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A computer program is described for the transient flow analysis of water pipeline networks. This program was developed by Kawasaki Steel to simulate transient phenomena in a complete water pipeline, including valves, pumps, reservoirs and leakage points. In order to check the accuracy of this program, a field test was run on an existing water transmission pipeline in Ishikawa prefecture. The numerical analysis show good agreement between experimental data and simulated results within a maximum error of 3.7% in pressure. This program can play an important role in managing a large-scale water pipeline network when used as part of the lifeline information management system (LIMAS), which was developed by computer mapping techniques. This flow analysis program extends the applicability of LIMAS to many fields of waterworks such as future water supply planning, short-term flow prediction in daily operation, and leakage flow control.

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Transient Flow Analysis for the Management of Water Pipeline Network Systems*



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Synopsis:

A computer program is described for the transient flow analysis of water pipeline networks. This program was developed by Kawasaki Steel to simulate transient phenomena in a complete water pipeline, including valves, pumps, reservoirs and leakage points. In order to check the accuracy of this program, a field test was run on an existing water transmission pipeline in Ishikawa prefecture. The numerical analysis shows good agreement between experimental data and simulated results within a maximum error of 3.7% in pressure. This program can play an important role in managing a large-scale water pipeline network when used as part of the lifeline information management system (LIMAS), which was developed by computer mapping techniques. This flow analysis program extends the applicability of LIMAS to many fields of waterworks such as future water supply planning, short-term flow prediction in daily operation, and leakage flow control.

1 Introduction

Computer mapping for facility management is widely used in many lifeline systems, including water, oil and gas pipelines, as well as traffic, power and telecommunication systems.

Most of this mapping is used as a support tool for facility maintenance and management, in which existing data and new information are processed, edited and recorded for use in daily operation and emergency action.

However, the computer mapping system for facility management has greater potential capability when used together with such analytical sub-systems as steady and transient flow analyses, planning and scheduling of renewal and retrofitting to existing deteriorated pipelines, and risk management in accidental leakage.

This report describes an analytical method and its application to steady and transient flow in a water pipeline network, in which a simulation program forms the analytical basis, and a computer mapping system is used as the pre/post processor for this simulation program.

A field test was run to verify this simulation program, using a water transmission pipeline in Ishikawa prefecture. In order to increase the applicability of the program, several sub-systems were incorporated to simulate water supply control under multi-demand change and emergency control after a major leakage.

In the subsequent sections, numerical examples will be shown to illustrate the potential capability of the analytical method.

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2 Flow Analysis for a Water Pipeline Network

2.1 Formula for Steady Flow

Consider a steady state flow in a single pipe with a node at each end. The water head (H) and flow rate (Q) at nodes are related by the following equations:[1)]

$$Q_{i,i+1} = F(H_i - H_{i+1}) = F(\mathrm{DH}_{i,i+1}) \quad \cdots\cdots(1)$$

$$\sum_{j=1}^{n} Q_{i,j} = q_i \quad \cdots\cdots(2)$$

where

F: Function which gives the flow rate based on head loss
q: Internal boundary condition of the flow rate
DH: The head loss between the two nodes
i,j: Suffices denoting the node number

Superimposing these equations for all the pipes in a total network produces Eqs. (3) and (4).

$$\mathbf{Q} = \mathbf{F}(\mathbf{DH}) \quad \cdots\cdots(3)$$

$$\mathbf{S}(\mathbf{Q}) = \mathbf{q} \quad \cdots\cdots(4)$$

where

Q: Vector giving the flow rate in every pipe
DH: Vector giving the differential head in every pipe
F: Matrix giving the flow rate based on head loss in every pipe
S: Matrix giving the summation of flow rate at every node

