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HYDRAULIC ANALYSIS OF WATER DISTRIBUTION SYSTEMS

There are presented some engineering problems that deal with modelling of the flows in 7 water distribution systems differing in size and in the structure of water-pipe network. Calibration of the parameters of the water supply network models was carried out based on the data sets obtained by measurements and on an analytical approach. Measurements were made for 7 days and included the following parameters: pressure (in selected nodes), water consumption (by major users), productiveness of water supply sources, flow (in selected pipes) and water levels (in all the reservoirs involved). The input data sets for the calibrating process encompassed the following items: topological descriptions of the water distribution systems, schematic representations of the joint nodes; pipe length, pipe diameter, pipe age and pipe material; information about actual conditions observed in service; first approximation of identified parameter values (consumption rate, pipe roughness, local head loss) and measurement results. Difficulties in obtaining satisfactory results of calibration are often caused by errors in initial estimating the values of the parameters being calibrated (e.g. neglecting some of the local head losses of networks), identifying equivalent sand roughness k_t with stipulated equivalent sand roughness k_{t0}, omitting the stage of verifying the literature-derived relationships that describe of hydraulic "ageing" of cast iron and steel pipes, neglecting the correlation between water use and pressure in a water pipe, errors in measurements of the variables that characterise the performance of the hydraulic network, as well as errors when describing pipe links at nodes, pipe section diameters and lengths.

1. INTRODUCTION

Known for several decades, computer-based hydraulic network models designed for water distribution systems are now in common use both in on-line operation of hydraulic networks and in their design, upgrading and development. However, practical applicability of these models crucially depends on the quality and reliability of input data for simulations. Generally, the accuracy of the system structure and topology is good enough; however, we can frequently make some errors in determining the actual pipe links at some nodes of the water main network (these errors can be eliminated

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during the process of calibrating the model). The most important causes of errors determining the usability of simulation results may be itemized as follows:

sets of parameter values and hydraulic characteristics of particular elements of the system in question: pump and pump station characteristics, pipe roughness values, local head loss coefficients;

nodal water use distribution (system forcing).

Some of those characteristics, e.g. current pump characteristics, might be determined quite easily by direct measurements, while some others (nodal water use distributions, equivalent roughness of all pipe walls, coefficient of local head loss due to e.g. partly closed valves, faulty fixtures, pressure reducers or controllers or flow controllers) – by model-calibrating. Calibration should incorporate the variables that characterise the performance of a hydraulic network: pressures at selected nodes of its skeleton, efficiences of all the external and internal water supply sources, flow rate in some of the pipes, water levels in reservoirs and greater values of water consumption by selected users. The number and location of measurement sites depend on the local conditions, among other things the structure, topology and the size of the system under consideration, as well as the number, spatial and altitude distribution of water supply sources. Thus, each system has to be adjusted in such a way as to meet the requirements of a given hydraulic network. Calibration of the models used in on-line operation of hydraulic network systems has been described by numerous researchers (for instance [1]–[8]). It is typically effected in 4 basic phases:

1. Initial estimating the values of the calibrated parameter, making it possible to initialise the calibration process.
2. On-site measurements and determination of the sets of the variables that control the calibration process.
3. Calibration of model parameters under steady-state conditions, taking into account many independent and precisely defined operation situations, which occurred during on-site measurements, including technically and hydraulically extreme situations.
4. Calibration based on the system performance in a longer (usually a few days) time interval.

The paper presents some of the problems connected with calibrating the hydraulic network models, the problem resulting from the author's practical experience in model calibration for 7 hydraulic network systems of different sizes and structures [9]–[17].

2. SOME OF THE RESEARCH PROBLEMS

One of important issues when calibrating water network models is locating and determining the coefficients of the local hydraulic head loss due to, for instance, partially closed valves, pipe aeration or faulty fixtures. In pump systems, the hydraulic losses due to these losses might be of significance to the costs of the energy used for water pumping. The local hydraulic head losses were found in all of the water distribution systems tested though their cumulative effect on the network efficiency varied. This issue is illustrated by the results of calibrating the models of hydraulic networks in Kielce [15] and Wrocław [14].

