Demand estimation method using reverse pipe network analysis in water supply network

Teruji Sekozawa, Kazuaki Masuda

Abstract**—**We present a demand estimation method using reverse pipe network analysis in a water supply network. In conventional method, many demand points set fixed component ratios. The objective of the pipe network analysis method using the demand estimation proposed herein is accuracy improvement on a level such that the analysis can also be applied to distribution control.

We first explain pipe network analysis using a conventional method and then clarify the problems and challenges in conventional pipe network analysis. A temporal trend can be observed in the deviation of node pressure calculated using the conventional pipe network analysis method from the measured pressure. The cause of this deviation is identified as being due to the fact that the node demand in the pipe network analysis problem is supplied as a boundary condition from outside the system. Therefore, the problem considered in the present paper is the degree of accuracy with which node demand, which is conventionally supplied from outside the system, can be estimated.

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. The basic approach of this estimation method is to minimize the deviation between demand and information from pressure/flow sensor measurements, and the demand estimation problem is formulated as a deviation minimization problem. Here, the number of demands to be estimated is equal to the number of nodes, which is a very large number (several thousand).

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. Furthermore, the improvement rate at sensor installation points was demonstrated to more than 25% on average.

Keywords**—** Pipe network analysis, Demand estimation, Demand area, Distribution control, Deviation minimization problem, Large-scale pipeline network

I. INTRODUCTION

WATER supply systems are public utilities that are essential for daily life, and the companies that operate these utilities are obligated to consistently supply water to consumers in a stable manner. If classified from the functional perspective of transporting water to consumers, water supply systems are composed of two systems, a delivery system and a distribution system. The delivery system fulfils the role of delivering water drawn from a river, for example, that has not been purified (raw water) to a purification plant and delivering water that has been purified at the purification plant (clean water) to a distribution reservoir where it is stored temporarily. Therefore, in the delivery system, an operating plan (water supply control and management) that sets out how to determine the amount of water to be delivered to the purification plant and the distribution reservoir is important [1][2]. Meanwhile, the distribution system fulfils the role of supplying (distributing) water from the distribution reservoir to the final consumers of the water in households, offices, and factories. Therefore, compared to the delivery system, the distribution system has an extremely large network in terms of total pipe length, and the number of pipes can range from several hundreds to several tens of thousands or more. This distribution system network, referred to as a water distribution network, is composed of closed pipelines (pipelines that distribute water in a pressurized state, without air entering). In distribution systems, water is distributed to consumers from distribution reservoirs via a distribution network by means of gravity flow using the difference in elevation or pressurized distribution using pumping facilities [3]. The guide for the minimum guaranteed level of water supply pressure (end pressure) to consumers is 1.5 kgf/cm^2 (0.147 MPa), and, in areas where the end pressure does not reach this level, it is increased using pumps installed in the distribution network, while in areas where the end pressure greatly exceeds this level, it is decreased using valves [4][5].

Since the minimum guaranteed level of pressure is just a guide, it is not necessarily the case that all water supply companies can adhere to this level over their entire distribution network. However, maintaining the distribution network at an appropriate pressure is an important responsibility of the water supply company.

Pipe network analysis is a technique for calculating end pressures and pipe flow rates in the type of water distribution network mentioned above. 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.

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Well-known solutions include the node method, which considers the pressure as an unknown, and the flow method, which considers the flow rate as an unknown. In the node method, the Newton–Raphson Method [6], which is a method of solving non-linear algebraic equations, is applied, and acceleration techniques using sparsity in iterative matrix computation are known. With respect to the flow method, it has been reported that by reducing the pipe network analysis problem to a minimum cost flow problem and using integer operation and piecewise linear approximation of cost coefficients, greater acceleration is achieved in proportion to the basic solution for the node method, i.e., the Marlow method [7].

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.