By introducing $\mathbf{\Delta DH}_i$ and $\mathbf{\Delta Q}_i$ to satisfy Eqs. (3) and (4), after substituting the assumed $\mathbf{DH}_i$ and $\mathbf{Q}_i$, Eqs. (3) and (4) can be rearranged into the following forms:

$$\mathbf{Q}_i + \mathbf{\Delta Q}_i = \mathbf{F}(\mathbf{DH}_i) + \left(\frac{\partial \mathbf{F}}{\partial \mathbf{DH}_i}\right)\mathbf{\Delta DH}_i \quad \cdots\cdots(5)$$

$$\mathbf{S}(\mathbf{Q}_i + \mathbf{\Delta Q}_i) = \mathbf{q} \quad \cdots\cdots(6)$$

Since Eqs. (5) and (6) are simultaneous linear equations, the Newton-Raphson method can be used to solve for **H** and **Q** in a steady state.

2.2 Formula for Transient Flow

Assuming an isothermal state and incompressibility, the equations of momentum and continuity in one-dimensional flow in a pipe are as follows:[2)]

$$g\frac{\partial H}{\partial x} + V\frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} + \frac{fV|V|}{2D} = 0 \quad \cdots\cdots(7)$$

$$V\frac{\partial H}{\partial x} + \frac{\partial H}{\partial t} - V\cdot(\sin\theta)\cdot\frac{a^2}{g}\cdot\frac{\partial V}{\partial x} = 0 \quad \cdots(8)$$

where

V: Fluid velocity
D: Internal diameter of the pipe
f: Friction factor
θ: Angle of pipe inclination
g: Acceleration due to gravity

Here, a in Eq. (8) is the velocity of the pressuree wave given by Eq. (9) in which elastic deformation of the pipe is assumed.

$$a = \sqrt{\frac{K_W/\rho}{1 + (K_W D/K_P e)}} \quad \cdots\cdots(9)$$

where

ρ: Fluid density ($\fallingdotseq 9.98 \times 10^2$ kg/m^3)
K_W: Bulk modulus of the fluid ($\fallingdotseq 2.10 \times 10^8$ kg/m^2)
K_P: Bulk modulus of the pipe ($\fallingdotseq 1.96 \times 10^{10}$ kg/m^2)
e: Pipe wall thickness

The characteristics method is adopted to solve Eqs. (7) and (8). These equations are combined linealy by using an unknown multiplier λ ($= \pm g/a$), and the substitution of the values of λ into the combined equation leads to two pair of equations that are grouped and identified as C^+ and C^-.[3)]

It is convenient to visualize the solution as it develops on an independent-variable plane, i.e., the x–t (location-time) plane.

$$C^+ \begin{cases} \dfrac{1}{a}\cdot\dfrac{dH}{dt} + \dfrac{1}{g}\cdot\dfrac{dV}{dt} + \dfrac{fV|V|}{2gD} - \dfrac{\sin\theta}{a} = 0 & \cdots(10) \\ \dfrac{dX}{dt} = a & \cdots\cdots(11) \end{cases}$$

$$C^- \begin{cases} \dfrac{1}{a}\cdot\dfrac{dH}{dt} + \dfrac{1}{g}\cdot\dfrac{dV}{dt} + \dfrac{fV|V|}{2gD} + \dfrac{\sin\theta}{a} = 0 & \cdots(12) \\ \dfrac{dX}{dt} = -a & \cdots\cdots(13) \end{cases}$$

The initial condition at $t = 0$ is incorporated into the solution of the steady state flow analysis, while the boundary conditions at the end nodes of the pipe are represented by the boundary conditions existing in the network.

2.3 Boundary Conditions for Various Applications

The following boundary conditions are possible for various applications:

(1) Researvoir unit makes it possible to simulate the demand or supply change by flow rate and/or pressure data.
(2) Pump unit makes it possible to simulate a pump trip and pump start-up according to the characteristics of pump and the operational conditions.
(3) Valve unit makes it possible to simulate valve closure and flow control by a valve according to the

specifications of the valve and data on the valve open ratio.

(4) Leak point makes it possible to simulate leakage by defining the diameter of the leakage hole or data on the leak flow rate.