The Kielce water supply system is fed by 2 main intakes: at Białogon and Zagnańsk and 8 wells located at different points of the city. The water supplied is an underground water of a good quality, thus its treatment is not necessary. The water from the intakes at Białogon is pumped into the water supply systems within Zone 1 and into 4260 m^3 reservoirs. The water collected at Zagnańsk is pumped into 3 land reservoirs totalling 15 000 m^3. Upstream the reservoirs, a pumping pipeline (∅ 600 mm) is linked by a pipe (∅ 500 mm) to the hydraulic network within Zone 1. There is a valve installed on the ∅ 500 mm pipe, which is constantly partly closed. Due to remarkable differences of altitude in the city area (ca. 110 m), the water supply network is run in a three-zone system.

Zone 1 (basic) covers ca. 70% of the entire municipal areas. It is supplied with water from the pump stations and single wells at the Białogon intake, the pump station at Zagnańsk (through the link of the ∅ 600 mm pipeline with the hydraulic network) and 8 single wells with deep-well pumps located at different points in the city. The internal source includes the 4260 m^3 reservoirs. There are 2 pressure-reducing valves installed in the network.

Hydraulic networks belonging to Zones 2 and 3 are fed by two pump stations that collect water from the 15 000 m^3 reservoirs. The internal sources include 2 reservoirs, each of the volume of 10 000 m^3.

In 1996, the average daily production of water was 57 700 m^3, 51% of which was supplied by the Białogon intakes, 31% by the Zagnańsk intakes and 18% by local wells located at different points in the city. Under the supervision of the author of the present paper, the model of the hydraulic network was designed and implemented between June 1996 and October 1997 [15]. The description of network topology includes all the pipes of 80–600 mm diameters. Their length totals 295 009 m, including 264 793 m of cast iron and steel pipelines subject to hydraulic "ageing", i.e. increase of hydraulic resistance during operation time. The age (operation time) of these pipes was: in the age range of up to 10 years, 19.7% of the total network length; in the range of 11–20 years, 28.8%; in the range of 21–50 years, 40.7%; and in the range of over 50 years, 10.8%. The system graph, taken into account during calibration, consisted of 1215 sections, including 1003 sections within Zone 1, 151 sections within Zone 2 and 61 sections within Zone 3. The field measurements, aimed at collecting the data (variables) controlling the process of calibration, were made during one week (4–10 September, 1996). They included:

continuous measurements of pressures at the selected nodes of the system graph;

water level measurements in all reservoirs and measurements of performance at 14 water intakes and pump stations.

Moreover, there were measurements of water consumption induced by those users who consumed large volume of water. They were followed by a water use survey performed in 1995. In order to minimise the number of necessary measurement points, additional operations were performed in the periods selected before on the basis of analyses for the first degree of calibration (referring to steady-state). Among other things, they consisted in disconnecting the 15 000 m^3 and 4260 m^3 reservoirs from the hydraulic network in Zone 1, and shutting down two of the pump stations feeding Zones 2 and 3 of the hydraulic network (at the time the water was supplied solely from two 10 000 m^3 reservoirs).

During the first stage of the calibration process, which consisted in field measurements, 21 independent events occurred. Special attention was drawn to the system working conditions under which the water consumption was relatively high and, in consequence, the pressure losses in the pipes could be estimated as great. These events were precisely defined. The calibration was performed separately for the water network in Zones 1, 2 and 3. It included: stipulated equivalent roughness k_{t0} (caused by sand grains) of all cast iron and steel water network pipes (the roughness was converted to the inner new pipe diameter D_0), local head loss coefficients due to partly closed valves and pressure reducers, as well as nodal water use. For cast iron and steel pipes, the stipulated equivalent roughness k_{t0} (greater than 1.5 mm) is referred to D_0 of a new pipe, not to the actual diameter D_t. It was calculated from the transformed Prandtl–Karman formula, valid for rough pipes showing a turbulent rough flow. We assume that the hydraulic head loss (Δh_t) in a pipeline of diameter D_0 and stipulated pipe roughness k_{t0} is the same as in a pipeline of actual diameter D_t and roughness k_t for $v = 0.7$ m/s. Such an assumption seems convenient in following practical applications of the model. The mean calculated value of k_{t0} for a specific section of the hydraulic network takes into account the decrease of the active pipe diameter resulting from sediments deposited on its walls and also the hydraulic losses due to local hydraulic resistance (they always occur, even in properly-maintained networks, with faultless fittings).

