# ON IMPROVEMENT OF REAL-TIME PRESSURE CONTROL IN A WATER DISTRIBUTION NETWORK

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Abstract. In Japan, leakage of water from water distribution networks amounts to more than 15% of the total outflow from reservoirs. For reduction of leakage, some means is necessary to regulate the pressure in the network as low as possible under the constraint that water is smoothly delivered to all users. In consequence, it is now strongly desired to establish means of advanced real-time control to maintain the pressure closely to 2 atm., the recommended value in Japan, against fluctuations of consumptions. A trial of such a control of a decentralized type was started in some supply zones of a middle-sized city in Japan. The control is actually working well, but its accuracy is slightly worse than expected. This paper is concerned with improvement of accuracy of the control: Through analysis of detailed data gathered in some supply zones, simulation studies by use of a reduced model of a supply zone and an analytical investigation to determine the values of parameters of the current control scheme, new schemes for improving the accuracy are developed.

Keywords. Water distribution network; real-time control; pressure regulation; decentralized control; single-loop control.

## INTRODUCTION

The uniform pressure control in a water distribution network, i.e., keeping the water pressure within a certain range at any point in the network, is strongly desirable in order to guarantee smooth water supply, to reduce leakage and waste of water, and also to protect pipes, etc. Especially in Japan, leakage of water from the network, which is proportional to the 0.5th to 1.15th power of the pressure, amounts to more than 15% of the total outflow from reservoirs. Then, it is now widely admitted that the pressure of 2 atm. (20m in water column) to 2.5 atm. is most desirable for water distribution mainly from the viewpoint of reducing leakage.

Nowadays in Japan, development of new water resources is becoming more and more difficult and expensive. Hence, for more efficient use of existing water resources, some public enterprises of waterworks have made up monitoring and controlling systems of their distribution networks and are making trials of pressure control.

The pressure control problem has traditionally been reduced to formulating and solving an optimization problem which is to find out proper settings of pumps and/or valves so as to set pressure in the network within a desirable range, prescribed with water levels in reservoirs and consumptions at all demand nodes /1-5/. According to such a method, one optimization is performed for each time period, e.g., one hour or a half one hour, where the consumptions are fixed to predicted maximum values in order to guarantee the minimum pressure, 20m, throughout the period. As a result, pressure is apt to get considerably higher than 20m, and fluctuates in a wide range, for example, 20-40m. In spite of those drawbacks, the effect of pressure regulation has been widely recognized /6/.

In consequence, it is now strongly desired to establish means of advanced real-time control to maintain the pressure more closely to 20m against fluctuations of consumptions. A trial of such a real-time control was started in some supply zones of Matsuyama City located at the north-west part of Shikoku Island, one of the main four islands of Japan. The control system is of a decentralized type: The network is partitioned into several supply zones and a type of single-loop pressure-control subsystem is introduced in each zone; the subsystems work independently of one another. Although the system is working well compared to the conventional ones, accuracy of the control is slightly worse than expected.

This paper is concerned with improvement of accuracy of the control. That is, through analysis of detailed data gathered in some supply zones, simulation studies by use of a reduced model of a supply zone and an analytical investigation to determine the values of parameters of the current control scheme, new schemes for improving the accuracy are proposed.

## PRESSURE CONTROL IN MATSUYAMA CITY

In Matsuyama City, about 380,000 people are getting service of water of about 126,000$m^3$ in total every day (in 1985). In recent years, development of new water resources in the city area is becoming quite difficult, and water service has to be sometimes restricted because of shortage of water. Additional demands in future shall be filled by water conducted from a storage dam at a remote site, but construction of the dam is quite time consuming and expensive as well. Therefore the staffs of Waterworks Bureau of the city have made up a monitoring and controlling system of their network and have been challengingly making many trials of pressure control for efficient use of the existing water resources.

In the following, real-time pressure control adopted in Matsuyama City is introduced.

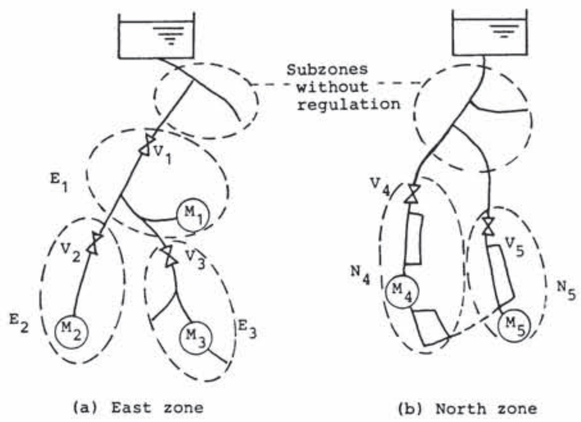



Fig. 1. Partitioning of supply zones.