2.4 System Configuration

Figure 1 shows the configuration of this system. Numerical results from the steady-state flow analysis are printed out as normal text data, and written on the files of restart data for the transient flow analysis and of graphic data for the plotter. The transient flow analysis needs initial condition data at $t = 0$ which is transferred from the steady-state flow analysis, and data on the boundary conditions.

2.5 Flow Analysis for Facility Management

The most effective facility managemeent can be achieved by a mapping technique which combines geographical information about the various facilities and their characteristics with a relational data base (RDB) system.[4)]

The following two points are special features of the Kawasaki Steel computer mapping system for managing facility maintenance:

(1) A large amount of geographical information and a wide variety of characteristics data on the pipeline can be easily handled by the RDB incorporated in the mapping system.

(2) Once the RDB has been constructed, the facility can be managed for its daily maintenance, operations, and risk in a case of accident or disaster.

In other words, it is possible to extract the potential capability of the system from the database and improve it by constructing of a variety of applications with the basic functions of the computer mapping system.

To achieve, it is necessary to prepare an application system to support maintenance activities when the information management system for the pipeline is constructed.

Figure 2 shows the concept of a facility management system assisted by computer mapping technology. The basic mapping system has an RDB which contains all the information about the pipeline, an RDB management system which controls this database, and a graphic control module which takes charge of the input/output of graphic information. By using the basic mapping system, application programs to support management and maintenance activities for pipeline facilities can be constructed strictly according to needs. These application programs are linked with the mapping system through an interface so that analysis and processing of the primary data from the RDB can be done. The solutions or results are then returned to the mapping system via the interface so that they can be processed and displayed graphic module. To manage facilities like a pipeline network that is spread over the wide area, it is very con-