The Kielce system of water distribution displays, among other things, a big number of totally closed valves and multiple local head losses mainly due to partly closed valves. This primarily results from the conditions and method of running the system, but at the same time it causes constant or temporary hydraulic drops in some of its sections. In addition, despite the relatively good quality of the water pumped into the network, the cast iron and steel pipes used for 20 years or more show a substantially elevated hydraulic resistance as compared to that of new pipes. In ca. 19% (49 677 m) of their total length, the values of k_{t0} appeared to be smaller than 0.3 mm; in 56% they ranged from 3.1 to 10 mm, in 20.6% – from 10.1 to 20 mm, whereas in 4.4% they were greater than 20 mm [15]. The main reason for this is an incrustation made of sediments on the inner surfaces of pipe walls, including densely occurring point-like encrustants of hard sediments, several mm thick, visible in pipe sections cut out during repairs. These encrustants also occur in network cast iron fixtures, which results in additional local hydraulic head losses taken into account in the calibrated values of the parameter k_{t0}.

Following the accomplishment of the iterative process of model calibration, 14 totally closed valves were found in Zone 1 of the hydraulic network. The valves on the pipes had the following diameters: 100 mm (2 valves), 200 mm (3 valves), 300 mm (6 valves), 350 mm (1 valve), 400 mm (1 valve) and 500 mm (1 valve). In addition, there were 15 partly closed valves on pipes of the following diameters: 150 mm (1 valve), 200 mm (5 valves), 300 mm (5 valves), 400 mm (2 valves), 500 mm (1 valve) and 600 mm (1 valve). The values of head losses due to them ranged from 4.57 (∅ 150 mm valve opening coefficient: 0.568) to ca. 8000 (∅ 400 mm valve opening coefficient: 0.004) [15].

Such a big number of totally or partly closed valves makes the Kielce water distribution system unstable and highly vulnerable not only to changes of global water consumption, but also to even slight changes of the proportions between the efficiences of its particular feeding sources. This is proved by the big differences between pressures at some of the network nodes and measurement points at different times of the day, even when the differences between the efficiency sums of all the supply sources are small.

The simulations of the work of water distribution system showed that it was recommendable to open some of the totally and partly closed valves, which improved pressure conditions in some areas of the hydraulic network without substantial changes of the working parameters of the deep-well pumps installed in single wells around the city.

We also found a big number of excessive local hydraulic head losses due to partly closed valves and faulty fixtures (primarily vents) during calibrating the hydraulic network model of Wrocław [14], [18]. In the first stage, hydraulic resistances of cast iron and steel conduits (two ∅ 1200 mm pipes 2120 m in length) and spotted excessive local hydraulic head losses were measured. After eliminating them, the measurements were repeated. Following elimination of air cushions and improving the work of fixtures, the hydraulic resistance in the system of the two pipelines dropped by about two times: the same referring to the reduction of hydraulic losses. Similar effects were shown in analogous papers and actions undertaken to improve hydraulic network in southern districts of Wrocław. Following the total opening of partially closed or damaged valves, the pump head of the pump station, which had an efficiency of 1.4–1.7 m^3/s during morning hours, could be lowered by 7.4–8.3 metres. At the same time the pressure conditions in the hydraulic network were maintained or even improved in some areas [14], [18].

3. ERRORS IN THE PROCESS OF CALIBRATING WATER NETWORK MODELS

Difficulties in obtaining the right effects of the process of calibrating flow models in water distribution systems are most often caused by the following reasons:

errors in approximations of the initial values of the parameters subjected to calibration;

errors in the description of topology and geometry of the network (e.g. in the description of pipeline links at nodes, diameters and lengths of network sections);

incorrect data that defined the history of events subjected to analysis during the first stage of calibration (e.g. erroneous: water levels in reservoirs, pump working parameters, pressure zone boundaries);

errors in measurements of the variables that characterise the performance of the hydraulic network.