Accordingly, with the goal of improving the accuracy of pipe network analysis, we herein propose a pipe network analysis method using demand estimation by proposing a demand estimation method that estimates demand points set on the basis of conventional, fixed component ratios. 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 ±0.2 kgf/cm^2 and an analysis calculation time that does not exceed 1 minute (Hitachi 3050RX/340G, PA-RISC 132 MHz). However, calculation time is not a critical problem in practical terms because, even in the conventional pipe network analysis method, the calculation time is only approximately 10 s.

In Section 2, we explain the conventional method of pipe network analysis and identify problems and challenges. In Section 3, we explain the proposed method, which is a demand estimation method that estimates node demand using measurements from pressure and flow sensors installed in the distribution network. In Section 4, we present and discuss results for improving the accuracy of pipe network analysis using the proposed method, and demonstrate the effectiveness of this method.

II. CONVENTIONAL PIPE NETWORK ANALYSIS AND PROBLEM AREAS

A. *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. Fig.1 shows a diagram of the flow balance and pressure balance equations in pipe network analysis.

The set of nodes that serve as supply points for the distribution network (e.g., distribution reservoirs) and the set of other nodes are represented by N_{in} and N, respectively. The flow rate in pipeline j is taken as x_j and the inflow (equivalent to the total amount of water supplied by the distribution reservoir) at node i is taken as w_i. In addition, the outflow (demand) at node i is taken as y_i. The set of pipes having node i as their starting point and the set of pipes having node i as their end point are denoted as $A^+(i)$ and $A^-(i)$, respectively.

Then, the flow balance equation is given as

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

The unit for the flow rate in the following equations is m^3/s. Pressure refers to the pressure head, the unit of which is m. When a set of pipelines is taken as B, the pressure at node i is p_i, the start point and end point of pipeline j are $s(j)$ and $e(j)$ respectively, and the resistance of pipeline j is R_j. The pressure balance equation is given as

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

Using the Hazen–Williams equation, the resistance, R_j, of pipeline j, is given as

$$R_j = 10.666\ C_j^{-1.85} D_j^{-4.87} L_j \tag{3}$$

$$\alpha = 1.85 \tag{4}$$

where C_j, D_j, and L_j represent, respectively, the coefficient of velocity, diameter, and length of pipeline j.

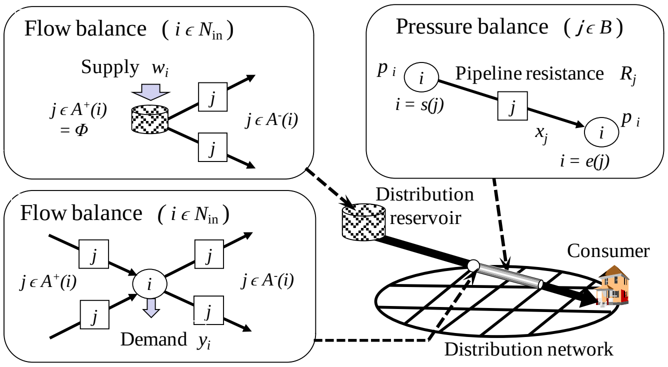

Fig.1 Diagram of the flow balance and pressure balance equations in pipe network analysis

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. In the pipe network analysis problem defined above, demand.

B. Problems and Challenges in Conventional Pipe Network Analysis

The node pressure in water distribution networks is commonly maintained within a range of 1.5–4.0 kg/cm^2, and the pressure at this node usually hovers around 2.0 kg/cm^2. As is evident from Fig.2, a difference of approximately 0.2kg/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. 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. Fig.2 shows the results of a pipe network analysis carried out for an existing distribution network. The figure shows the transition over 24 hours in the difference between the node pressure obtained using the conventional pipe network analysis method and measurements from a pressure sensor installed at the same node. The vertical axis shows the pressure difference, the unit of which is kg/cm^2. The node pressure in water distribution networks is commonly maintained within a range of 1.5–4.0 kg/cm^2, and the pressure at this node usually hovers around 2.0 kg/cm^2. As is evident from Fig.2, 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.

As is evident from Fig.2, 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.

