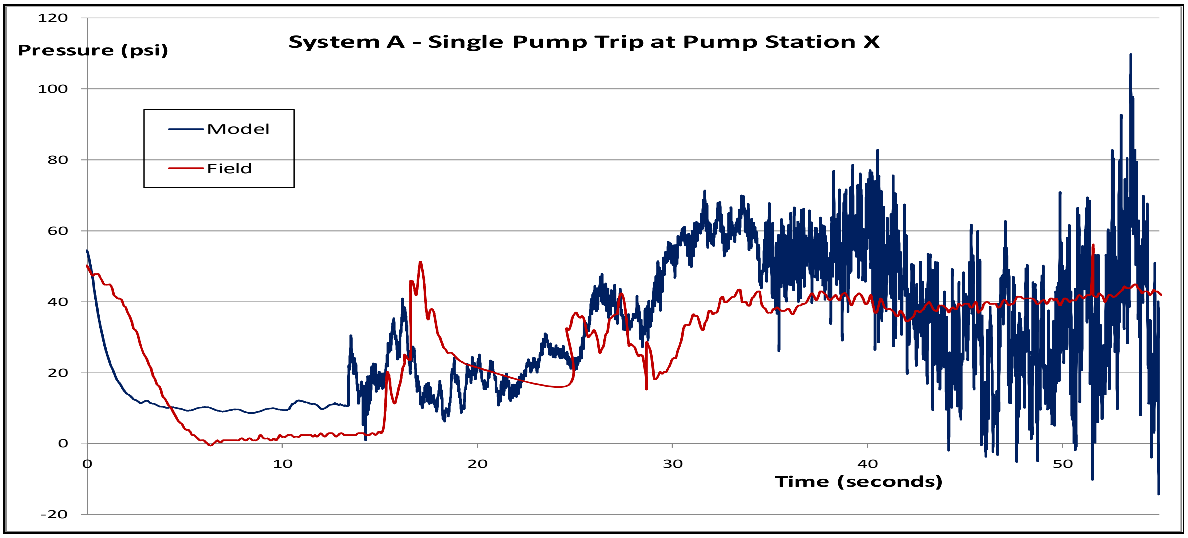

Figure 1: Model versus Field Results for a Transient Event at Pump Station X of System A