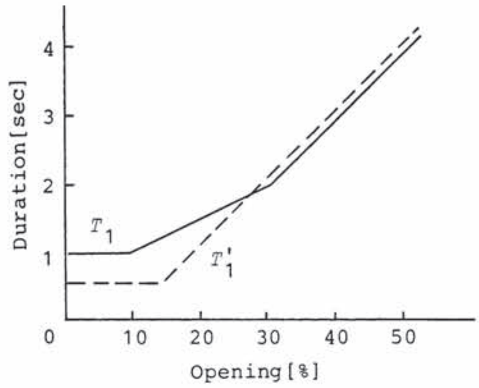



Fig. 3. Duration of a change of the opening.

## Partitioning of the Network

Purified water is once pumped up into reservoirs located at high grounds, and the water is conveyed to users through pipes by the force of gravity. Without regulation by valves, the pressure becomes 40-60m throughout the network.

The overall network is partitioned into 10 supply zones each of which is usually supplied from a reservoir. Although there are many connecting pipes among zones, they are usually closed by valves and then each zone is operated independently of the other zones.

Furthermore, each zone is partitioned into 2-6 subzones so that the ground level within each subzone is almost uniform. Daily consumption in each subzone is 1,000-10,000m³. Figure 1 shows the partitionings in East zone and North zone. A remote-controllable valve (V) is put at the most upperstream point in each subzone, and a telemeter (M) for monitoring pressure at a downstream point. The distance between the points of V and M is in the range of 1,000m to 2,000m.

## Dead-Band Control Scheme

In each subzone, a type of single-loop pressure-control subsystem is formed as is shown in Fig. 2: A standard value of pressure around 20m is set for each monitoring point, and if the pressure deviates by more than 2m from the standard value at the point, the opening of the valve in the same subzone is adjusted to reduce the deviation.

The rate of change of the opening of valves $d\theta/dt$ is 100%/180s, which is a rate free from an outbreak of water-hammer. The duration of a change, $T_1$, is determined as a function of the opening $\theta$. After a change, the opening $\theta$ is fixed for a period, $T_2$. We call $T_1$ the changing time and $T_2$ the halting time. After a change and a halt, if the deviation of pressure is still more than 1.8m, another change and halt is repeated. Such a dead-band scheme is adopted because (1) maintaining the pressure strictly to a standard value is not necessary, and (2) changing the opening of the valve frequently is undesirable.

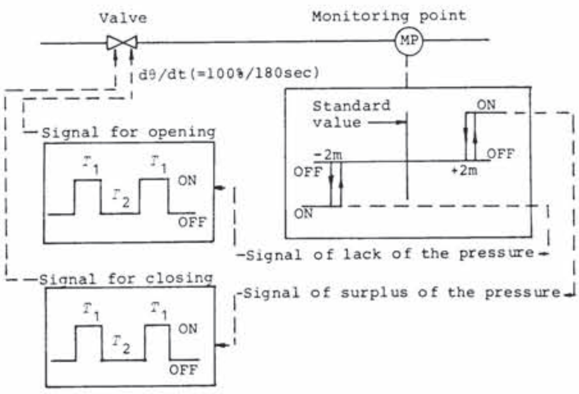



Fig. 2. Single-loop pressure control.

$T_1$ for North-4 subzone is shown in Fig. 3 by a solid line. $T_2$ is 20 sec. after a change for opening, and 30 sec. for closing. These values are determined empirically. In some zones, $T_2$ as well as $T_1$ can be given as a function of $\theta$.

The variable gain scheme of the above has made it possible to control a wide range of water-flow by a single valve, coping with the nonlinearity of the valve characteristic.

