

Pipe Network Analysis for Demand Estimation in Water Distribution Network

TERUJI SEKOZAWA^{*}, KAZUAKI MASUDA^{**}, TOMOHIRO MURATA^{***}

^{*}Graduate School of Engineering

Kanagawa University

3-26-1, Rokkakubashi, Kanagawa-ku, Yokohama, 221-8686

sekozawa@kanagawa-u.ac.jp

<http://www.kanagawa-u.ac.jp>

^{**}Kanagawa University Department of Information System Creation

Kanagawa University

3-26-1, Rokkakubashi, Kanagawa-ku, Yokohama, 221-8686

masuda@kanagawa-u.ac.jp

^{***}Graduate School of Information, Production and Systems

Waseda University

2-7, Hibiino, Wakamatsu-ku, Kitakyushu-shi, 808-0135

t-murata@waseda.jp

<http://www.f.waseda.jp/t-murata>

JAPAN

Abstract: - We propose a pipe network analysis method using demand estimation by proposing a demand estimation method that estimates demand points set based on conventional, fixed component ratios.

We first explain pipe network analysis using a conventional method and then clarify the problems and challenges in conventional pipe network analysis. Next, we describe the proposed method. This is a demand estimation method that estimates node demand using measurements from pressure and flow sensors installed in the distribution network. Finally, the proposed method is applied to a large-scale pipeline network of 3,000 pipes. As a result of this experimental application, the improvement rate at all of the sensor installation points increased using the proposed method, as compared to the conventional pipe network analysis method.

Key-Words: - pipe network analysis, demand estimation, demand area, distribution control, deviation minimization problem, large-scale pipeline network

1 Introduction

Pipe network analysis is a technique for calculating end pressures and pipe flow rates in the type of water distribution network. Pipe network analysis is widely used to clarify the distribution situation in distribution networks as well as in simulations for the control of pumps/valves and the design of distribution networks for example. In pipe network analysis, the distribution network is defined as the number of nonlinear simultaneous equations equivalent to the total number of pipes and nodes making up the network.

Each of these conventional pipe network analysis methods consider the consumer demand assigned to a node as an input. Since there are between several hundreds and several tens of thousands of nodes, it is

impossible to measure node demand for the implementation of pipe network analysis and so demand cannot be set accurately. In node demand used in real pipe network analysis, component ratios for node demand are determined in advance as fixed values in regard to overall demand in the distribution network based on monthly usage through water supply metering conducted in monthly units. One overall demand is supplied for the situation that requires analysis, and this overall demand multiplied by the component ratios mentioned earlier are given as the node demands. Therefore, discrepancies considered to result from the method of providing node demand arise between analysis results and pressure measurements from sensors installed in the

network. This problem is particularly serious when analysis results are used to control pumps and valves in the distribution network (distribution control), for example.

The objective of the proposed pipe network analysis method using demand estimation is an improvement in accuracy such that the analysis can also be applied to distribution control. This requires the achievement of a 24-hour average difference from pressure measurements of approximately $\pm 0.2 \text{ kgf/cm}^2$.

2 Conventional Pipe Network Analysis and Problem Areas

2.1 Pipe Network Analysis Problem

Pipe network analysis obtains all pipe flow rates and node pressures in a distribution network by regarding the water flow in the network as a steady flow and solving simultaneous equations made up of the flow balance and pressure balance equations described below, which are formed at all nodes and pipes. Pipe network analysis is used to analyze the pressure distribution and flow distribution in the distribution network.

The flow balance equation is given as

$$\sum_{j \in A^-(i)} x_j - \sum_{j \in A^+(i)} x_j = \begin{cases} -w_i & (i \in N_{in}) \\ y_i & (i \in N) \end{cases} \quad (1)$$

The pressure balance equation is given as

$$P_{s(j)} - P_{e(j)} = R_j |x_j|^{\alpha-1} \cdot x_j \quad (j \in B) \quad (2)$$

In the pipe network analysis problem defined above, demand y_i is supplied as a known value at all nodes. However, since there are usually between several hundreds and several tens of thousands of nodes, it is impossible to measure node demand for implementation of pipe network analysis, and so demand cannot be set adequately. In node demand used in real pipe network analysis, component ratios for node demand are determined in advance as fixed values in regard to overall demand in the distribution network based on monthly usage through water supply metering conducted in monthly units. Overall demand is supplied for the situation that must be analyzed, and this overall demand multiplied by the earlier-mentioned component ratios is given as the node demand.

