FIELD APPLICATION OF INVERSE TRANSIENT ANALYSIS TO CALIBRATE LONDON'S WATER DISTRIBUTION SYSTEM MODEL

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ABSTRACT

A comprehensive set of transient field tests were performed on the City of London's Water Distribution System on the 19th of June, 2006. The field test induced several controlled transient events into the water network using a sequence of pump starts and stops at the Arva supply station. High frequency pressure transducers were installed at convenient locations within the northwest quadrant of the London system. Concurrently with the field work, a transient model was used to represent the associated system connections, pipes, and the properties of various hydraulic devices. An inverse transient procedure was then used to calibrate and update a distribution system model of this portion of the City. This inverse transient procedure essentially uses the processing power of modern computers to progressively reduce the discrepancy between the measured and predicted values. More specifically, an optimization routine is used to adjust the model parameters (primarily friction and demand) so as to gradually improve the agreement between predicted and measured results. This set of tests – conducted through cooperation between Earth Tech, Hydratek Associates Inc., and the City of London – is perhaps the most ambitious and demanding application to date in the world related to using inverse transients on real systems with measured data. The potential, success, and challenges of the inverse transient approach are presented while highlighting the specific experience in London with this test case.

KEYWORDS—Hydraulic modelling, Transients, water hammer, inverse transient analysis, system calibration.

INTRODUCTION

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 or long-lasting decisions are made, since 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. 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. These advantages are only achieved if the model is sufficient simple to implement – that is, much simpler and cheaper than the decision being considered – and if it is suitably accurate.

However, when one is considering infrastructure systems, such as a water distribution system, one almost never has to pretend the modeling decision is an "all or nothing" proposition. 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.

The Calibration Challenge

The challenge of calibrating complicated systems, though, such as a water distribution system, is that they so often contain a great 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. 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 London 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 the Field Test

In London, five sensor locations were chosen in the Northwest quadrant of the system to install high frequency pressure transducers. On June 17, 2006 a pressure sensor was installed in the Arva pumping station, at Chambers 12 and 13, and within two pumping stations connected to the zone (Hyde Park and Horton & Maitland stations). A plan view of the associated system and location is sketch in Figure 1.