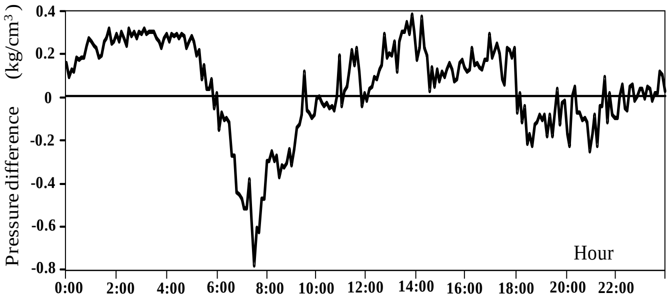

Fig.2 Temporal variation in difference between node pressure according to the conventional pipe network analysis method and measured pressure

As mentioned in previous section, 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 component ratios are for monthly average demand and do not necessarily provide appropriate node demands in pipe network analysis.

For this reason, the differences, which, as shown in Fig.2, 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.

III. DEMAND ESTIMATION METHOD

A. 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, that, 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:

$$\min_{\mathbf{y}} \quad J(\mathbf{y}) = \sum_{i \in N_{\mathrm{m}}} (p_i - p_i^*)^2 \tag{5}$$

$$\text{s.t.} \quad \sum_{j \in A^-(i)} x_j - \sum_{j \in A^+(i)} x_j = \begin{cases} -w_i & (i \in N_{\mathrm{in}}) \\ y_i & (i \in N) \end{cases} \tag{6}$$

$$p_{s(j)} - p_{e(j)} = R_j \left| x_j \right|^{\alpha-1} \cdot x_j \quad (j \in B) \tag{7}$$

$$\sum_{i \in N} y_i = \sum_{i \in N_{\mathrm{in}}} w_i \tag{8}$$

where the node demand is $\boldsymbol{y} = (y_1, y_2, \cdots, y_i, \cdots)$, $\boldsymbol{y}$ 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 (5). The demand estimation problem defined by Equations (5) through (8) 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 $\boldsymbol{Y} = (Y_1, Y_2, \cdots, Y_k, \cdots)$. The set of demand areas is taken as L, and the set of nodes i belonging to demand area i is taken as N_k. Here, the demand estimation problem in Equations (5) through (11) can be rewritten as Equations (9) through (14), as follows:

$$\min_{\mathbf{Y}} \quad J(\mathbf{Y}) = \sum_{i \in N_{\mathrm{m}}} (p_i - p_i^*)^2 \tag{9}$$

$$\text{s.t.} \quad \sum_{j \in A^-(i)} x_j - \sum_{j \in A^+(i)} x_j = \begin{cases} -w_i & (i \in N_{\mathrm{in}}) \\ y_i & (i \in N) \end{cases} \tag{10}$$

$$p_{s(j)} - p_{e(j)} = R_j \left| x_j \right|^{\alpha-1} \cdot x_j \quad (j \in B) \tag{11}$$

$$\sum_{k \in L} Y_k = \sum_{i \in N_{\mathrm{in}}} w_i \tag{12}$$

$$y_i = \gamma_i^{\,k} \cdot Y_k \quad (j \in N_k) \tag{13}$$

$$Y_k > 0 \qquad (k \in L) \tag{14}$$

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.

With regard to the division of demand areas, since it is difficult to determine a unique optimum solution if no measurement points exist in the demand area, the distribution network is divided in such a manner that there is at least one measurement point inside each demand area.

B. Method of Solving the Demand Estimation Problem Final Stage

In this section, we present a method of solving the demand estimation problem. It is possible to derive a solution for the demand estimation problem composed of Equations (9) through (14). Fig.3 shows a flowchart of this method of solving the demand estimation problem.

Since the demand estimation problem includes the pipe network analysis problem, the decision variables of the pipe network analysis problem are further increased due to the addition of area demands. For this reason, if we attempt to optimize all of the variables simultaneously, the amount of calculation becomes enormous. Therefore, in this solution, the variables are separated into area demand Y_k and variables of the pipe network analysis problem (pipe flow rate x_j and node pressure p_j). A hill-climbing search is carried out for area demand Y_k after the pipe network analysis has been solved.

