SIMULATION OF POST-EARTHQUAKE RESTORATION FOR LIFELINE SYSTEMS

Masanori Isumi
Norlaki Nomura
and
Takao Shibuya
Department of Architecture
Faculty of Engineering
Tohoku University
Sendai 980, Japan

To have a national methodology for pre-earthquake planning, a model for predicting the post-earthquake behavior of city lifeline systems was developed. We discussed three factors in the model: structural damage, functional damage, and the restoration process after the earthquake. The restoration process is basically described by a differential equation applicable to a service area represented by a census mesh, and is applied to the lifelines (i.e., supply systems of gas, electric power, and water) of Sendai city in Japan. The model, in addition, indicates the lifeline network properties, and serviceability indices are defined in order to assess the functional damage of each system. In the case of the 1978 Off-Miyagi earthquake, a computer simulation of the restoration process was carried out by using step by step calculations and the Monte Carlo method. The simulated results, using indices as a function of time, were well in agreement with actual results, which indicates that the model is capable of predicting the restoration process. Through further simulations which varied the restoration strategies of the Emergency Headquarters, we show that the recovery of the gas system is sensitively affected by the strategy used. However, the electric power and the water systems were more influenced by the network properties rather than the strategies used. Our approach can provide useful information in undertaking pre-earthquake countermeasures for city lifeline systems.

International Journal of Mass Emergencies and Disasters, 1985
Introduction

A process of taking measures to counter earthquake risks to lifeline systems in urban areas is proposed and the analytical results of a computer simulation are compared with actual damage and recovery of the systems after an earthquake. The analyses are made on gas, electricity and water systems which are frequently severely damaged by earthquakes which is very unfortunate since they are essential to the lives of citizens in the post-impact period. The proposed process may be applicable to other lifeline systems such as those of transportation and telecommunication.

Lifelines and the cessation of their functioning due to earthquakes have recently attracted public attention. At the Off-Miyagi earthquake in 1978 at Sendai city, it took about a month to fully restore the gas supply system. This focused public attention on the necessity of aseismic measures for lifelines.

Outline of Analytical Method

As structural damage to civil and building structures may be called "hard" damage, so the cessation and slowing down of the functions of various systems caused by "hard" damage may be called "soft" damage. Lifelines usually have complex structures that form complicated networks spreading in long lines and over wide planes. Consequently, their "hard" damage, even a slight one, may possibly lead to damage in the "soft" severe enough to stop all functioning. Nevertheless, it is impossible, from the view of finance, to make every part of the structures strong enough to endure the earthquake forces. Naturally, one should accept the possibility of some "hard" damage to lifelines. Therefore, one may consider at least three items as follows:

A. Improving and strengthening the complex structure which consists of the "hard" elements.
B. Minimization and localization of the repercussions of the "hard" damage to the "soft."
C. Design and construction of such a system that would enable us to find out and repair the "hard" damage promptly after earthquakes.

The above statements that indicate the aseismic measures of lifelines require not only that method A be used, but also B and C, and that we should develop methods to make synthetic judgments.
In order to meet these requirements, one should first predict the series of phenomena caused by a predicted earthquake. Computer simulations based on a modeling of the phenomena can be used to arrive at the necessary estimations. Our research group considered the following three models corresponding to A, B and C.

a) A model to estimate the "hard" damage of the lifelines.

b) A model to estimate the "soft" damage caused by the "hard."

c) A model to estimate the recovery process of both the "hard" and the "soft."

When the modeling is properly made, the computer simulation may show us the features of the phenomena. In this paper, in order to attest to the adequacy of the models, a sample calculation is made and the results are compared with the real phenomena experienced in 1978 in Sendai.

a) Model for the Hard Damage

Up to the present, much research concerning the "hard" damage has been done. These studies deal with markedly difficult problems such as estimating the seismicity of a certain area and estimating the behavior of structures and damages to them. However, a few appropriate methodologies to assess the comprehensive "hard" damage seem to be firmly established.