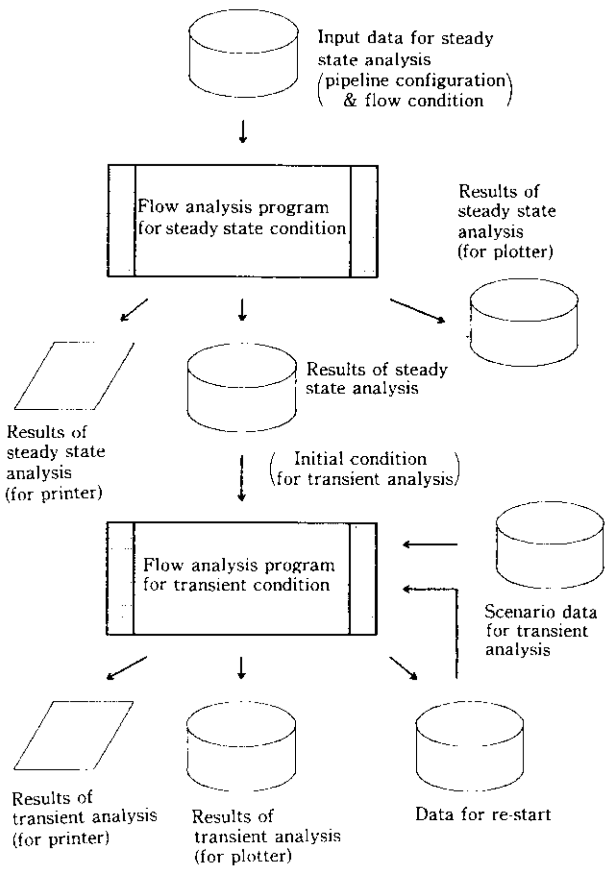

Fig. 1 System configuration

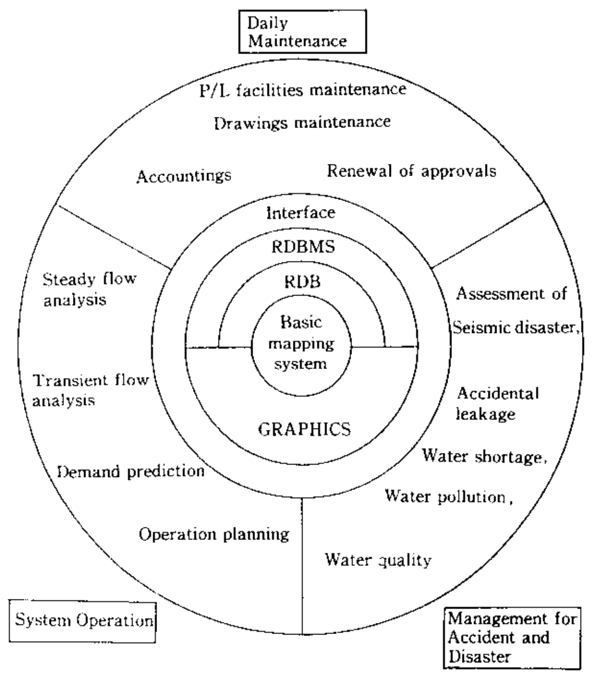

Fig. 2 Correlation between computer mapping and its application systems

enient to use this type of system for understanding the omplete picture, because the numerical results of the nalysis are expressed by a graphic display of the pipene network and a base map.

The flow analysis program is the basic tool used to nalyze the network flow characteristics in order to plan ›perations, evaluate the efficiency of the pipeline net›ork, and plan renewal or repair. Prior to simulating the ransient water flow in a pipeline network, it is necesary to prepare input data that define the boundary conlitions at every node, pipe specifications and network opology. This preparation work can take a great deal of ime and effort if a suitable data processing system is ıot available for a large-scale network. The computer napping system allows this work to be done more asily and accurately than before. In this way, the com›uter mapping system can be used as the preprocessor or an application system such as a flow analysis pro;ram, and as the post-processor to provide a visual dis›lay of the results.

Photo 1 illustrates a screen example of data editing for flow analysis with the computer mapping system. nteractive operation with a mouse and keyboard can nake it easy to maintain the accuracy of various types ›f input data, because the location and topological conlitions of pipe links can be easily confirmed on the ;raphic terminal. The mapping system incorporates the ›asic functions of graphic control for zooming, panning, crolling, composing graphic layers, and controlling the ine type and color that are needed to make the most ıppropriate types of maps.

In Photo 1, such geographical data as contour lines, oads, and rivers are shown, because these background lata help the operator to easily locate a particular pipeine and reduce the data that needs to be input.

The simulated results are shown on the pipeline network together with the map to give a quick and clear understanding of the large amount of numerical data.

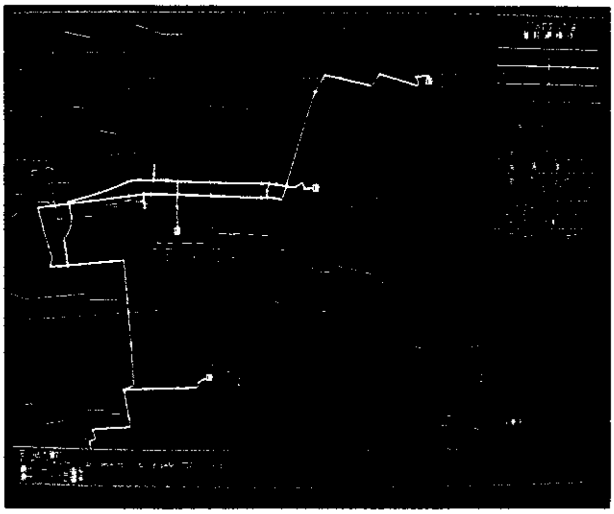

Photo 1 Graphic screen of computer mapping system

3 Experimental Study

3.1 Hydraulic Transient Flow Test and Its Numerical Analysis

A test was carried out to check the accuracy of the transient flow analysis program with the actual results from a water pipeline network of 28 km in total length which forms part of the water transmission pipeline in Ishikawa prefecture. **Figure 3** illustrates the pipeline network model for the test, and the specifications of pipes involved are shown in **Table 1**. This network has one supply and six demand stations, including three reser-