2.2 Problems and Challenges in Conventional Pipe Network Analysis

The node pressures and pipe flow rates obtained from the results of pipe network analysis often differ greatly from measurements obtained by actual pressure sensors and flow sensors. A difference of approximately 0.2 kg/cm^2 (approximately 10% of the measured value) from the pipe network analysis result frequently arises, and in the worst case, a difference of 0.8 kg/cm^2 (approximately 40% of the measured value) arises.

A temporal trend can be observed in the above-mentioned differences. Here, in the pipe network analysis problem defined by Equations (1) and (2), node demand y_i exists as a given parameter that fluctuates temporally and does not accurately reflect real data. As mentioned in Section 2.1, in the conventional method of pipe network analysis, it is extremely difficult to measure node demand and supply the nodes as input values because there are between several hundreds and several tens of thousands of nodes in the distribution network. Therefore, when using pipe network analysis, in general, component ratios for node demand are determined in regard to the predetermined overall demand of the distribution network, and node demands are obtained by multiplying these component ratios by the overall demand in the situation that requires pipe network analysis.

The demand component ratios are for monthly average demand and do not necessarily provide appropriate node demands in pipe network analysis.

For this reason, the differences have a temporal trend, are considered to be caused by the method of setting node demand in the pipe network analysis problem. Therefore, the question of how to set node demand, and thereby improve the accuracy of pipe network analysis, is the subject of the present paper.

3 Demand Estimation Method

3.1 Demand Estimation Problem

As mentioned in the previous section, in conventional pipe network analysis, there is a difference between the values obtained using the analysis and measured values, and it is predicted that this difference is attributable to the node demands supplied as inputs in the pipe network analysis problem. It is well known, even in accounts of experiences of staff at water supply companies, in reality, there are differences in usage trends between ordinary households and offices/factories.

Since pipe network analysis is a method of

analyzing steady flow, the analysis results can be considered to be for a given temporal cross-section. Based on the temporal cross-sections, the trends in water consumption of the above-mentioned consumers indicate that spatial variation in water demand is occurring. Here, the total demand is the total amount distributed by the distribution reservoirs and does not change regardless of whether the water demand varies.

From the above approach, the demand estimation problem, which estimates the spatial variation in demand using information from measurements taken by pressure/flow sensors, is set as the following type of minimization problem:

$$\min_{\mathbf{y}} J(\mathbf{y}) = \sum_{i \in N_m} (p_i - p_i^*)^2 \quad (3)$$

$$\text{s.t.} \quad \sum_{j \in A^-(i)} x_j - \sum_{j \in A^+(i)} x_j = \begin{cases} -w_i & (i \in N_{in}) \\ y_i & (i \in N) \end{cases} \quad (4)$$

$$p_{s(j)} - p_{e(j)} = R_j |x_j|^{\alpha-1} \cdot x_j \quad (j \in B) \quad (5)$$

$$\sum_{i \in N} y_i = \sum_{i \in N_{in}} w_i \quad (6)$$

where the node demand is $\mathbf{y} = (y_1, y_2, \dots, y_i, \dots)$, \mathbf{y} is one of the decision variables in this problem, N_m is a set of nodes with pressure sensors installed, and p_i^* is the measured pressure at node i . If there is a pipeline with a flow sensor installed, the sum of squares of the difference between the value measured by the flow sensor x_i^* and the flow rate in the pipeline with the flow sensor installed x_i is added as a second term on the right-hand side of Equation (3). The demand estimation problem defined by Equations (3) through (6) can be taken as the problem of minimizing the difference from measured values, under the constraints of the flow balance and pressure balance equations in the pipe network analysis problem and constant total demand.

However, between several hundreds and several tens of thousands of nodes exist in a distribution network, and it is impossible to measure the pressure at every one of those nodes. In reality, measurement sensors are only installed at several or several tens of representative nodes within the distribution network. Therefore, the nodes are consolidated to be equal to the number of measurement points, and the demands of the consolidated node groups are estimated. In other words, the distribution network is divided into several areas.