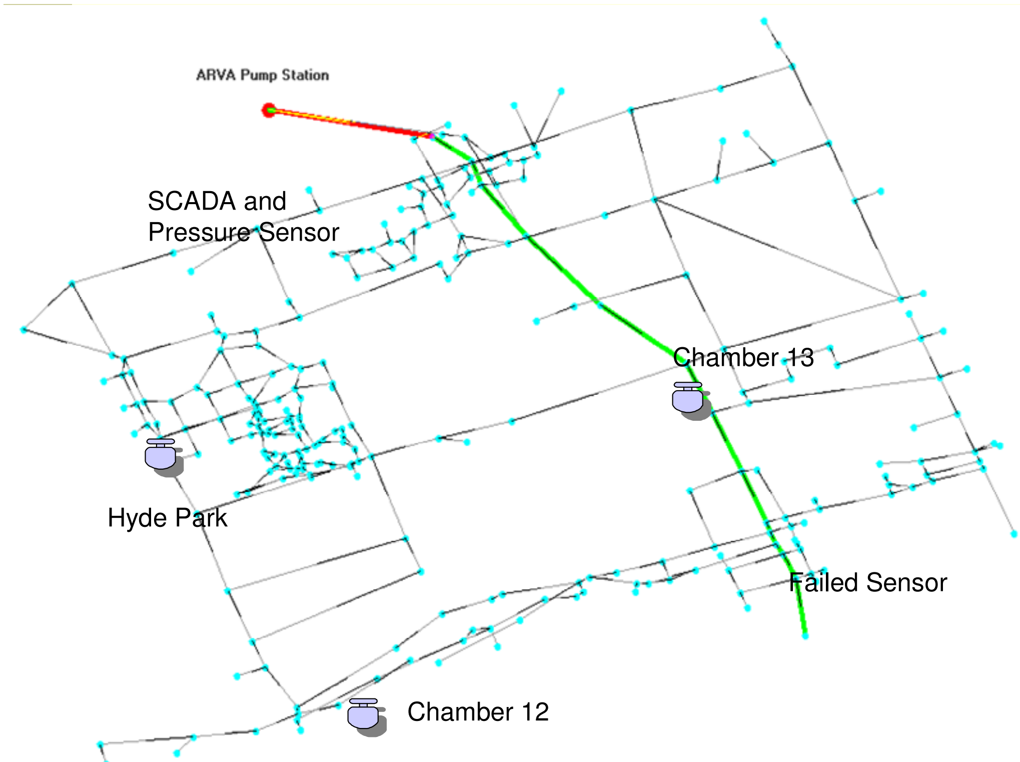

FIGURE 1: LONDON TEST REGION AND SENSOR LOCATIONS

Once the sensors were installed by the City of London staff, a sequence of transient events was initiated at the Arva station. The goal was to create a controlled and distinct transient signal that would propagate through the connected transmission and distribution system. By watching and modeling how this signal propagated through the system, the modeling and calibration procedure was in a position to estimate the nature of the system conditions that permitted the measured response. The initiating transient events included starting and stopping various pumps at Arva. The events were chosen to be essentially routine, though the concentration of so many adjustments within a short period of time was a little atypical. Indeed, the power implications of such a set of adjustments made the selection of a Saturday for testing particularly desirable. A secondary advantage of using a Saturday for the test was the expected flatter and more gradual change in demands over the duration of the test; Saturday morning demands often change more slowly than would have been typical on a week day.

Figure 2 shows the pressure fluctuations at Arva as a result of bringing pumps on and off line. Figure 3 shows the measured response from within the system, in this case a Chamber 13, as a result of the same set of disturbances. Clearly the signal at Chamber 13 roughly mimics the initiating signal at Arva, though the magnitude of the pressure changes has been subdued due to the nature of the intervening pipe system. But what does this kind of trace mean and how does it help to achieve an accurate system calibration?