Therefore, in our approach, no particular new model to estimate the "hard" damage is proposed. We utilize the actual damage rates of lifeline systems during the Ofu-Miyagi earthquake, which are regarded as the rates for the results. This will be explained later in the "Damage Distribution Model" for each lifeline system.

b) Model for the Soft Damage

As mentioned above, even slight "hard" damage may greatly affect the "soft," and "hard" damage and "soft" damage are nonproportional. It is not really true that to decrease the "hard" damage is more effective than to decrease the "soft" one. Consequently, it should be noted that at the place where we start our repairing work, it is important to restore the functions as fast as possible.

Therefore a model is required which can properly transform the "hard" damage into the "soft" damage. In the proposed model, the functions of the life line systems are represented by the following indices:

* City gas supply: "Valve open ratio" (percent);
* Electric power supply: "Outage recovery ratio" (percent);
* Water supply: "Water supply ratio" (percent).
By the way, there are very important factors in the predictions of damage to urban lifeline functioning. One of them is the factor of time. Estimation of the "hard" damage may be sufficient if the phenomena just after the earthquake are properly predicted in deterministic or probabilistic ways. But the "soft" damage appears throughout the process from the time of the earthquake until the entire recovery of the function. Urban residents may be patient for a short time during such troubles, but not for too long. Therefore, the time factor is an important one of the model, where the recovery of the functions and citizens' inconvenience are understood as function of time $t$. The functions thus obtained are those of the predicted urban-life function itself.

c) Restoration Model

The restoration work is considered as a kind of social phenomena, which is generally difficult to express quantitatively. In the model, elements are severely selected so that only very effective ones may be considered and quantitatively expressed. The fundamental formula of the model are Equations 1, which are derived from an assumption that the restoration process of a lifeline system is described by the decrease in the structural damage and by the functional recovery following the structural recovery.

\[
D_i(t+\Delta t) = D(t) - \Delta t \cdot r_i(t) \tag{1}
\]

\[
 r_i(t) = E_i(t) \cdot W_i(t) \cdot C_i(t) 
\]

\[
 W_i(t) = W(t) \cdot U_i(t) / \sum U_k(t) 
\]

where $i$ = a number of "division" of a lifeline system,

$D_i(t)$ = Number of damaged points in $i$-th division,

$r_i(t)$ = Repair work rate in $i$-th division (number/hour),

$E_i(t)$ = Efficiency of the repair work in $i$-th division,

$C_i(t)$ = Influence factor of $i$-th division,

$U_i(t)$ = Degree of repair urgency of $i$-th division,

$W_i(t)$ = Number of workers in $i$-th division, and

$W(t)$ = Amount of workers.

The equations are applied to the unit supply area (we call it the "division") of individual lifeline systems and are solved step by step; thus, the recovery process is obtained with the lapse of time.
Allotment of workers to division is made by the decision of the Emergency Headquarters. The decision is made according to the strategy of the reconstruction, and a subroutine is provided for that strategy. The degree of urgency is determined on the basis of priorities of reparation, and it shifts according to the applied strategy. When workers finish reparation work at a division, they are redistributed in proportion to the degree of urgency. The time necessary for workers to move depends on the road conditions and is considered as a phase delay in the computation. The workers consist of two groups; one of those are regularly from the city, and the other, workers who are temporarily gathered from various places. Their number varies with time. The influence factor includes effects of climate, weather and time, and acts on the efficiency of reparation works.

In the computer simulation, models are formed for each system and then interconnected and synthesized for consideration as mutual influences of the system. For the synthesis, it is convenient that each model be considered within a unified space. We adopted the national census mesh called the 4th Local Division Mesh of the Statistic Section made by the Prime Minister's Office. It has the following advantages for modeling.

a) Data, such as population, number of houses, etc., are available for each of the elements in the census mesh.
b) I/O of the computer is clarified with the code number of each mesh in damage, reparation and recovery analyses.
c) Programs are applicable without any change, to other cities where the data are provided according to the mesh unit.