## Effect of the Control/7,8/

The control abovementioned was first introduced into East zone and North zone, and the pressure had become to be kept approximately in the range from 20m to 25m throughout these zones. Figure 4 shows the hourly change of the flow rate through the valve of East-2 subzone. The broken curve shows the mean value in a half month without control and the solid curve that with control. The mean of the maximum daily temperatures was 18.7°C in the former period and 22.8°C in the latter period. The difference between the curves is especially wide in

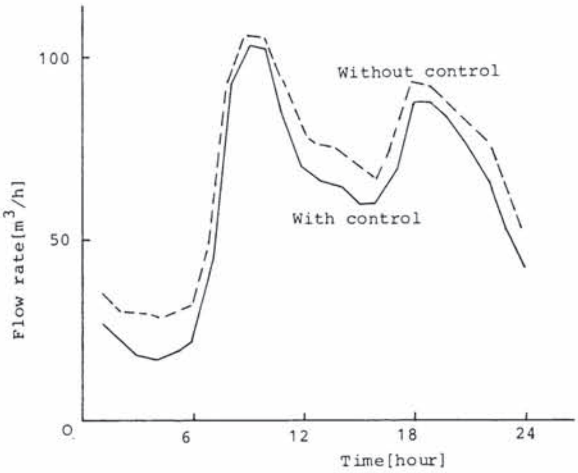



Fig. 4. Hourly change of the flow rate through the valve of East-2 subzone.

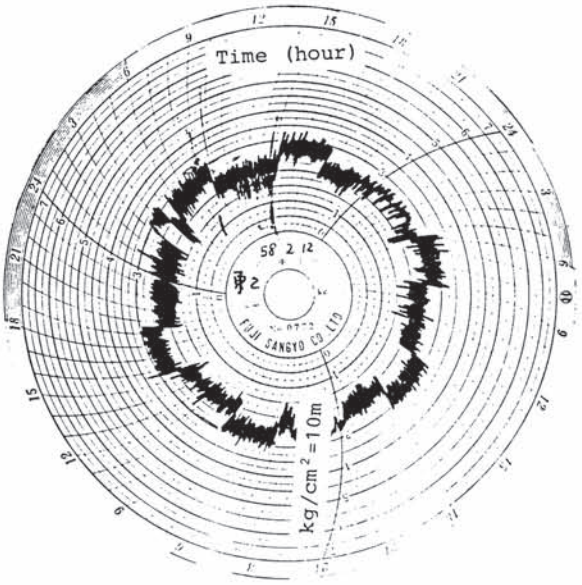



Fig. 5. Chart of change of the pressure in East-2 subzone.

the night time (9 p.m.-6 a.m.) and in the day time (11 a.m.-5 p.m.), i.e., the periods when the pressure becomes high without control. Daily total flow was reduced from 1,647$m^3$ to 1,431$m^3$. Namely, water is economized about 13% by the control. This value is to be evaluated larger considering the temperature difference between the periods.

Problem in the Accuracy

The pressure control has proved to be very effective for ecomization of water use, as mentioned above. However, accuracy of the control is slightly worse than expected: The pressure deviates by a large extent from the desired range and often gets oscillatory. Figure 5 shows a time variation of the pressure observed in East-2 subzone. The radial direction indicastes the pressure and the circular direction the time.

As a question in East zone, it is readily pointed out that the interaction between the subzones connected in series is disregarded in the present scheme. Consider the simple system of Fig. 6. Let shortage of the pressure at $M_1$ be $\Delta h_1$ and that at $M_2$ be $\Delta h_2(>\Delta h_1)$. If the upperstream valve $V_1$ works to cancel $\Delta h_1$, the shortage at $M_2$ becomes $\Delta h_2-\Delta h_1$, which should be cancelled by $V_2$ as its charge. In the present scheme, however, $V_2$ works to cancel the deviation $\Delta h_2$, yielding an excessive feedback.

Although North zone is free from this kind of problem, the behavior of the zone is also not so satisfactory. This suggests us to reexamine the present control scheme and the tuning of control parameters, $T_1$ and $T_2$, as well. Thus, in order to get deep insight of the system characteristics, real data were logged every one minite during two days in East and North zones.

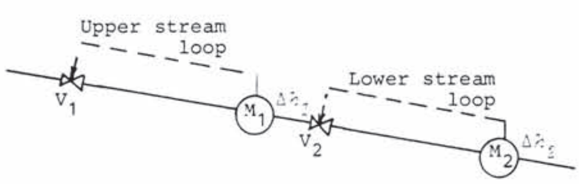



Fig. 6. Two control loops connected in series.