Errors in the initial estimations of hydraulic parameters most often appear because we do not take into account all of the local hydraulic head losses in the network and we assume incorrect relationships between cast iron or steel pipe wall roughness and the time of its exploitation and its diameter. These relationships are often found in the papers written by other scientists, but each time they should be verified on the basis of measurements in a given water distribution system. A striking discrepancy between the literature data and actual values can be exemplified by the results of modelling the water distribution system in Jelenia Góra [9], [17]. In order to verify the literature-based relationships describing the process of hydraulic "ageing" of cast iron or steel pipes during use, in 1990 field measurements of hydraulic resistance were made. The measurements covered 15 active hydraulic network pipes [19]. Through a drilled hole, the following elements were driven into the pipeline: a three-opening pilot rods, rendering it possible to measure water flow velocity, and a probe to measure, in two planes (horizontal and vertical), the inner diameter of the pipe, decreased, in comparison to the diameter of a new pipe, due to the incrustation or sediment. The results of the study showed that under the conditions of hydraulic network in Jelenia Góra the increase of hydraulic resistance in steel pipes was, in general, several times as high as that in cast iron ones. For instance, a hydraulic resistance of a 40-year old steel pipeline (200 mm in diameter) was over 5 times as high as that of a new pipeline, hence it lost ca. 56% of its initial flow capacity. At the same time the drops of flow capacity in cast iron pipelines of a similar age and diameter did not exceed 25% [17]. These differences stem from physicochemical properties of water collected from 8 sources. Investigations of water networks in other cities (Wrocław [14], Kielce [15], Brzeg [13] and Polanica Zdrój [11], [16]) did not reveal such big differences between the rates of hydraulic "ageing" of cast iron and steel pipes.

One of the reasons for the difficulties in hydraulic network model calibration might be identifying an equivalent sand roughness (k_t) determined from "punctual" measurements of hydraulic resistance in selected pipes with a stipulated (referred to the diameter D_0 of a new pipe) equivalent sand roughness k_{t0}. The values of k_t (given in numerous literature items) are referred to some specific pipeline cross-section. In order to guarantee the necessary accuracy of the measurements and to eliminate distortions, straight pipe sections, possibility without fittings or fixtures, are chosen for "punctual" measurements. However, in water supply networks, we always deal with local hydraulic head losses due to linking and separating water streams, valves and changes in pipe diameter. The resulting hydraulic losses depend on the network topology, its hydraulic efficiency and a technical state of fixtures. Typically, during calibrating the models of water networks, the hydraulic resistances of the water pipelines used are characterised by means of stipulated equivalent sand roughness (k_{t0}). The mean calculated value of k_{t0} refers to a specific section of the network (not a single pipe cross section) and is determined taking into account all the hydraulic losses, including those due to local head losses. For this reason, the values of k_t (often taken from literature) and k_{t0} are not identical.

In many cases, we observe big differences between the hydraulic resistance in steel and cast iron pipes of a similar age and the same diameter, but fulfilling different functions in a hydraulic network. Such differences might be exemplified by pipes that supply treated water to the water main systems of Wrocław [14] and Łódź [20], [21]. The investigations of the hydraulic resistances of two ∅ 1200 pipelines in Wrocław showed [14], [18] that the values of stipulated equivalent roughness (k_{t0}) along six sections built in 1972, 1973 and 1984 ranged from 15.5 mm to 56.6 mm. The average annual increments of roughness k_{t0} (from 1.42 mm/year to 2.62 mm/year) turned out to be incomparably higher if referred to the values of this increment determined for water main pipelines in the southern districts of the city (0.5 mm/year on average) [14], [18]. Among other things, this was caused by the technology of surface water treatment and the way the water treatment plant was run. Even higher values of the annual increase of the roughness k_{t0} (ca. 5.1 mm/year after 9 years of use) were detected in ∅ 2200 mm steel pipeline, 5974 m in length, supplying treated surface water to the water supply system of Łódź [20], [21], [23]. In other systems, where treated underground water was supplied to water mains, the rates of hydraulic "ageing" in pressure conduits and water mains were comparable. This can be exemplified by two cast iron pressure conduits, 350 mm and 500 mm in diameters and 3837 m in length, in the water supply system of Brzeg. The 350 mm pipeline, used for 87 years, showed an annual increase of k_{t0} equal to 0.31 mm/year, while the 500 mm one, used for 17 years, 0.56 mm/year [13], [22].