The demand in demand area k is taken as Y_k , and

$\mathbf{Y} = (Y_1, Y_2, \dots, Y_k, \dots)$. The set of demand areas is taken as L , and the set of nodes i belonging to demand area k is taken as N_k . Here, the demand estimation problem in Equations (3) through (6) can be rewritten as Equations (7) through (12), as follows:

$$\min_{\mathbf{Y}} J(\mathbf{Y}) = \sum_{i \in N_m} (p_i - p_i^*)^2 \quad (7)$$

$$\text{s.t.} \quad \sum_{j \in A^-(i)} x_j - \sum_{j \in A^+(i)} x_j = \begin{cases} -w_i & (i \in N_{in}) \\ y_i & (i \in N) \end{cases} \quad (8)$$

$$p_{s(j)} - p_{e(j)} = R_j |x_j|^{\alpha-1} \cdot x_j \quad (j \in B) \quad (9)$$

$$\sum_{k \in L} Y_k = \sum_{i \in N_{in}} w_i \quad (10)$$

$$y_i = \gamma_i^k \cdot Y_k \quad (j \in N_k) \quad (11)$$

$$Y_k > 0 \quad (k \in L) \quad (12)$$

where γ_i^k is the component ratio for demand at node i in demand area k and is a constant determined using the component ratio for demand allocation used in the conventional pipe network analysis. Therefore, the relationship $\sum_{i \in N_k} y_i = Y_k$ is formed.

3.2 Method of Solving the Demand Estimation Problem

In this section, we present a method of solving the demand estimation problem shown in Section 3.1

It is possible to derive a solution for the demand estimation problem composed of Equations (7) through (12). Fig.1 shows a flowchart of this method of solving the demand estimation problem.

4 Application Results and Discussion

The distribution network subject to application of the proposed method is shown in Fig.2. This distribution network is a municipal network existing in Japan, serving a population of approximately 300,000 with a maximum total distribution amount of 8,000 m³/h.

4.1 Division of the Distribution Network into Demand Areas

In the proposed demand estimation method, since measured pressure is taken as an indicator of the degree of fluctuation from the demand assigned in the initial stage in the demand area, when dividing the demand areas it is preferable that areas with similar trends in demand fluctuation are collected and taken

as the same demand area. However, pressure sensors are items that are installed physically, and they cannot be installed without the consent of the land owner. Therefore, when dividing the demand areas in this situation, areas that were estimated to have similar trends in demand fluctuation were assumed to be located in the same demand area, with the focus on the existing pressure sensor installation points. This means that, even if an area was far from a pressure sensor and could not really be considered to have similar demand fluctuation, the areas were always included in a neighboring demand area that has a pressure sensor, and demand areas without pressure sensors were not created. If a demand area without a pressure sensor were created, then the estimated demand in this demand area would become a simple adjustable parameter for matching pressure from the analysis results with the measured pressure in the surrounding demand areas, which is wide of the target of the demand estimation method proposed in this section. Conversely, if numerous pressure sensors were included in one demand area, no problem would arise as long as the pressure sensors were in areas with similar demand fluctuation trends. However, if the pressure sensors were located in areas with different demand fluctuation trends, then the situation would be inappropriate because the region of the solution search for estimated demand in the demand area would be narrowed.