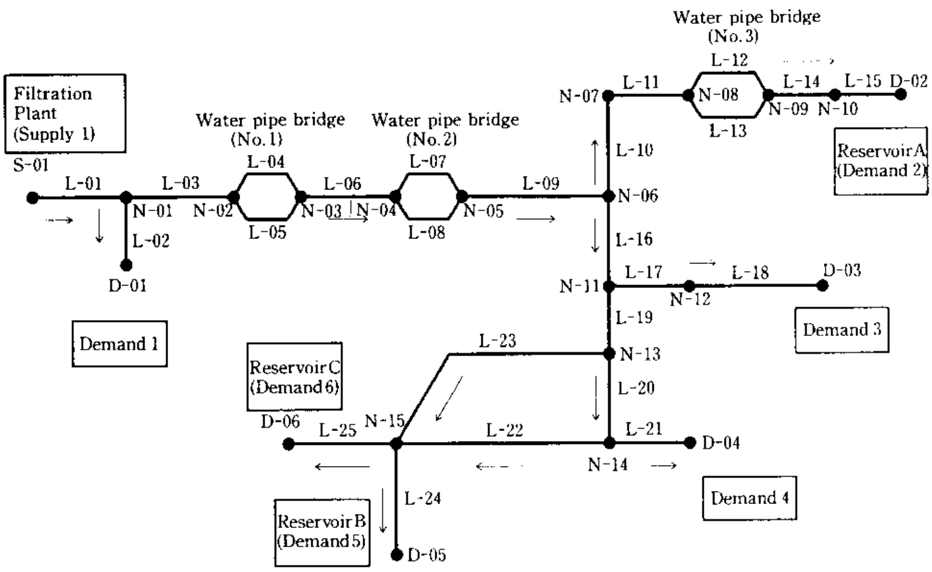

Fig. 3 Network model for simulation

Table 1 Pipeline specifications

No.	Link ID	Dia. (mm)	Length (m)
1	L-01	1 800	1 142
2	L-02	300	217
3	L-03	1 800	829
4	L-04	1 350	274
5	L-05	1 350	274
6	L-06	1 800	264
7	L-07	1 350	286
8	L-08	1 350	286
9	L-09	1 800	4 718
10	L-10	1 350	2 319
11	L-11	1 200	641
12	L-12	700	636
13	L-13	700	636
14	L-14	1 200	783
15	L-15	1 200	2 137
16	L-16	1 600	1 378
17	L-17	350	552
18	L-18	300	654
19	L-19	1 600	2 058
20	L-20	1 350	1 701
21	L-21	300	573
22	L-22	1 350	810
23	L-23	1 000	2 875
24	L-24	1 200	490
25	L-25	1 000	2 315

voirs. Based on daily supply planning, water is conveyed from the supply station to each demand station, at which the flow is controlled to maintain a constant water level at the supply station by a flow control valve installed at the supply station.

During this test, the flow rate at demand station 5, which is the receiving reservoir, was manually controlled to increase or decrease the initial flow conditions, while the valve opening ratio was fixed at the other two reservoirs. All the other demand nodes, apart from these specified demand stations, had the flow fixed by automatic flow control valves.

Changes in the pressure and flow rate were measured at each point when the flow rate at demand station 5 was changed to scheduled levels based on the test plan. These measured data were used for the numerical simulation as the boundary conditions. The following parameters were changed to provide 16 cases for the test: the initial flow level at demand station 5 under steady state conditions, the demand, the absolute flow rate due to changing demand, and the valve control speed. **Figure 4** shows one of models for these various boundary conditions.