Errors in the initial approximation of nodal water use distributions, both referring to the model calibration and model practical use, may appear when we do not take account of correlation between the rate of water use, its leakage in internal in-house installations, network pipes and network pressure. This problem is of special significance in the water distribution systems which are subjected to:

high over-pressure in the network, exceeding the optimum pressure sufficient for the system's in-house fixtures to work properly (e.g. in water supply systems in mountainous areas);

permanent or periodical deficits in water supply if we take into account the needs of water consumers.

Model of hydraulic networks are used in algorithms of optimised control of water distribution systems. In order to forecast water demand, typically 24 hours in advance, commonly used ARIMA-class stochastic models are applied. Under the circumstances of Polish towns, their effectiveness appeared to be satisfactory [24]–[27].

4. SUMMARY

The practical usefulness of the models of water distribution systems largely depends on the quality and reliability of simulation input data. The most important errors appear if we deal with sets of parameters and hydraulic characteristics of the system's particular elements (pump characteristics, pipe wall roughness and local hydraulic head loss coefficients of network as well as nodal water use distributions. The above characteristics should be determined in a 4-stage process of calibrating the model parameters, and in the process the appropriately designed and accomplished field measurements should be taken into account. Difficulties in obtaining satisfactory results of calibration are often caused by: errors in initial estimating the values of the parameters being calibrated (e.g. neglecting some of the local head losses of networks), identifying equivalent sand roughness k_t with stipulated equivalent sand roughness k_{t0}, omitting the stage of verifying the literature-derived relationships that describe the process of hydraulic "ageing" of cast iron and steel pipes, neglecting the correlation between water use and pressure in a water pipe, errors in measurements of the variables that characterise the performance of hydraulic network, as well as errors when describing pipe links at nodes, pipe section diameters and lengths.

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ANALIZA HYDRAULICZNA SYSTEMÓW DYSTRYBUCJI WODY

Zaprezentowano praktyczne problemy modelowania przepływów w 7-miu systemach dystrybucji wody o różnej wielkości i odmiennych strukturach systemów wodociągowych. Tarowanie parametrów modeli przeprowadzono na drodze pomiarowo-analitycznej. W okresach 7-mio dobowych wykonywano terenowe pomiary: ciśnienia w kilkudziesięciu węzłach grafu systemu, większego poboru wody przez jej wybranych odbiorców, wydajności wszystkich źródeł zasilania, przepływów w wybranych przewodach oraz stanów wody we wszystkich zbiornikach. Zbiory danych wyjściowych do procesu tarowania parametrów modeli obejmowały: dane inwentaryzacyjne, informacje o konkretnych sytuacjach eksploatacyjnych uwzględnionych w procesie tarowania, wstępne przybliżenia wartości identyfikowanych parametrów oraz wyniki pomiarów. Przyczynami niezadowalających rezultatów tarowania są najczęściej: błędy we wstępnych oszacowaniach wartości tarowanych parametrów, utożsamianie zastępczych chropowatości k_t rur żeliwnych i stalowych z umownymi, zastępczymi chropowatościami k_{t0}, niezweryfikowanie podanych w literaturze zależności opisujących proces hydraulicznego „starzenia się” przewodów żeliwnych i stalowych, nieprawidłowości w opisie topologii sieci (np. w opisie połączeń rurociągów w węzłach oraz średnic i długości odcinków sieci), nieprawidłowe dane definiujące analizowane w I stopniu procesu tarowania (w warunkach stanów ustalonych) sytuacje historyczne (np. błędne poziomy zwierciadeł wody w zbiornikach, parametry pracy pomp, charakterystyki pomp, granice stref ciśnienia) oraz błędy pomiarów zmiennych charakteryzujących działanie systemu dystrybucji wody.