The downhill simplex method is used in the hill-climbing search. A weakness of the downhill simplex method is that this method exhibits poor convergence in the neighborhood of the optimum solution, making it difficult to obtain a strictly optimum solution. However, problems set in a similar way to this demand estimation problem can be solved approximately twice as fast using this method, as compared to the conjugate gradient method and the steepest descent method.

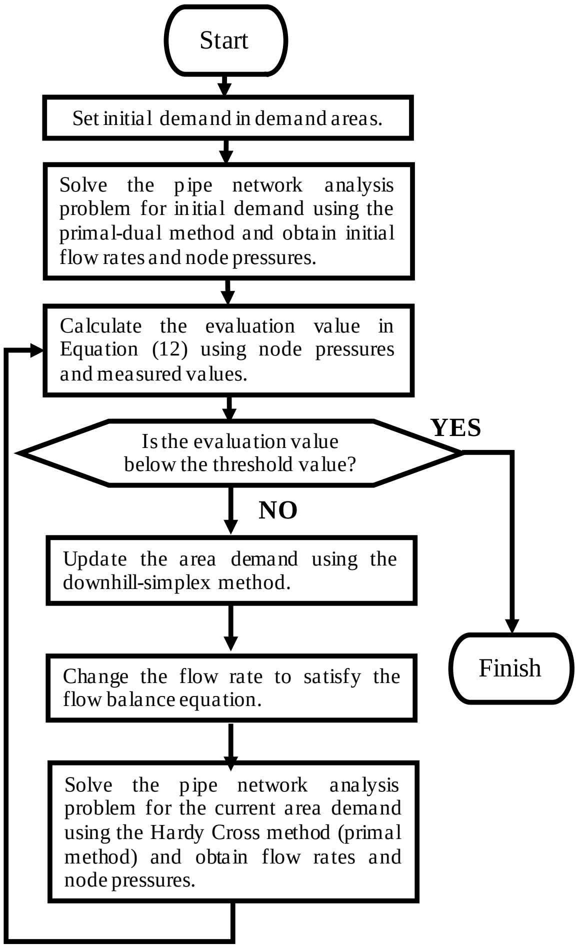

Fig.3 Flowchart of the method of solving the demand estimation problem

IV. APPLICATION RESULTS AND DISCUSSION

The proposed method was applied to the following distribution network:

- No. of distribution reservoirs: 6
- No. of nodes: 2,421
- No. of pipelines: 3,043
- Pressure sensors: nine locations
- Flow sensors: six locations

This distribution network is a municipal network existing in Japan, serving a population of approximately 300,000 with a maximum total distribution amount of approximately 8,000 m^3/h. The distribution network subject to application of the proposed method is shown in Fig.4.

A. 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.

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.4.

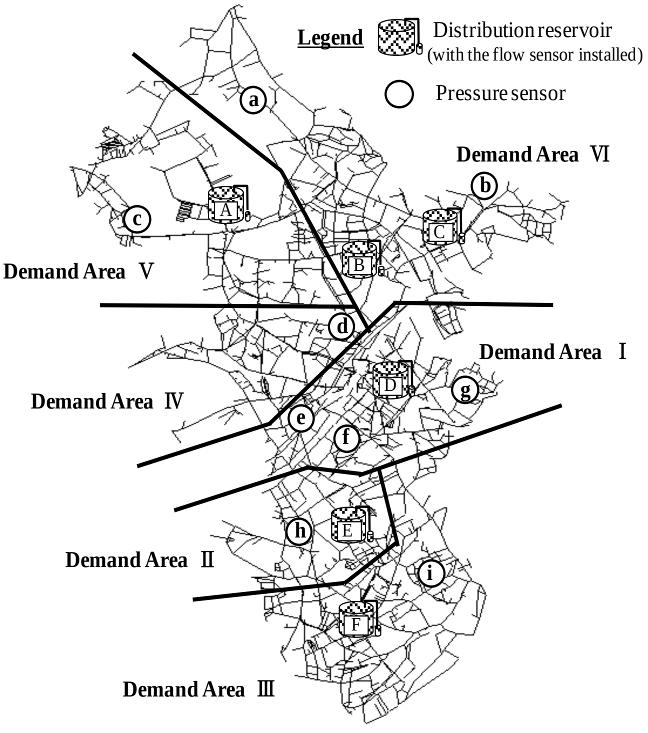

Fig.4 Division of the distribution network into demand areas

In this division of the demand areas, the distribution network was divided so that there was as 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.