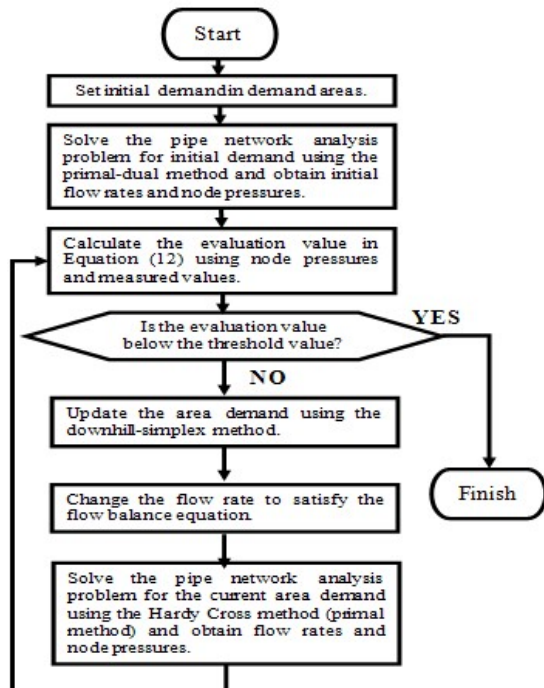


Fig.1 Flowchart of the method of solving the demand estimation problem

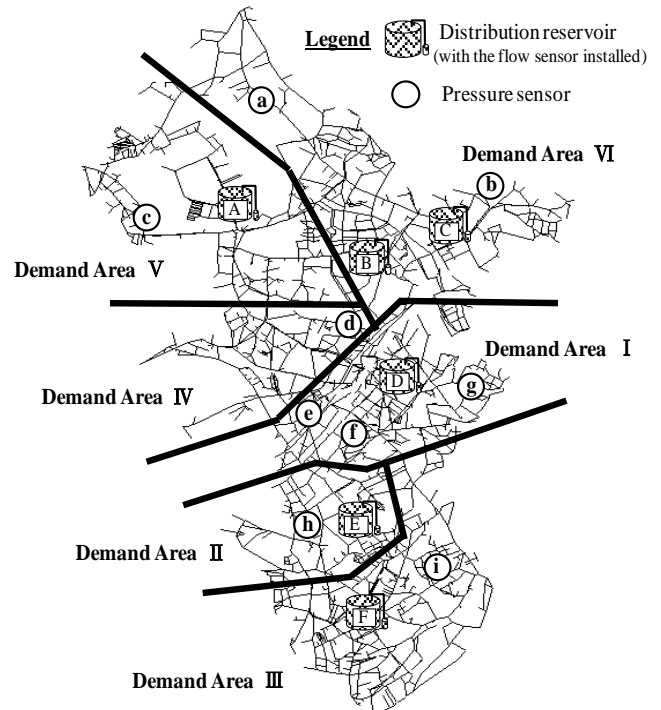


Fig.2 Division of the distribution network into demand areas

Based on the above discussion, when applying the proposed demand estimation method, the distribution network was divided into six areas, Demand Areas I through VI, as shown in Fig.2. In this division of the demand areas, the distribution network was divided so that there was at least one measurement point inside each demand area, and the physical pipeline connections were also taken into account. Specifically, pipelines and nodes that were clustered together were placed into the same demand area by dividing the network, so that the network was demarcated by railways and main roads, for example. This approach assumes that the style of daily life in areas varies according to the boundary of railways and main roads. In addition, there are two distribution reservoirs in Demand Area VI. This is because the scale of Distribution Reservoir C is approximately 1/10 that of Distribution Reservoirs A, B, D, E, and F, and water distribution from Distribution Reservoir C is suspended during the night. Therefore, Distribution Reservoir C was judged to have very little effect on the pressures and flow rates in the distribution network, as compared to the other distribution reservoirs. In addition, if Distribution Reservoir C and the surrounding area were made into a separate

demand area, the number of nodes and the node demand would be small compared to the other demand areas. Although there is no distribution reservoir in Demand Area IV, Demand Area IV was made into a separate demand area because precedence is given to the above-mentioned pipeline clusters, including railway and road demarcations and because this area is as large as other demand areas in terms of number of nodes and node demands.

4.2 Results and Discussion of Pipe Network Analysis using Demand Estimation

Here, we present and discuss the pipe network analysis results obtained when the proposed demand estimation method proposed was applied.

Fig.2 shows the difference between pipe network analysis results and pressure sensor measurements at nodes at pressure sensor **b** in the distribution network shown in Fig.2.

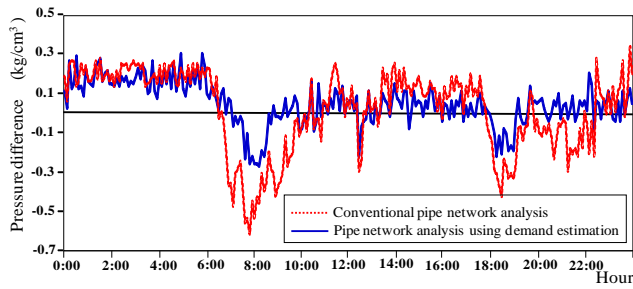


Fig.3 Difference between analysis value and measured value at a node at which Pressure Sensor **b** is installed

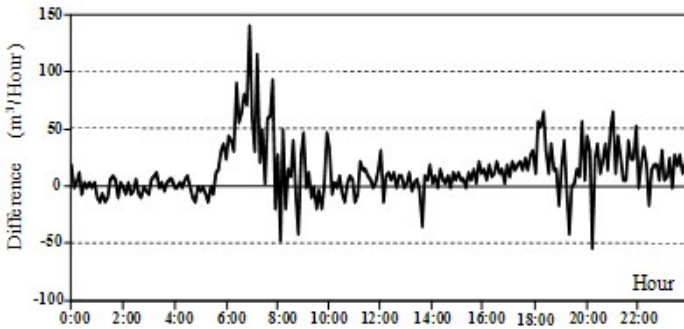


Fig.4 Estimated demand in Demand Area III (difference from the initial value)