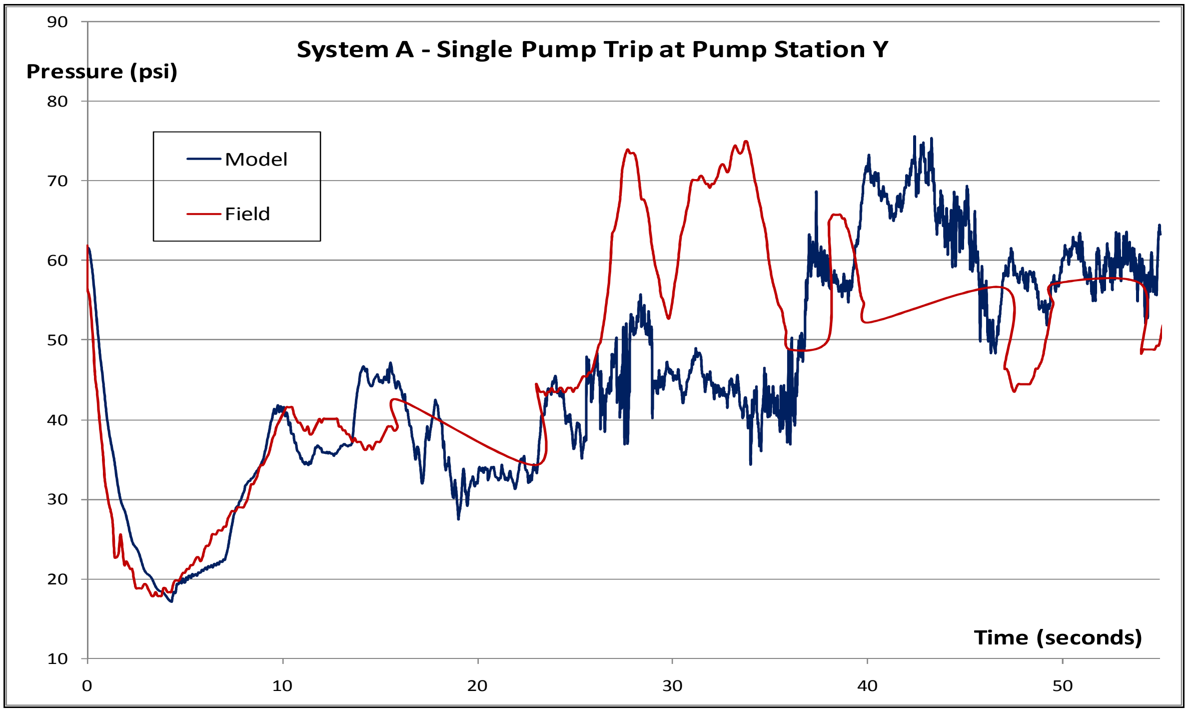

Figure 2: Model versus Field Results for a Transient Event at Pump Station Y of System A

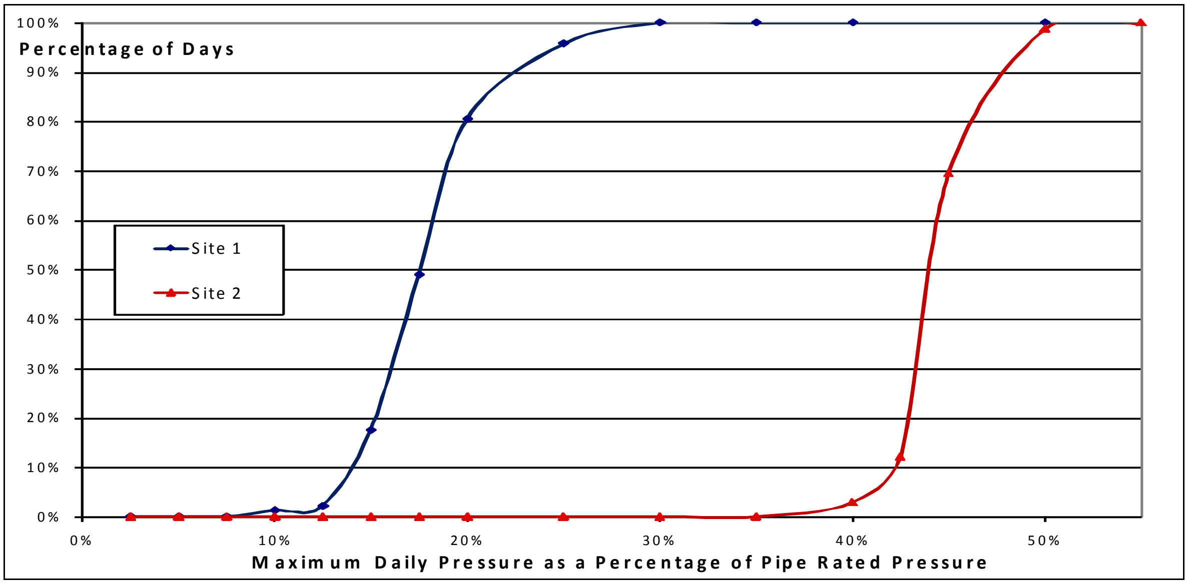

Figure 3: Sample Cumulative Probability Distribution

A radically different view of the system is shown in Figure 3. In this case, we neglect much of the relative complexity of the field traces and work with the cumulative field data directly in the form of a probability distribution function. This tells at a glance the range of conditions experienced at different locations, and this kind of plot can be related directly to design decisions and protection choices.

CONCLUSIONS

The modeling of water distribution systems have been followed a natural path of adding progressively more complexity into the numerical representations of systems, essentially throwing the ever more impressive range of computer resources that are available at a complex and nearly intractable problem or real water delivery systems. This paper argues that for the most complex of modelling tasks – that is, for distribution systems of medium to large urban areas – that an alternative modelling approach may be possible and attractive. This alternative approach makes direct use of the possibility of obtaining real time system performance of the existing system, and learning how to associate direct decision variables to statistic summaries of performance. Unfortunately, space limitations prohibit a full exploration of the mechanism of connecting momentum and pressure changes to statistical parameters.

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