B. 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.

Figures 5 through 13 show the difference between pipe network analysis results and pressure sensor measurements at nodes at pressure sensors a through i in the distribution network shown in Fig.4. The horizontal axis shows the time and represents a period of 24 hours for a given day. The analysis is carried out 288 times at five-minute intervals. The vertical axis shows the difference between the measurement from a given pressure sensor and the pressure value obtain through the analysis. The unit is kg/cm^2. The thick lines in the figures indicate the results of the pipe network analysis using the proposed demand estimation method, while the fine lines indicate the results of carrying out conventional pipe network analysis without demand estimation. Therefore, the closer the result is to 0 on the vertical axis, the better the performance of the pipe network analysis. From the perspective of pipe network analysis accuracy, this difference between pressure sensor measurements and analysis results simply means that the accuracy of the analysis is poor, regardless of whether the difference is positive or negative. From the perspective of distribution control, when there is a difference between the control target value and the pressure value resulting from the analysis, if the difference is positive, the analysis result is lower than the control target value, indicating a decline in distribution service, whereas if the difference is negative, the analysis result exceeds the control target value, indicating distribution at excess pressure, i.e., an energy loss is occurring.

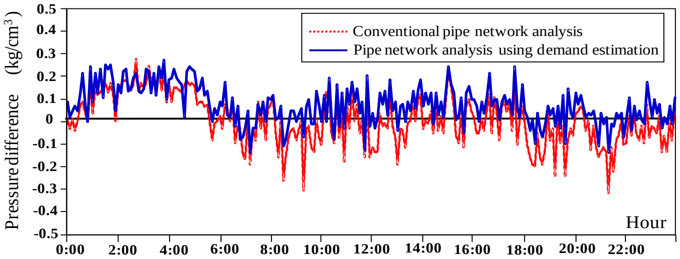

Fig.5 Difference between analysis value and measured value at a node at which Pressure Sensor a is installed

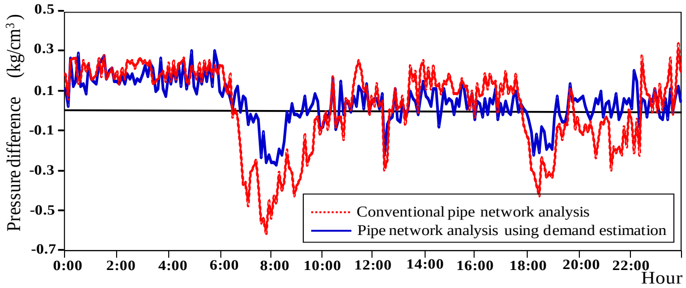

Fig.6 Difference between analysis value and measured value at a node at which Pressure Sensor b is installed

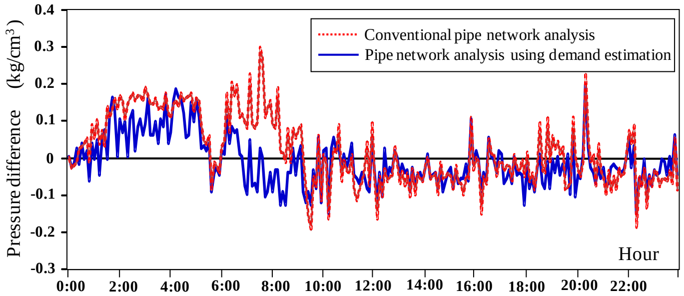

Fig.7 Difference between analysis value and measured value at a node at which Pressure Sensor c is installed