The improvement rate at the measurement points in Fig.3 is defined as follows:

$$\text{Improvement rate} = \frac{D_c - D_e}{D_c} \quad (13)$$

D_c :Difference using conventional pipe network analysis

D_e :Difference using pipe network analysis with demand estimation

The improvement rates from Equation (12) averaged over 24 hours are shown in Table 1, along with the difference obtained using the conventional pipe network analysis method and the difference obtained using the proposed pipe network analysis method with demand estimation. The node where Pressure Sensor **b** is installed shows an improvement of more than 40%.

In addition, the calculation time for the proposed pipeline network analysis method using demand estimation was confirmed to be less than the required level of one minute by Hitachi 3050RX/340G (PA-RISC 132 MHz).

Table 1. Improvement rate (mean) at nodes with a pressure sensor installed

Pressure sensor	Difference using conventional pipe network analysis (mean)	Difference using proposed method (mean)	Improvement rate (mean)
a	0.088 kg/cm ²	0.071 kg/cm ²	19.18 %
b	0.167 kg/cm ²	0.096 kg/cm ²	42.64 %
c	0.078 kg/cm ²	0.054 kg/cm ²	31.09 %
d	0.183 kg/cm ²	0.137 kg/cm ²	25.18 %
e	0.371 kg/cm ²	0.256 kg/cm ²	30.89 %
f	0.232 kg/cm ²	0.213 kg/cm ²	8.40 %
g	0.223 kg/cm ²	0.157 kg/cm ²	29.44 %
h	0.247 kg/cm ²	0.182 kg/cm ²	26.49 %
i	0.154 kg/cm ²	0.122 kg/cm ²	21.22 %
Mean	0.194 kg/cm ²	0.143 kg/cm ²	26.17 %

4.3 Demand Estimation Results and Discussion

Next, the estimated demands in Demand Area III using the proposed method are shown in Fig.4.

It is immediately obvious that the estimated demand varies greatly from the initial value during the time periods of from around 5 a.m. to 9 a.m. and from around 5 p.m. to midnight. Moreover, the variation can be categorized into two types. In one type of variation, demand increases compared to the initial value in the morning and evening/nighttime (Demand Areas II, III, and V). In the other type of variation, demand decreases compared to the initial value during the same time periods (Demand Areas I, IV, and VI). The difference in style of daily life depending on the type of consumer, as mentioned in Section 3.1, is thought to yield the demand estimation results shown in Fig.4. In particular, estimation results with a shape similar to that of the water consumption trend of ordinary households

appear clearly in Demand Areas II, III, and V. Thus, it is evident that there is a relatively large concentration of water consumption by ordinary households compared to water consumption by offices and factories.

In the present study, it was confirmed that, in areas with several residential zones, electricity demand increases in the morning and evening. Conversely, in areas with several offices and factories, demand increases during working hours. Based on the demand estimation results in the present paper, in the case of water demand, fluctuation in demand in the morning and evening can be observed to follow a trend similar to electricity demand fluctuation.

5 Conclusion

This paper demonstrated that the difference between pipe network analysis results and sensor measurements is largely attributable to the method of assigning node demand set based on fixed distribution ratios in the conventional pipe network analysis. We also formulated a demand estimation problem for estimating node demand and proposed a method of solving this problem.

We considered the problem whereby the deviation between node pressures calculated using the conventional pipe network analysis method and measured values occurs because node demand in the pipe network analysis problem is provided as a boundary condition from outside of the system. As a basic approach to solving this problem, a method was devised for estimating demand by correcting it so that the deviation between demand and information from pressure/flow sensor measurements is minimized. The demand estimation problem was formulated as a minimization problem that minimizes the sum of squares between sensor measurements and analysis values at nodes with a sensor installed.

In comparison to the number of nodes at which demand is to be estimated (several thousand), the number of measurement points at which information that can be used in demand estimation is obtained is equal to the number of points where measurement sensors are installed (several tens). Therefore, the distribution network was divided into a number of demand areas based on the utilization characteristics of the land, and the demand estimation problem was reformulated in the divided demand areas. In order to solve this demand estimation problem, a new

solution that combines the primal-dual method, the downhill simplex method, and the Hardy Cross method was presented.

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