## ANALYSIS OF REAL DATA

In this chapter, important characteristics extracted from real data of North-4 subzone are discussed. At the outset, some fundamental equations are presented as a preliminary. We use the system of international units (SI) throughout the paper.

### Fundamental Equations

Loss of pressure in a pipe Let the relationship between the loss of pressure $h$ and the constant flow rate $q$ in a pipe be described by Darcy-Weisbach's formula:

$$h=flv|v|/(2gd)=8flq|q|/(\pi^2gd^4) \tag{1}$$

where
- $f$ : coefficient of Darcy-Weisbach
- $l$ : length of the pipe
- $v$ : velocity of flow in the pipe
- $d$ : diameter of the pipe

Loss of pressure in a valve The characteristic curve of a valve is given by

$$h=kv|v|/(2g)=kr_vq|q|,\quad r_v\triangleq 8/(\pi^2gd^4) \tag{2}$$

where $k$ is the coefficient of loss determined by the opening of the valve, $\theta$.

### Some Characteristics of North-4

Macroscopic characteristics of North-4 Figure 7 shows the relationship between $q$, the flow rate through the valve, and $h_2$, the loss of pressure between the outlet of the valve and the monitoring point. In the figure, the loss of pressure includes the difference of the height of these points. From the figure, we can see the following macroscopic relationship between $q$ and $h_2$:

$$h_2=r_2q|q|,\quad r_2\text{: constant} \tag{3}$$

A similar relationship holds between $q$ and $h_1$, the loss of pressure between the reservoir and the inlet of the valve:

$$h_1=r_1q|q|,\quad r_1\text{: constant} \tag{4}$$

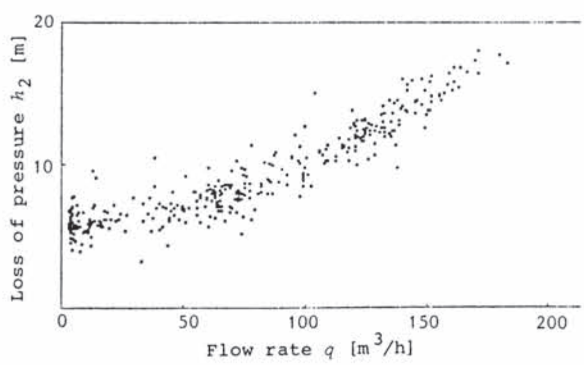



Fig. 7. Relationship between $q$ and $h_2$.

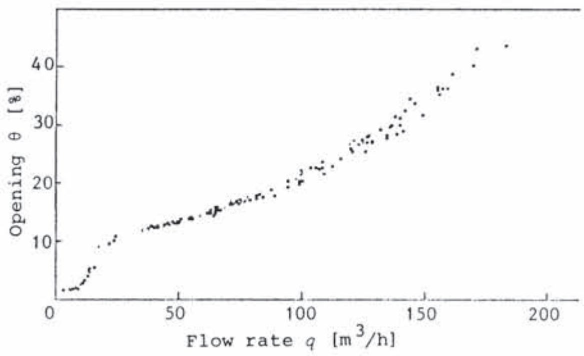



Fig. 8. Relationship between $q$ and $\theta$ when the pressure at the monitoring point is in the adequate range.

The opening of the valve for giving adequate pressure Figure 8 shows the relationship between $q$, the flow rate through the valve, and $\theta$, the opening of the valve, when the pressure at the monitoring point is in the adequate range, 18-22m. A regression curve can be uniquely determined between $q$ and $\theta$. Let us denote this curve by

$$\theta=\phi(q) \tag{5}$$

As $q$ becomes larger, the dispersion of $\theta$ becomes a little larger. This is because the ratio of the change of $k$ to the change of $\theta$ becomes smaller as $q$ and, in consequence, $\theta$ become larger.

Equation (5) is considered to be a normative curve for pressure control: If $\theta$ is adjusted so that Eq. (5) holds, the pressure at the monitoring point will fall in the adequate range. The uniqueness of Eq. (5) enables us to analyse the control scheme by a technique of steady-state flow analysis, because the setting of the valve will be reflected to the pressure at the monitoring point without delay. This is a very favorable finding because dynamics of water distribution networks is described by nonlinear partial differential equations in general /9/.