Model of Sendai Lifeline Systems

The method of this model for life line systems was applied to the city of Sendai in Miyagi prefecture, whose lifeline systems experienced great functional damage caused by the Off-Miyagi earthquake in 1978. The lifeline systems modeled were the city gas supply system, the electric power supply system and the water supply system. Since each supply system has individual supply material, supply manner, service area and procedure to repair damage, we took many kinds of system properties into consideration in modelling.

City Gas Supply System

a) Damage in the Off-Miyagi earthquake: The gas system has a plant in the Sendai harbor and stores the gas produced
in accordance with varying demand. The plant was in good condition after the earthquake. Gas is controlled by its pressure equipment and is transported to the service areas within the city through medium pressure pipings (195.9 km) which lay underground and constitute a rough network. Seven pressure regulating instruments and five points of medium pressure pipe were broken by the earthquake. Fine and complex networks consist of low pressure pipings which were distributed close to the dwellings of the customers. Twenty points of damage to the low pressure main pipe (633.2 km) and 199 points of damage to the low pressure branch pipe (591.9 km) were observed after the earthquake. Gas was supplied for each customer through low pressure supply pipings (320.0 km). The number of points damaged to them was 147, and also 2,488 damaged points of domestic pipings and gasmeter occurred.

The majority of damage mentioned above is concentrated on hilly housing area on soft subsoll. Serviceability of city gas was wholly stopped by shutoff valves after the earthquake.

Restoration of the city gas supply took more than one month. The service area was divided into subisolation units by cutting pipes and shutoff valves where there were a number of failures in low pressure pipe. Surveys of leakages of dangerous invisible gas vapor was important in this repairing work. We call the subisolation area as "division." Early work provided 8 divisions which contained from 15,000 to 20,000 customers. Continuous division of the heavily damaged area finally generated 34 subdivisions.

b) Damage Distribution Model: The damage of low pressure pipings and supply pipings was taken into account by the model. This damage was represented only by number, and, ignored the mode of failure, i.e., cracking, slippage, loosening. We call the total number of the damaged points "damage." The recovery of damage within the plant and medium pressure pipings could be described as delay in restoration since their damage was less extensive than that of the other parts of the system. The "damage" for each census mesh was calculated according to Poisson's distribution for a unit of pipe by using "damage rate" and amount of pipe length.

c) Restoration Model: By using a repair work manual printed by Sendai City Bureau of Gas, we could extract two types of working procedures from the repair work described in order to create a model for it. They are "pipe repair work" and "valve open work." The former means physical repairing of some breaks of pipe, and the latter means opening of household gasmeters. In the model simulation, these working procedures provide decrease in "damage" and increase in the number of customers.
to whom gas supply is restored. In the restoration model these are given by:

\[ D_i^G(t + \Delta t) = D_i^G(t) - \Delta t \cdot r_i^G(t) \] (2)

\[ V_i(t + \Delta t) = V_i(t) + \Delta t \cdot o_i(t) \]

where \( D_i^G(t) \) = "Damage" in a "division,"

\( V_i(t) \) = Number of the customers who can use gas,

\( r_i^G(t) \) = Number of breaks repaired per a unit of time by "pipe repair work," and

\( o_i(t) \) = Number of gasmeters opened per a unit of time by "valve open work."

Two working procedures represented by \( r_i^G(t) \) and \( o_i(t) \) are in a series relationship, as shown in Figure 1. The \( r_i^G(t) \) is determined by the number of repair workers, \( W_i^G(t) \), and by the efficiency of repairing work, \( E_i^G(t) \). \( E_i^G(t) \) can explain some kinds of factor which influenced the speed of repairing work, which is given by

\[ E_i^G(t) = EO \cdot T(t) \cdot C1 \cdot C2 \] (3)

in which, \( EO \) is the efficiency of usual repair work, that is, not in emergencies.

\( T(t) \) is a switch function for representing the working time. In an emergency,

\( T(t) = 1; \) from 6:00 a.m. to 6:00 p.m.

