Assessing Performance of a water Transmission System using an Inverse Transient Method

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Abstract
Traditionally, transient pressures have been considered as a potentially destructive influence in systems, possibly leading to pipe or equipment failures and representing a threat to both water quality and smooth operation. More recently it has been realized that transient pressures also carry considerable information about system state and condition. This has lead to so-called inverse transient methods, where a transient signal is used to infer system characteristics and parameters. The current work goes further than even this, specifically by considering the possibility of permanent installations to monitor and assess the system's transient response. This paper describes a collaboration between the Regional Municipality of Peel, the University of Toronto, Earth Tech consultants, and the Pressure Pipe Inspection Company to bring this transient data into focus and to greatly magnify and explore its value. While the final verdict is not yet out, the overall performance of this monitoring system, initial indications are that fruitful and economic partnership between data, sensors and monitoring technologies is possible.

Introduction
Transient pressures, sometimes called water hammer or surge events, can occur whenever flow conditions in a pipeline change; they can be both dramatic and destructive if conditions change rapidly. Common causes include turning pumps on and off, opening or closing of valves (including those associated with demand changes), and the rapid expulsion/admission of air that can occur during line filling or emptying. Transient pressures have been known to cause catastrophic failure of pipelines but more commonly are associated with latent damage which may eventually lead to failure. Moreover, transient failures can be progressive, where one failure, perhaps even a small one, can itself create a transient event, which can cause another failure, and yet another transient event. These are all reasons enough to be aware of transient pressures and to try and mitigate them.

But, in addition, basic information on the performance and condition of a pipe or transmission main can also be obtained by observing how the transient pressures travel

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and attenuate as they moves through the transmission system. In particular, by inducing a controlled transient into the system, a measured response can be compared to a predicted transient response at two or more different locations. This comparison is not only intrinsically interesting, it is rich in system data, and can be used to calibrate numerical models. Thus transient calibration has been used to do things such as calculate an average C factor, find evidence of obvious leaks or faults, and to calibrate a dynamic transient model. Such information is of great value in system planning, upgrade and replacement decisions, as well as for refining and improving surge protection equipment and procedures.

The Region of Peel in Ontario, which includes Mississauga, Brampton and several other communities, owns two water treatment facilities and has over 3215 km of water mains. The Region takes pride in striving to build some of the most innovative, technically-advanced water and wastewater systems in the world. This paper discusses the results to date of an ongoing transient pressure study that began in 2005 and is being conducted by authors of this report and their associated organizations, including, the Region of Peel, the University of Toronto, Earth Tech Engineering Inc., Hydratek and Associates Inc, the Pressure Pipe Inspection Company and the Ontario Clean Water Agency.

Modelling Challenges

There are a great many reasons for creating a model of an engineered system. Chief of these almost invariably is the desire to predict the behaviour of a real system over a range of expected or design conditions, with the model predictions allowing prior adjustment, modification, fine-tuning and control of the design decisions before any expensive or time-consuming implementation of them is made in the field. The benefits of the modeling approach are particularly desirable when durable products are being installed or maintained, or when long-lasting decisions are made. In such contexts, the true design conditions, such as the full development of water demand in a distribution system, may well not occur for a considerable time into the future and thus cannot be reasonable measured or recorded. Naturally, though, to be of benefit to the designer or owner, any model must present real advantages relative to the alternative of field adjustment and guesswork. That is, the artificial or substitute "world" that the model encompasses must capture enough of the behaviour of the real system to permit sensible predictions. Thus, all models must be sufficiently simple so they can be to implemented in real time and with finite budgets – that is, much simpler and cheaper than the worst consequences of decision being considered – and to be accurate enough to allow improved decision making.

However, when considering infrastructure systems, such as a water distribution system, designers are almost never making "all or nothing" modeling decisions. Rather, a large part of the system is probably already built and implemented, and important real-time decisions are not truly needed for the system as a whole, but rather for specific questions and purposes. For example, if a new section of transmission main has recently been installed and put into service, the pressing question is not whether it should be used or kept in service, for such things are obvious, but rather what other parts of the system are now best candidates for replacement, rehabilitation or extension? For such questions, creating and calibrating a distribution system model is of great benefit, and it is exactly this question that is considered in this paper.

Model Calibration

The challenge of calibrating complicated systems, though, such as a water distribution system, is that they so often contain many components with a great many uncertain parameters. As time goes by, uncertainty about the state of the system – say the condition or deterioration of friction in each pipe, the status of key values, or the real time varying nature of demands – often gradually increases from much better known conditions at installation. As a direct result, the number of things a designer or modeler would like to know about in the system typically ranges from many hundred to many thousands of variables.