By the way, the propagation velocity of pressure in the pipe is about 1,000m/s, and the time required for signal transmission etc. from a monitoring point to the associated valve is 1.5-1.8sec.

Change of flow rate In Fig. 9, (a) shows time variation of $p_2$, the pressure at the outlet of the valve, (b) that of the flow rate $q$, and (c) $\Delta q$, the difference of $q$ at the beginning and the end of every one minute, through off-peak hours in the afternoon to peak hours in the evening of a day. In the off-peak hours, since the pressure loss in pipes between the valve and the monitoring points is small, variations of the pressure at these points are almost congruent. The flow rate $q$ is varying incessantly. Since $\Delta q$ has no clear relation with $q$, $|\Delta q/q|$ tends to become large when $q$ gets small. It should be noted that the pressure shows its peaks when $|\Delta q/q|$ is large.

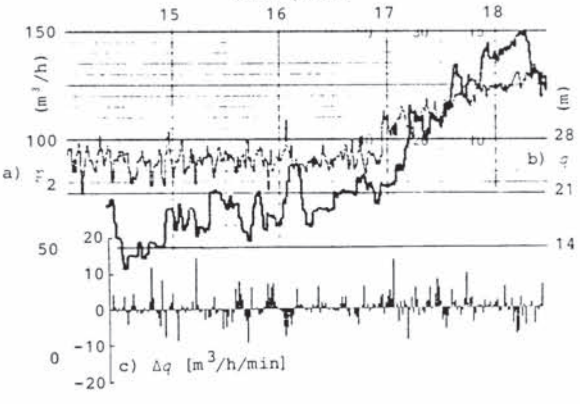



Fig. 9. Time variation of $p_2$, $q$ and $\Delta q$.

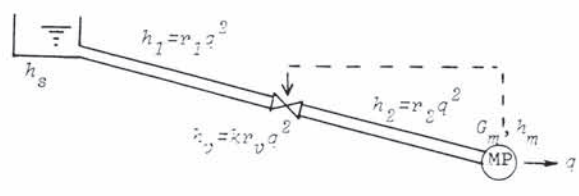



Fig. 10. Simplified model of North-4 subzone.

Similar characteristics to those derived in this section are also obtained from data of the other subzones.

## ANALYTICAL METHOD OF DETERMINING THE CHANGING TIME

As a result of the foregoing discussion, North-4 subzone can be simplified as shown in Fig. 10. The flow rate $q$ is constant everywhere. The pressure is monitored at the most downstream point MP. By use of this model, we try to find the changing time $T_1'$ to cancel the deviation of pressure $\Delta h$.

### Analytical Method of Determining $T_1'$

In the steady-state where the pressure takes the standard value at MP, the balance of pressure is described by

$$\begin{aligned} h_s &= h_1+h_v+h_2+h_m+G_m \\ &=(r_1+kr_v+r_2)q^2+h_m+G_m \end{aligned} \tag{6}$$

where $h_s$ is the water level in the reservoir scaled from the sea level, $h_m$ and $G_m$ are the standard pressure and the ground level at MP, respectively. From Eq. (6), we readily obtain

$$k=f(q)\triangleq(H_0-(r_1+r_2)q^2)/(r_vq^2) \tag{7}$$

where

$$H_0\triangleq h_s-h_m-G_m$$

A small change of $k$ from the state of Eq. (6) causes a small change in the pressure at MP, i.e., $\Delta h$. This relationship is expressed by

$$\Delta h=\Delta k\cdot r_vq^2 \tag{8}$$

By use of Eqs. (5), (7) and (8), we obtain

$$\Delta\theta=\phi'(q)\Delta h/(r_vq^2f'(q)) \tag{9}$$

Further, by use of Eq. (5), the right side of Eq. (9) can be written in $\theta$ instead of $q$. We denote this by

$$\Delta\theta=\eta(\theta)\Delta h \tag{10}$$

The change $\Delta\theta$[%] is obtained by changing the opening for the time period

$$T_1'=1.8\eta(\theta)\Delta h \quad \text{[sec]} \tag{11}$$

$T_1'$ for $\Delta h$=2m is calculated for North-4, and shown in Fig. 3 by the broken line. $T_1'$ agrees with $T_1$ quite well in the range $\theta\gtrsim30\%$, while $T_1'$ is smaller than $T_1$ in the range $\theta$<30%. We investigate this difference in the next section.