\( T(t) = 0; \) from 6:00 p.m. to 6:00 a.m.

Of course in a special emergency it could occur that \( T(t) \) would always be 1, which means all-night work. The coefficients \( C1 \) and \( C2 \) are given by

\[ C1 = \frac{1}{(1 + \exp(-2 \cdot d_i(t) - 1.2))} \]

\[ C2 = \frac{D_i(0)}{200 \cdot C1 \cdot 0.3} / \left( \frac{D_i(0)}{200 \cdot C1 \cdot 0.3} + \frac{P_G}{36} \right) \]

in which \( d_i(t) \) = Damage density in i-th division, and \( P_G \) = Amount of low pressure pipe length.
C1 signifies that a minorly damaged division, which can be repaired easily, needs much time to repair one point of damage. The fact that leakage surveys take much time is reflected by the coefficient C2 which decreases a usual working efficient, EO. The EO is given as 0.03 (damage/man hour) from data of Sendai City Bureau of Gas. The efficiency of "valve open work" can be represented by the equation similar to Equation 3 without coefficients C1 and C2. Because a "valve open work" is carried out by visiting customers door to door, its efficiency is influenced less by other factors than are other repairs.

d) Index of Serviceability: Since the network of transmission pipes is cut into pieces for subisolation it is not necessary to consider the characteristics of the network. The index of restoration of serviceability of the gas system for each division is defined as follows:

\[ IG_i(t) = \frac{V_{\perp}(t)}{CG_i} \times 100(\%) \]  

where \( IG_i(t) \) = "Valve open ratio" in i-th division, and

\( CG_i \) = the number of customers.

Electric Power Supply System

a) Damage in the Off-Miyagi earthquake: The electric power supply system has a multiple network of transmission lines because electricity cannot be stored. It can provide stable serviceability using a supply from plural power stations. A number of customers accept power supply through overhead and subsurface distribution lines which follow a secondary network containing secondary substations and distribution substations.

The Tohoku Electric Power Company has three secondary substations and eighteen distribution substations in Sendai City. Facilities within them were damaged by the earthquake. Especially heavy damage of the Sendai substation, which was a key of the secondary network, stopped serviceability in the network. In the distribution facilities, 1,745 damaged poles, 2,432 overhead transformers, and 911 breaks and contacts of wires were observed. The primary network positioned above the secondary network received no damage and maintained its serviceability.

b) Damage distribution model: The area where the electric power facilities were damaged was localized, although the major transmission network covers a wide region, that is, the Tohoku District consisting of six prefectures. Consequently, the network below the major one was modeled. It consists of the two key
bulk power transformer substations, one transformer station, eighteen distribution substations and many feeders between substations and customers. The damage within the network is regarded as only the number $D^B(t)$ with modes of failure neglected, i.e., falling of poles, breaking or crossing of wires, etc. However, it is considered that it takes more time to repair wire trouble than a fallen pole.

The "damage" $D^B(t)$ for i-th division is calculated as follows. The number of damaged poles is obtained from Poisson's distribution and assumes that there will be an equal number of fallen poles in the division. The number of trouble in wires is calculated using the conditional probability which assumes that those troubles follow the same pattern as the damage to poles. Then $D^B(t)$ is the summation of the two "damages" just discussed.

c) Restoration Model: The model representing repair work is given by Equation 1, similar to that describing the gas system. The usual working efficiency is 0.1 (damage/man hour). The number of customers under power outage, $S_i(t)$, decreases with an increase in the "damage" $D^B(t)$ according to,

$$S_i(t+\Delta t) = S_i(t) - \Delta t \cdot n_i(t)$$

where $n_i(t)$ is the number of customers per point of damage.

d) Index of Serviceability: The index of serviceability of electric power system is defined by "outage recovery ratio" $IE_i(t)$ as:

$$IE_i(t) = \frac{CE_i - S_i(t)}{CE_i} \quad \text{(\%)}$$

The $IE_i(t)$ means the ratio of the customers who can use electricity to the number of customers $CE_i$, in i-th division. When it is calculated, the connectivity among substations (nodes) in network model is considered. If the i-th substation is connected to the two key bulk substations through any pass, the number of customers without power is that of the result of the restoration model. If not, it coincides with the number of customers in the area covered by the i-th substation ("division").