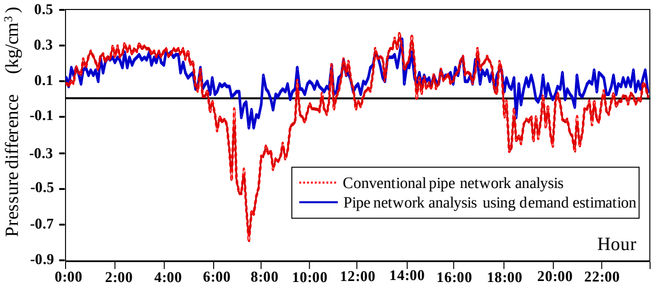

Fig.8 Difference between analysis value and measured value at a node at which Pressure Sensor d is installed

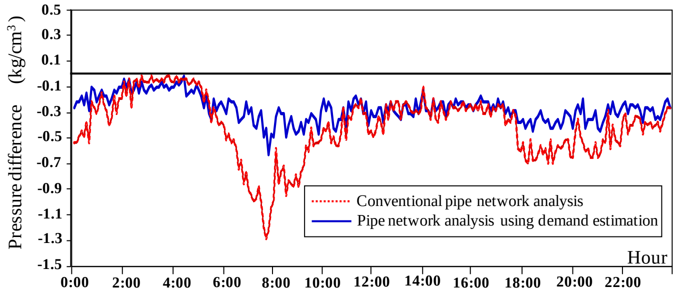

Fig.9 Difference between analysis value and measured value at a node at which Pressure Sensor e is installed

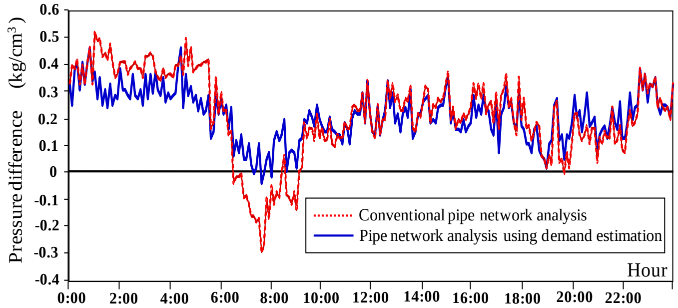

Fig.10 Difference between analysis value and measured value at a node at which Pressure Sensor f is installed

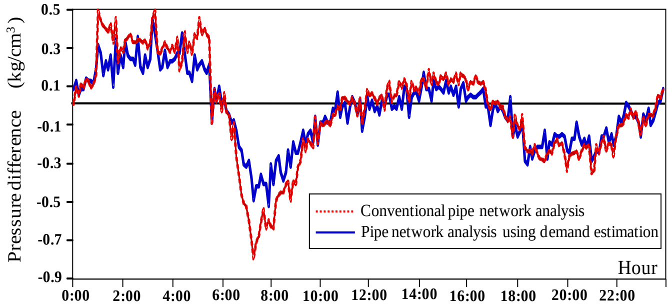

Fig.11 Difference between analysis value and measured value at a node at which Pressure Sensor g is installed

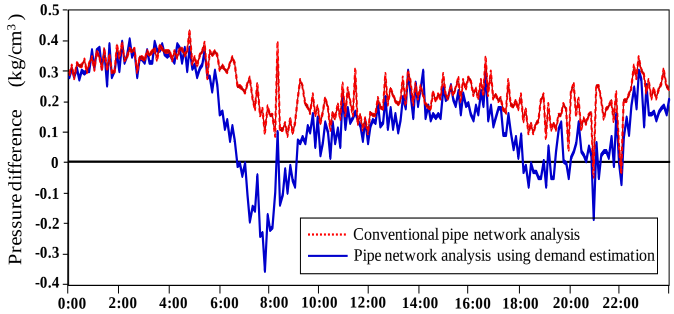

Fig.12 Difference between analysis value and measured value at a node at which Pressure Sensor h is installed