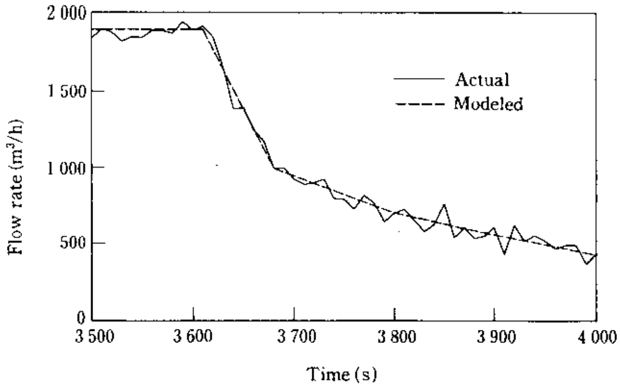

Fig. 4 Boundary condition at the demand 5

3.2 Comparative Study of Results from the Test and Numerical Analysis

The data recorded from the field test were compared with the numerical results obtained from a flow simulation of the pipeline network model. **Figure 5** shows a comparison of the pressure profile at demand station 5 between the test data and simulated results for the case of the demand flow change shown in Fig. 4. In this case, the flow rate at demand station 5 was decreased to the lower pre-set flow level in 60 seconds with the flow control valve. This operation generated a positive pressure wave at this point and subsequent periodic waves until the system settled down to another steady state.

Comparing the test data with the simulated results, good agreement within a 3.5% error is apparent, the actual and simulated pressure waves being approximately identical in their amplitude and frequency. The minor difference between both results seem to have been influenced by the use of an ultrasonic flow meter, which was temporarily installed instead of the normal electro-magnetic flow meter at one measurement point, and which gave cause for doubt about its accuracy.

A comparison of the flow rate profile at supply station 1 between the test and simulated data for the same case

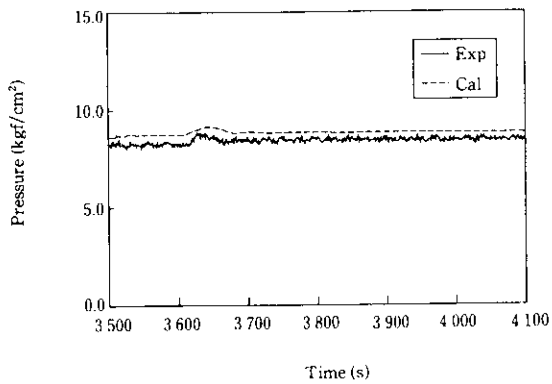

Fig. 5 Comparison of pressure profile at demand 5 between the experimental data and simulated results

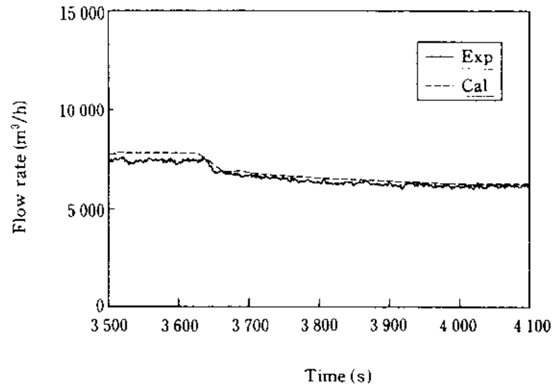

Fig. 6 Comparison of flow rate profile at supply 1 between the experimental data and simulated results

is shown in **Fig. 6**. The supply flow rate at this station decreased due to the demand change at demand station 5, and there is some difference between the flow rate profile at this point and the boundary conditions at demand station 5 as shown in Fig. 4. The flow rate at this point shows a decreasing periodic behavior, as was shown with the pressure wave in Fig. 5.

This periodic behavior in the flow rate at this point is assumed to have resulted from the influence of the demand flow change at demand station 5 on the other reservoirs that had a constant valve opening ratio. As shown in Fig. 4, the calculated value is in good agreement with the measured one within a 3.5% error. This results provide enough confidence for this transient flow analysis program to be used in practice with sufficient accuracy.

3.3 Case Studies of the Application for Management of Water Pipelines

Two case studies involving the application of this transient flow analysis program are presented, although the program is applicable to many other subjects such as operation planning, water availability studies, and rehabilitation planning.