Water Supply System

a) Damage in Off-Miyagi Earthquake: Water is supplied through the facilities for water-intake, filtration, and distribution. The Sendai water supply system, which has two sources from the Hirose River and the Natori River, uses gravity flow for most
of its service areas. The service areas are mainly divided into six divisions based on filtration plants and distribution plants; furthermore, it is possible to divide these further into 26 divisions. The filtration facilities sustained no severe damage from the earthquake except that the operation of standby generators was necessitated because of electric power failure. The majority of breaks were observed in the distribution pipings.

The Sendai City Bureau of Water Supply presented 215 "broken points" and 288 "leak points." The "broken points" were defined as damage which had to be repaired in order to recover all customers' stoppage of water. The "leak points" were defined as points which were found and repaired after recovery of the "broken points" was achieved. This damage caused water stoppage to 7,000 customers.

b) Damage Distribution Model: The model contains two types of damage, the broken points, and the "leak points" in distribution pipings. The number of damaged points similar to those of the gas system is generated in the model according to the Poisson's distribution, ignoring the modes of failure.

c) Restoration Model: Equation 1 is rewritten for water supply system as follows:

\[
D_i^W(t+\Delta t) = D_i^W(t) - \Delta t \cdot R_i^W(t) \tag{7}
\]

\[
L_i(t+\Delta t) = L_i(t) - \Delta t \cdot Z_i(t)
\]

where \(L_i(t)\) = the number of "leak points" in i-th division 
\(Z_i(t)\) = its repair rate.

The "leak points" are recovered only after the regular workers fully repair the "broken points."

d) Index of Serviceability: In order to introduce the characteristics of this network with 26 serviceable nodes (divisions) the water flow analysis of leakage and pressure was applied to the model. The water flow analysis can provide "nodal consumption" which is the amount of water available from a node. The "broken points" and the "leak points" mentioned above are used to calculate a leakage factor, \(l(t)\) in this analysis, i.e.,

\[
l(t) = C_H \cdot D_i^W(t) / D_i^W(O) + C_L \cdot L_i(t) / L_i(O) + C_N \cdot N_w \tag{8}
\]

where \(C_H = 0.01255\),
\[ C_L = 0.00227, \text{ and} \]
\[ C_N = 0.0003853. \]

They are obtained by real data as the amount of supplied water and change of leakage during the post-earthquake period.

The \( N_w \) is the number of nodes excepting the distribution plants. Leaks in the area where water is supplied by a pump system is independent of the water flow analysis.

Index of serviceability for the water system is defined by the "nodal consumption" \( H_i(t) \) as follows:

\[ IW_i(t) = \frac{H_i(t)}{H_i^W} * 100 \text{ (%)} \quad (9) \]

in which \( H_i^W \) = water demand in \( i \)-th node.

We call the \( IW_i(t) \) "water supply ratio."

Whole Model

As the restoration models are described by the difference equation, we can use a flow diagram of a System Dynamics technique to represent the relationships among the many variables in the models, as shown in Figure 1. The flow diagram shows that the total system consists of the three restoration submodels: gas, electric power and water. This whole model enables us through computer simulation to predict a complex restoration process for the three supply systems, although in the case of the Off-Miyagi earthquake such conditions hardly occurred because of the quick restoration of the electric power system.