Difference between $T_1$ and $T_1'$

In the system of Fig. 10, keep the valve opening constant and find the change of flow rate $\Delta q$ which causes the pressure change of $\Delta h$ at MP. Equilibrium state before the change is denoted by Eq. (6) and that after the change by

$$h_s=(r_1+kr_v+r_2)(q+\Delta q)^2+G_m+(h_m+\Delta h) \qquad (12)$$

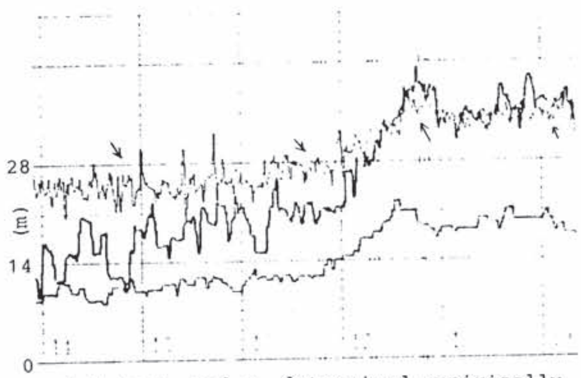
By subtracting Eq. (6) from Eq. (12), we obtain

$$\Delta h=-(2\Delta q/q)\left[(r_1+kr_v+r_2)q^2\right] \qquad (13)$$

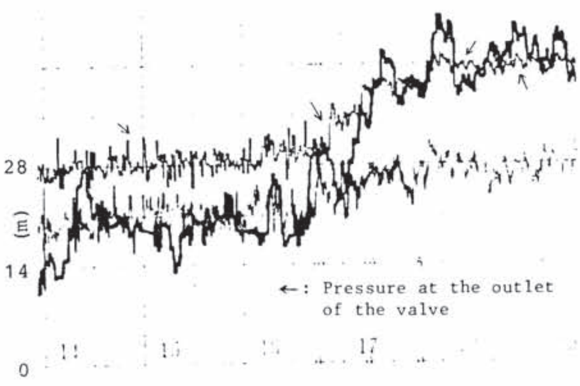
The quantity in [ ] is the pressure loss between the reservoir and MP, and the control works to keep its value constant. Therefore, if the opening of the valve is kept constant, $\Delta h$ will be proportional to $\Delta q/q$. In reality, as shown in Fig. 9, the deviation of the pressure from the standard value becomes large when $|\Delta q/q|$ is large. Thus, the present control can not manage sudden changes of pressure so well.

When $q$ is small, $\Delta h$ is apt to become large and then a large $T_1$ is desirable to cancel the deviation quickly. This is a main cause that $T_1'$ is larger than $T_1$. However, a large $T_1$ causes excessive feedback for a small deviation around $\pm$2m, and then a large $T_2$ is needed to prevent the outbreak of oscillation. As a matter of course, a large $T_2$ spoils responsibility of the system.

Based on the above discussion, in North-4, recently $T_1$ has been replaced by $T_1'$, and at the same time $T_2$ has been reduced to 50% of the former setting. The ratio of $T_1$ to $T_2$ is kept as before for small $\theta$, and is increased for $\theta$ larger than 16%.



(a) By $T_1$ and $T_2$ determined empirically



(b) By $T_1$' and $T_2$ determined analytically

Fig. 11. Time variation of the pressure in North-4 subzone.

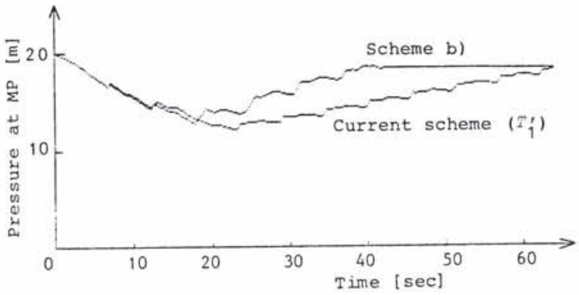


Fig. 12. Example of results of simulation.

Figure 11 compares time variation of the pressure by the new setting of parameters and that by the former one. $\theta$ is around 14% in the off-peak hours and around 27% in the peak hours. Although the feedback gain has been increased as mentioned above, no unacceptable result has been observed.

Halting Time $T_2$

In order to increase the response speed of the system, a shorter $T_2$ is desirable. Therefore, $T_2$ will be shortened with care in the future.