3.3.1 Case study 1: Simulation of synchronized demand flow changes due to multiple demands

The boundary conditions for this study are given by the demand flow change at one reservoir (demand station 5).

The following cases for demand flow were simulated:

(1) Synchronized demand flow changes at demand stations 5 (reservoir B) and 6 (reservoir C).

(2) Synchronized demand flow changes at demand stations 5 (reservoir B), 6 (reservoir C), and 2 (reservoir A).

Figures 7 and **8** indicate the simulated results of the pressure–time profile at each point in cases (1) and (2). As shown in Fig. 7, negative pressure waves appear at demand stations 5 and 6 at the moment of starting the synchronized demand flow changes (t = 100 s), and these waves spread to the other points after some delay. The characteristics of these pressure waves are similar to those in the case of the single demand flow change already indicated except for some differences in the wave pattern and their comparatively large amplitude. It took about 300 seconds for the periodic wave motion to decay and disappear.

In the case of the synchronized demand changes at 3

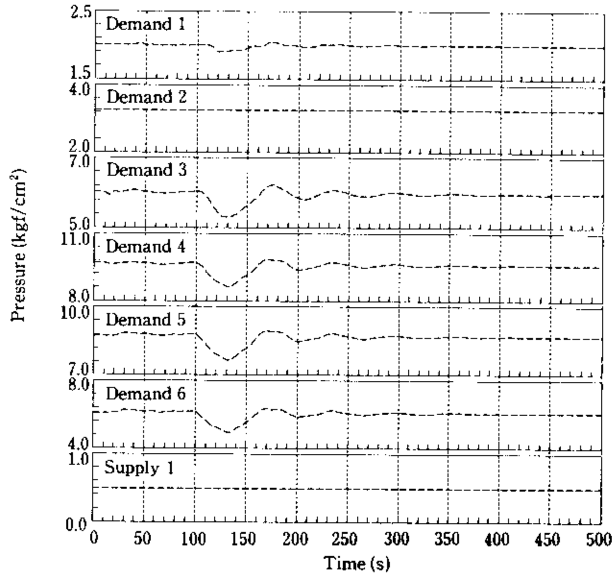

Fig. 7 Simulated results of pressure–time profiles in case of synchronized demand change at the reservoirs B and C

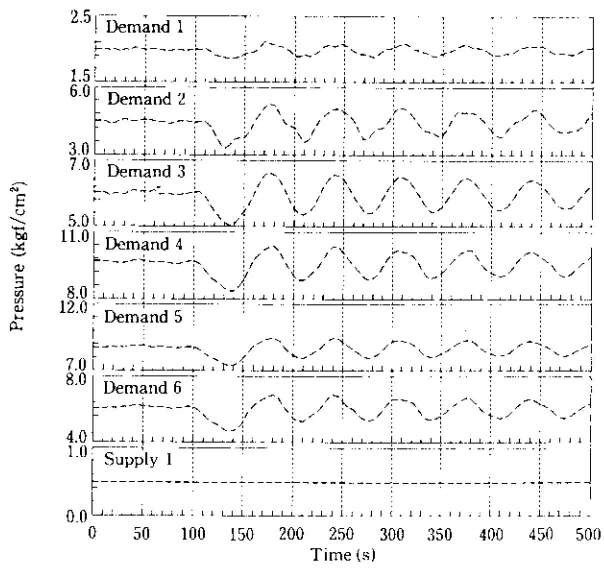

Fig. 8 Simulated results of pressure-time profiles in case of synchronized demand change at the reservoirs A, B, and C

reservoirs shown in Fig. 8, on the other hand, the pressure amplitude was slower to decrease, taking more than 400 seconds until the flow conditions returned to their steady state. Since the maximum amplitude of these pressure waves was higher by as much as 2.5 kgf/ cm^2, it must be noted that these phenomena should be avoided in order to protect the pipeline system from structural damage.