This mere count of unknowns creates an instant and inescapable calibration problem: to be mathematically well defined, an analyst needs to collect in the field at least as many data points as there are unknowns in the associated model. The alternative – that is, of having fewer data points than unknowns – creates what is called an underdetermined system. In any underdetermined system, the trick is not so much to solve it, but to obtain a unique and reliable answer. For example, consider the trivial equation $x + y = 2$; it is not difficult to find solutions, but it is much more difficult to pin down the answer to single solutions. How does one distinguish between $x = 0$ and $y = 2$, or the converse, or indeed any other of the infinite number of valid possibilities? We simply need more data.

The solution to this essential problem of calibration, and thus to obtain enough information to achieve reasonable calibration results, was resolved in Peel by using a transient data collection approach. Transient calibration collects thousands of data points from several locations with fast sensors recording over a sequence of hours. In order to make use of this data, though, the analyst must use a transient model of the water distribution system, one that models not equilibrium conditions, but rather how equilibrium conditions transform with time.

An Overview of a Typical Data Report

To have a sense of these transient events it is helpful to recall that transients invariably occur as a result of short-term imbalances in the rate of inflow and outflow in any pipeline system. In particular, if inflow into a segment, say, is suddenly to increase, the outflow cannot typically respond instantly; rather a pressure signal, in this case a higher pressure wave, propagates into the system to carry the news of the change. The increased pressure then signals the outflow to increase and become more in line with the new rate of inflow. Due to inertial and friction effects, the convergence of the system back to equilibrium usually requires the exchange of several distinct waves between inflow and outflow locations. A transient simulation program can capture such changes as well, and then a kind of supervisory computer model can be used to bring the predicted and measure response into agreement.

This paper summarizes, as an example of what kind of information is possible, data collected on January 16th, 2008, through an online web access system to the transient pressure units installed in Peel during the summer of 2007. This new data will include the period 01/01/08 through 01/15/08. A summary of the data retrieved is shown in the following tables. Overall, the surge chambers at the stations were found to be effective at suppressing the transient shocks occurring in the system and thus all measured events can be classified as routine or normal for daily operations that most commonly include pump starts and stops, and routine valve activity in the network.

Table 1: Period 01/01/08 through 01/15/08

Location	TP-1 ID	File Size*	Total No. of Transients	Maximum Pressure (psi)	Previous Maximum and Date	Comment
Peel Region / Lakeview Pumping St./ Inlet of small air chambers @ 924 East Ave., Mississauga	No. 58 Pressure Zone 1	6.04 MB	47	121	120 - 12/20/2007	OK
Peel region / Lakeview Pumping St./ Inlet of big air chambers @ 924 East Ave., Mississauga	No. 59 Pressure Zone 2	11.5 MB	41	184	178 – 12/28/2007	OK

*File size is based on downloading the data on 01/16/2008

The specific unit, a "TP-1" sensor (#58) was installed at 924 East Ave., Mississauga, inside pump Station and just before a pair of 75 cubic meter air chambers that were specifically installed to protect the Peel system. As is typical of this equipment, all the data was valid throughout the collection period, and has collected 47 short lived transients which can all be considered normal and routine events. The overall trace of the data collected is depicted in Figure 1.