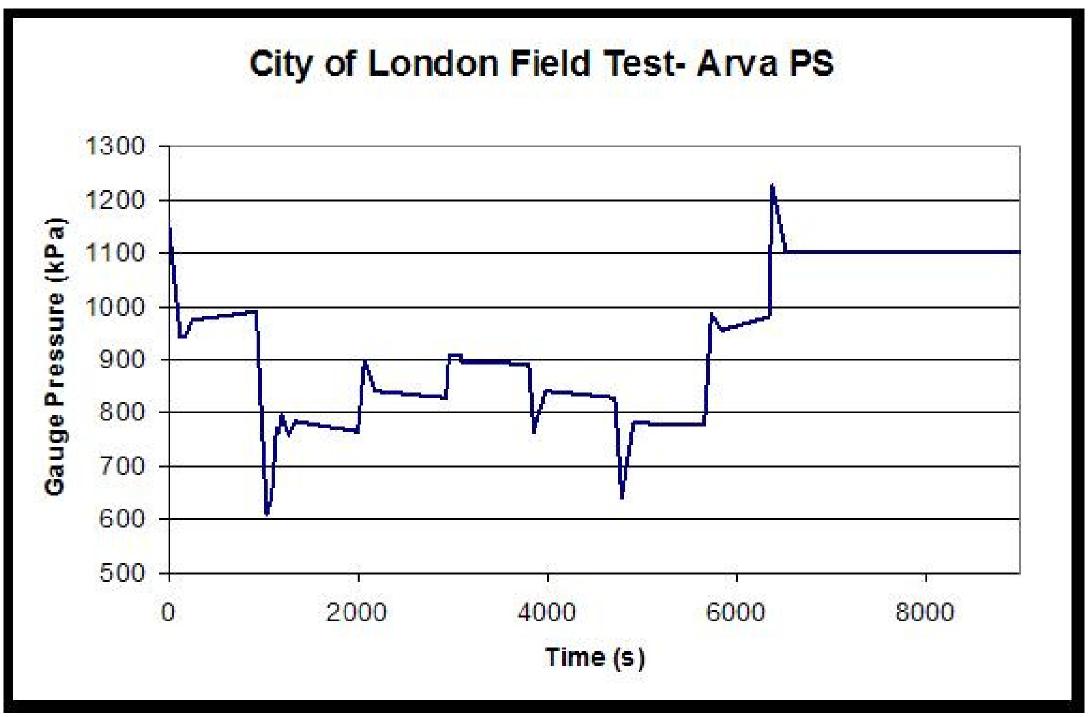

FIGURE 2: MEASURED PRESSURE TRACE AT THE ARVA PUMPING STATION

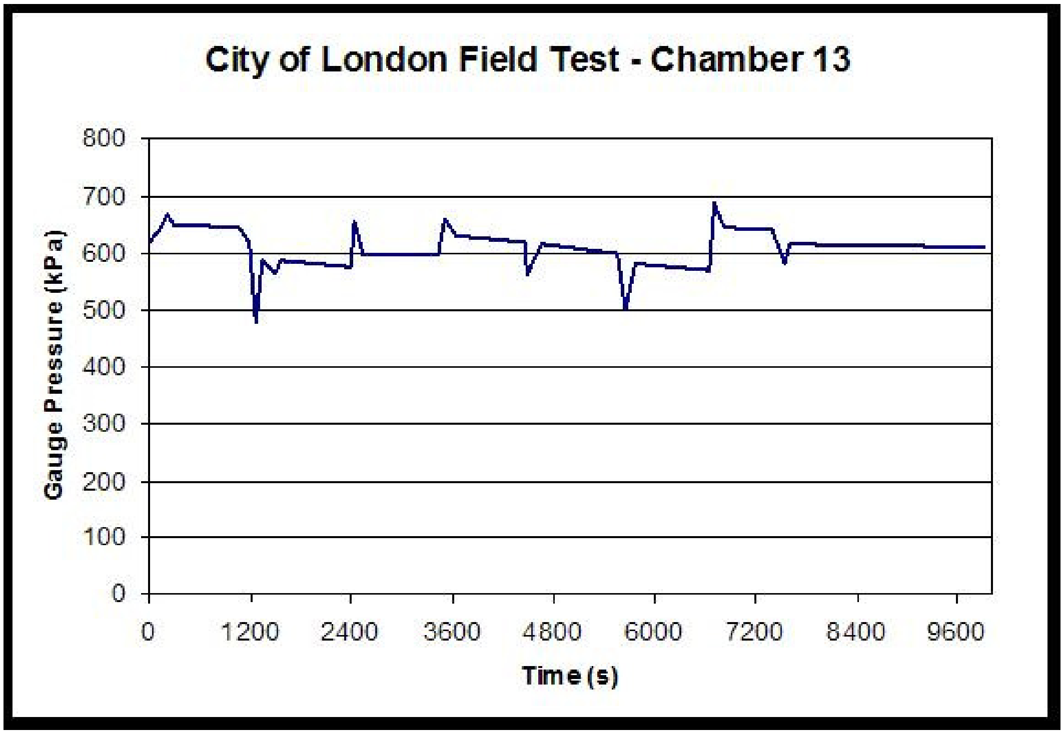

FIGURE 3: MEASURED PRESSURE TRACE AT CHAMBER 13

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 affects, 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.

CALIBRATION PROCEDURE

The nature of the transient calibration procedure is now not difficult to outline. In essence, the field data collected from London was simulated using a transient simulation model (in this case 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 ran smoothly, and sufficient data was obtained to carry out the calibration procedure. After the tests were completed, the data had to be analyzed and the numerical model(s) of the water distribution updated. Later, a verification step can be undertaken, and a prediction made of the response to any subsequent tests.

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 London 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 London system.

Figure 4 provides a good sense of how closely the predicted and measured values can be made to agree to each other during this test process. These plots are only representative windows throughout the simulation period but give a good impression of the quality of the overall agreement, and the nature of the minor variations that remain unaccounted for.