PROPORTIONAL CONTROL AND FLOW-RATE BASED CONTROL

The study of the preceding chapters leads us naturally to the following control schemes which adjust the changing time of the valve opening according to the extent of the pressure deviation from the proper range. Especially, b) is effective even for zones where more than one subzone equipped with valves are connected in series.

a) Calculate $T_1'$ of Eq. (11) by using the current value of the pressure deviation, $\Delta h$.
b) Calculate the optimal opening $\theta^*$ by using Eq. (5) for the current value of $q$, and determine the duration of change $T_1''$ by

$$T_1''=1.8\,|\theta^*-\theta| \quad [\text{sec}] \qquad (14)$$

where $\theta$ is the current opening.
That is, the opening becomes $\theta^*$ in $T_1''$ sec.

Various cases are simulated on the simplified model of North-4 (Fig. 10) by use of the characteristic-curve method /9/, and both a) and b) give satisfactory results as well. Figure 12 shows the result when the consumption of about 50 m$^3$/h is increased by 50% in 20 sec. and $T_2$ is set to 5 sec.

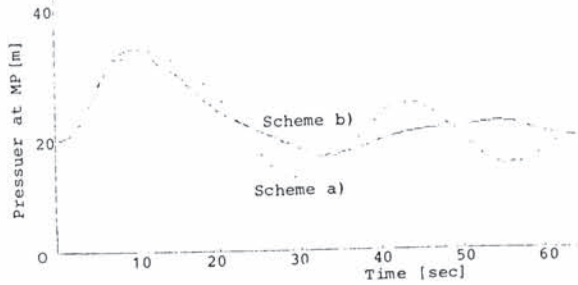


Fig. 13. Example of results of simulation.

Moreover, Schemes a) and b) are mutually compared by use of a model where two control blocks are connected in series like in Fig. 6. Figure 13 shows the result when the consumption of the downstream part is reduced from about $60m^3/h$ to about $30m^3/h$ in 5 sec, keeping the consumption of the upperstream part at about $30m^3/h$ and putting $T_2$ to 2 sec. As the rate of change of the consumption is high and $T_2$ is small, the response is oscillatory by a), while not by b).

## CONCLUSION

A type of single-loop pressure-control scheme introduced in Matsuyama City is under study. The behavior of North-4 subzone has already been improved by determining analytically the values of control parameters. The new schemes proposed in the foregoing chapter will be tested on a zone in near future.

Finally, the authors wish to express their hearty thanks and deep respects to the staffs of the Waterworks Bureau of Matsuyama City, for their nice cooperation and strong interest in advanced technology of pressure control.

## REFERENCES

/1/ Y. Sato: A study on the Uniform Pressure Control in Water Distribution Networks, Jour. JWWA (Japan Waterworks Association), No.446, 7/32, 1971 (in Japanese).
/2/ K. Kazama et. al.: Pressure Control for Minimization of Leakage of Water, Proc. of 33-th Annual Conference of JWWA, 156/158, 1982 (in Japanese).
/3/ Y. Nishikawa, A. Udo and S. Sugihara: Planning of Pressure Control in Water Distribution Networks Including Location of Control Points, Trans. Innstitute of Electrical Engineers of Japan, Vol. 98-C, No. 6, 1978 (in Japanese).
/4/ T. Sekozawa et. al.: Feasibility Analysis of an Overlapping Decentralized Control Method for Water Distribution Networks, Trans. Society of Instrument and Control Engineers, Vol. 21, No. 1, 1985 (in Japanese).
/5/ F. Fallside and P. F. Perry: Hierarchical Optimization of a Water-supply Network, Proc. IEE, Vol. 122, No. 2, 1975.
/6/ N. Nakamura and M. Fujito: A Trend of a Regulation System for Water Distribution by valves, Proc. of 34th Annual Conference of JWWA, 270/272, 1983 (in Japanese).
/7/ Y. Saeki and S. Kurita: On the Pressure Control of Matsuyama City, Proc. of 35th Annual Conference of JWWA, 220/222, 1985 (in Japanese).
/8/ N. Watanabe and T. Kainou: On the Pressure Control of Matsuyama City, Proc. of 36th Annual Conference of JWWA, 402/404, 1986 (in Japanese).
/9/ V. L. Streeter and E. B. Wylie: Hydraulic Transients, McGraw-Hill, 1967.