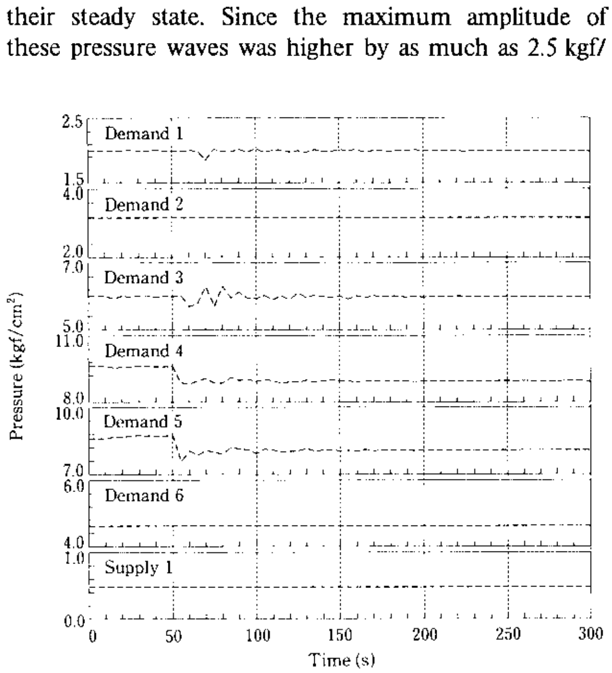

Fig. 9 Simulated results of pressure–time profiles in case of leak occurrence at the middle point of L-19

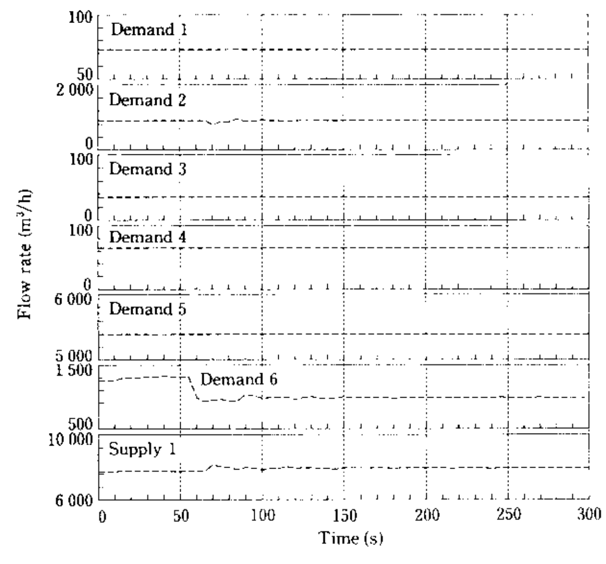

Fig. 10 Simulated results of flow rate–time profiles in case of leak occurrence at the middle point of L-19

3.3.2 Case study 2: Simulation of a leak

Figures 9 and **10** indicate the simulated results when a leakage flow of $500\,m^3/h$ was assumed to have occurred at the mid-point of L-19 in Fig. 3. The pressure values dropped sharply downstream of the leakage point, while periodic pressure waves appeared at upstream of the leakage point.

This hydraulic behavior near the leakage point may provide effective information on how to identify the location of a leak in a pipeline network system when the transient flow simulation technique is available.

4 Conclusions

The major accomplishments on this study can be summarized as follows:

(1) A steady and transient flow analysis program was developed for a water pipeline network as an application system for facility management with computer mapping technology.
(2) The simulated results from this program were in good agreement with test data measured in a water transmission pipeline in Ishikawa prefecture within a 4% error. This indicates that the system has sufficient accuracy for practical use in water pipeline networks.
(3) Several simulations were run as case studies for the management of water pipeline facilities. This system proved capable for use in managing water pipeline, and can be used for operation planning, water availability studies, and rehabilitation planning.

Further studies will be made to develop other application programs which can support the computer mapping system for facility management.

The authors express our grateful thanks to Ishikawa Prefectural Bureau of Public Utilities for giving us the opportunity to run this test.

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