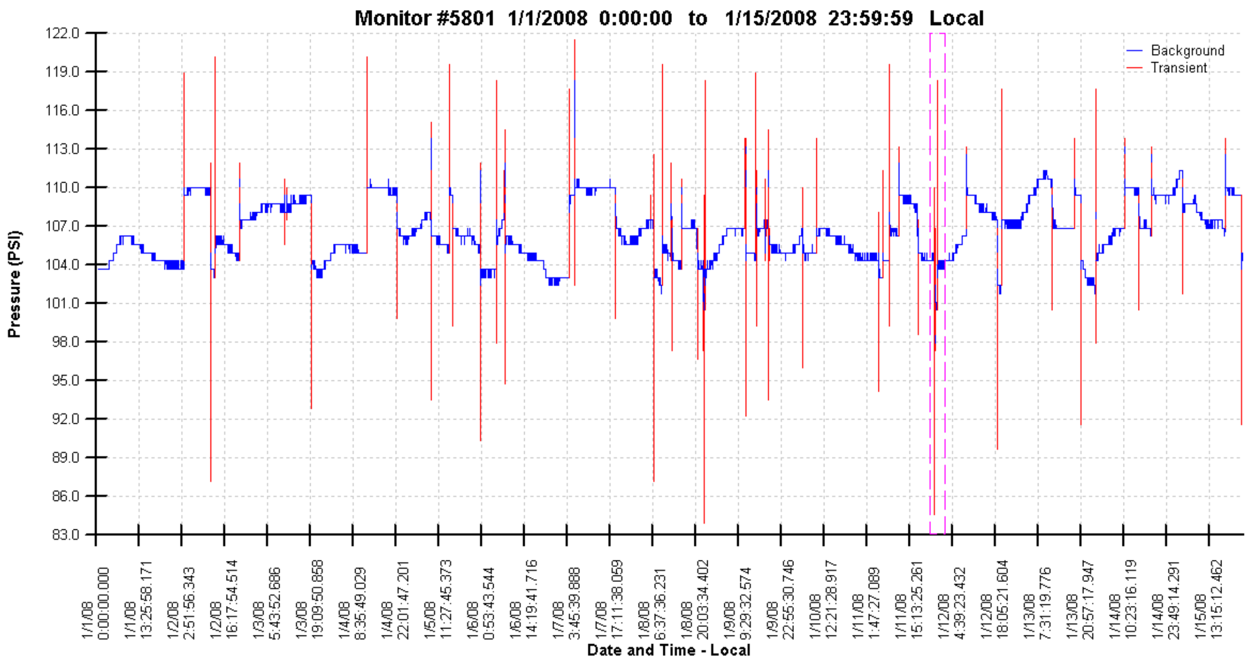

Figure 1: Pressure Profile

Of particularly importance in such records are the maximum events. The largest transient was identified further, and shown in the graph below. It had an overall range of only 24 (psi) with a fluctuation that occurred within an activation window of 9 min 23 s. Possible causes of transients are associated with pump or valve adjustments, such as by changing the number of on-line pumps or through a VFD adjustment.

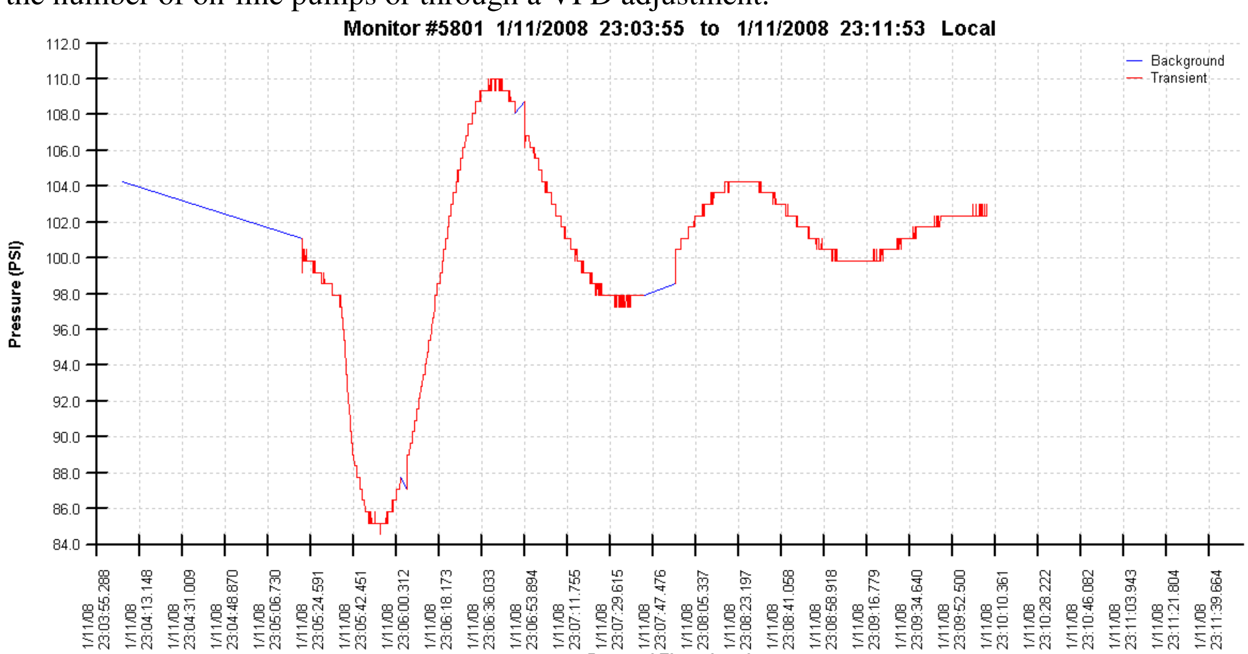

Figure 2: Transient Pressure Profile: TP-1 #59 at 924 East Ave., Mississauga, inside pump Station and just before small air chambers

CALIBRATION PROCEDURE

Given this conceptual background, the nature of the inverse transient procedure is now not difficult to outline. In essence, the field data collected from Peel was simulated using a transient simulation model (in this case, a simulation called TransAM), and a genetic algorithm process (GAP) was used to minimize, by selectively changing various pipe friction factors and water demands, the discrepancy between measured and predicted field results.