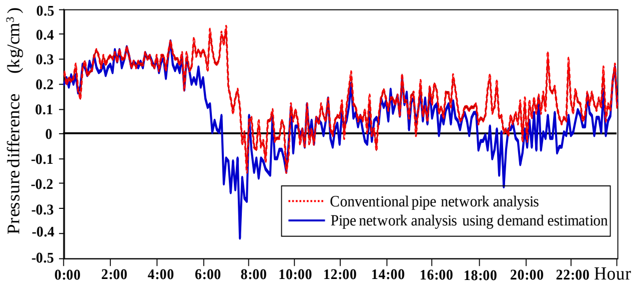

Fig.13 Difference between analysis value and measured value at a node at which Pressure Sensor i is installed

The improvement rate at the measurement points in Figures 5 through 13 is defined as follows:

$$\text{Improvement rate} = \frac{\text{Dc} - \text{De}}{\text{Dc}} \qquad (15)$$

Dc : Difference using conventional pipe networkanalysis
De : Difference using pipe network analysis with
demand estimation

The improvement rates from Equation (15) 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. First, the difference using the proposed pipe network analysis method with demand estimation exceeds 0.2 kg/cm^2 at two points (e and f), but is generally less than 0.2 kg/cm^2, and so satisfies the required level of difference, as anticipated. In addition, with regard to the two points exceeding 0.2 kg/cm^2, it was discovered through a final review of the distribution network data (elevation data and pipeline connection information) that there were flaws in the data, and, by correcting these flaws, the required level was satisfied.

Next, we will discuss the improvement rate defined by Equation (15). The improvement rate where Pressure Sensor f is installed is comparatively low but, at the other pressure sensor nodes, the improvement rate is almost 20% or above, and the node where Pressure Sensor b is installed shows an improvement of more than 40%. The improvement rates in Table 1 are averaged over 24 hours, and as evident from Figures 5 through 13, there is variation in the time periods in which the difference is improved, and if considered locally, there are several points at which the difference is greatly improved. However, little improvement in the difference appears in any of the demand areas from around midnight to 6 a.m. This is because the water demand during this time period is extremely small to begin with (approximately 1/10 of the maximum demand and 1/4 of the mean demand), and even if the demand in the demand area is changed due to demand estimation, this will have little effect on the pipe network analysis results. In addition, on the whole, the difference in this time period is a positive value in all of the areas, and so, in accordance with Equation (12), this difference will not be eliminated in the proposed demand estimation method. The difference in this time period is caused by something other than demand fluctuation, for example, mistakes in data concerning joint information for pipes in the distribution network, or flaws in the pipe attribute data (e.g., pipe length or pipe diameter) or node attribute data (e.g., elevation). In fact, based on the above conjecture, we reviewed the node elevations and pipeline connections from the analysis results for the late-night time period and discovered several flaws in the data on joint information for pipes and the attribute data for pipes and nodes.

It is also possible that the pipeline resistance model in Equation (2) of the pipe network analysis problem does not correspond to the actual situation. In particular, the coefficient of velocity C_j in the Hazen–Williams equation used in Equation (3), which is a pipeline resistance model, is identified as a coefficient that differs for each pipeline. However, like nodes, there is a very large number of pipelines, and it is impossible to set the coefficient of velocity accurately for each pipeline. Therefore, when considering further improvement of the accuracy of pipe network analysis, it is necessary to consider the pipeline resistance model. 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 %

V. 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.

The effectiveness of the proposed method was demonstrated quantitatively by applying this method to a large-scale existing municipal pipeline network of 3,000 pipes. As a result of the 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. Furthermore, the improvement rate at sensor installation points was demonstrated to more than 25% on average. In addition, by inspecting data from each demand area, it was possible to observe water demand characteristics in each demand area, which could not be inferred from static land use data only. In other words, it was found that by adding data from sensors in the distribution network to static, spatial land use classification data, it is possible to comprehend temporally-fluctuating, dynamic water utilization characteristics.

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