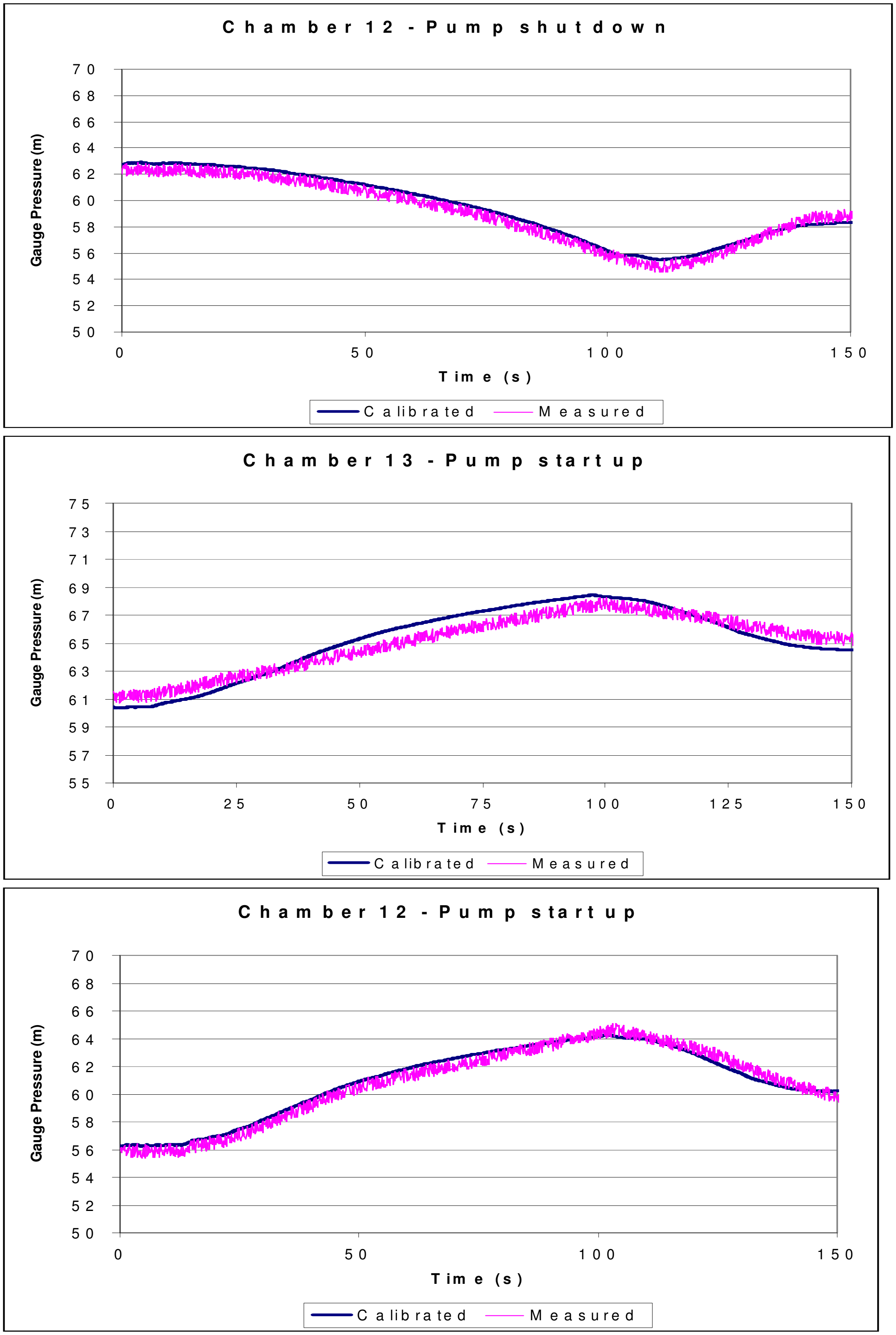

FIGURE 4: MEASURED AND PREDICTED RESPONSES AT SELECTED LOCATIONS

CONCLUSIONS

This particular examination of the water supply transmission mains for the Region of London 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.