The field tests and data collection has generally run smoothly, and sufficient data was obtained to carry out the calibration procedure. As the tests are completed, the data can be analyzed and the numerical model(s) of the water distribution updated. Later, a verification step was undertaken, and a prediction made of the response to any subsequent tests. The goal is that this calibration part of the operation can ultimately become routine and continuous.

As mentioned, one of the primary goals of the field tests is to collect the data sets that are used to calibrate the numerical model. The calibrated model can then be used with a high degree of confidence as a powerful, efficient, and economic tool. The most probable behaviour of the system due to future changes – such as additional or modified pumps, additional relief valves, or proposed network expansions – can be modeled to give reliable computer results. In other words, simulations or experiments on computers can be performed so that the system can be continually optimized and refined to achieve a high performance. The desired suitable surge protection measures may eventually be determined and tested through the use of a calibrated numerical model of transient analysis.

Some of the primary parameters that influence the development and dissipation of transient pressures include acoustic wave speeds and friction factors of pipes, pump inertia, and nodal consumption. These parameters are given special attention in the model calibration.

Calibration Specifics

Before the inverse calibration is performed, the raw data obtained in the field must be conditioned to filter out unreliable, artificially induced signals that might have been picked up by the high speed pressure transducers and the data loggers. For this reason, a large sampling rate was required.

The data was processed with a 60-Hz filter program to eliminate line interference, the most common type of interference encountered during this process. Following the conditioning step, the data are formatted into one of the input streams for the genetic algorithm processor (GAP). The processed field data is used to determine the fitness of each calibration member in each generation.

The GAP was programmed to run the transient simulator (TransAM) for populations between 100 and 400 members and for 10 to 20 generations. The calibration objects were nodal demands and pipe friction factors. For each generation, information about the simulated pressures at field measurement locations are recorded and analyzed by the GAP. At the end of each generation, the individuals are ranked and the best performer – that is, the data set having the smallest error between predicted pressure traces to the actual measured pressures – is identified and allowed to "continue" into the next generation. The other members of the new generation are formed from the superior performers of the current generation through reproduction (i.e., gene swapping between parents) and a small probability of mutation. The mutation process helps to create and maintain a diversity of characteristics in the test population and thus reduces the chance the procedure will converge to a local minimum. The process continues until a single individual (or in some cases a set of individuals) is identified as the best performer. Normally, the entire procedure is run several times, for several different random starting conditions, to ensure the stability of predicted results, and to provide a qualitative assessment of their reliability.

Calibration Results

There are many ways to utilize the field test data and the computer model. In particular, what parameters should be adjusted to reflect the current study area. Two major contributors are friction factor and pipe diameter changes due to aging of the pipes. Therefore, two different types of inverse calibration were carried out. One looked at friction factors alone while the other studied a combination of friction factors and diameter changes. In all cases in the Peel system the diameter effects in the transmission mains were found to be quite small and the overall performance was well captured by the adjusted Hazen-Williams conductance values.

Note that the transient program was not run on a complete and fully detailed system model. The computer execution requirement of such a complete transient model would be completely prohibitive, taking long times for execution of even a single simulation, and the inverse procedure requiring tens of thousands of runs. Thus, by necessity, the system had to be "skeletonized" to include key transmission and distribution system pipes, excluding many smaller and more numerous pipes from the system. Thus, another factor that merits attention in assessing the results is the effect of this "simplified" network representation. This approach may in some instances assign the included pipes slightly more hydraulic capacity than would otherwise be the case, effectively attributing a slightly higher Hazen-Williams C factor as a mimic for the neglected pipes. Sensitivity results indicate that this effect was small, but it could not be entirely eliminated in the context of current computer technology.

Despite these effects, the ability to accurately simulate the measured response in the inverse calibration procedure is a strong indication of the overall reasonableness of the resulting calibrated hydraulic model. Although, for the reasons presented here, the calibrated results should be viewed with proper appreciation that these are not precisely pinpointed, the overall representation and trend in the reported results is believed to accurately represent the state and hydraulic performance of the Peel system.

CONCLUSIONS

This particular examination of the water supply transmission mains for the Region of Peel provided fruitful information about the system behaviour to the daily operations of pump switching, shut-down and start-up as well as to some of the demands and pipe friction factors. This analysis also provided important information on the feasibility of carrying out inverse calibration with genetic algorithms and the details and requirements of such tests.

The overall performance of the analysis is quite good. The potential of the inverse method has certainly not yet been fully exhausted. The low cost and overall effectiveness of this approach is quite evident considering the minimal field testing and human-power required for this analysis to be completed.