Prediction and Verification

Analytical Conditions

Input data to the model is the "damage rate" of pipes, wires, poles and so on. In a strict sense, these should be derived from a seismic analysis of the subsystems which considers both the intensity of the expected earthquake and the strength of the subsystems. However, in this analysis, the observed damage rate in the Off-Miyagi earthquake was utilized as input data. They are the damage rate of the low pressure gas pipe, the damage rate of wooden houses and the damage rate of the water distribution pipe.
Figure 1: Outline of the Whole Model and Flow Diagram of Damage Restoration
Restoration is carried out according to the strategy decided on by the Emergency Headquarters. In the model, this situation is represented by the distribution of workers according to the degree of urgency. The strategies in the simulation are the following. For the city gas system, priority of restoration is given to minorly damaged areas (notation G1). No priority is G2, and priority to heavily damaged areas is G3. For electric power and water restoration, priority is given to the center of the city (E1, W1). No priority is E2 and W2 with priority to housing areas being E3 and W3. The strategies for G1, E1, and W1 correspond to the ones that the Emergency Headquarters adopted in the Off-Miyagi earthquake. Simulated results for G1, E1, and W1 will be shown in this section. Some of the results for other strategies will be presented in the next section.

A Monte Carlo simulation which proceeds step by step using 100 samples was done for the given damage rate. A maximum, minimum and mean value for the ailed valuables were calculated as functions of time. The time period of step by step simulation, $\Delta t$, was an hour.

Results

a) Restoration of the Gas Supply System: Figure 2(a) shows the simulated mean value of the "valve open ratio" which is an index defined by Equation 4, in order to evaluate functional restoration of the gas supply. In the diagram the thin solid line means the observed one. The valve open ratio is calculated from the sum of the number of opened valves in all divisions. Therefore, this number can provide an indicator of the total recovery of serviceability in Sendai city. We call the time-valve open ratio relationship the "restoration curve." In the sense of total recovery, the simulated result shown by the thick solid line in the diagram agrees well with the observed one.

b) Restoration of the Electric Power Supply System: The restoration curve of the electric power supply as well as the gas system was predicted by the simulation, as shown by the thick solid line in Figure 2(b). The ordinate is the "Outage Recovery Ratio" for all divisions. The outage recovery ratio in Miyagi Prefecture is also drawn as observed, instead for Sendai city since we have no particular reported data with respect to the actual restoration in Sendai. Consequently, few strict comparisons can be made, but their rough properties are similar to each other.

The meshed map based on the census mesh of Sendai city shown in Figure 3 represents a state of restoration simulated in terms of the "outage recovery ratio," when it reaches about 51 percent at seven hours after the earthquake. The part of
Figure 2: Simulated Restoration Process.
Electric Power Supply System

Total Restoration Ratio (%) = 58.77

TIME (hour) = 7

Figure 3: Distribution of Restoration for Electric Power Supply.
the meshes painted out on the map reflects the strategy of restoration which gives priority to repair in the central area of the city containing most of the customers. Such a map could be useful in studying the influences of other supply subsystems.

c) Restoration of the Water Supply: The restoration curve of the water supply is simulated as shown in Figure 2(c). It shows the "water supply ratio" for all supply areas with respect to the time. The actual restoration curve was calculated from,

\[
\frac{\text{"Customers"} - \text{"Number of Stoppages"}}{\text{"Customers"}}
\]

because we had no data to use Equation 9. The simulated and observed curves are in good harmony. Figure 4 is the amount of water leakage due to Equation 8 in each supply subsystem.

---

**Figure 4:** Leakage in the Whole Water Supply System Based on Water Flow Analysis.
and in the whole system, respectively. The simulated result in Figure 4 shows that our model is capable of estimating the actual behavior of the water system during the post-earthquake period in spite of the simplification of Equation 8 for exactly estimating the leakage factor.

Discussion

Since it was confirmed that the model enables us to estimate restoration processes during the post-earthquake period, further simulation was done varying the restoration strategies for the purpose of obtaining available information for pre-earthquake aseismic planning.

The restoration curves for the gas system simulated according to two other strategies are shown in Figure 2(a). The longer dash line indicates the result of a strategy where the damage to every division is equally repaired, that is, no particular division is given priority. The shorter dash line is when the highest priority is given to the most heavily damaged division. As shown in the figures, both strategies lead inefficient restoration curves. Although those strategies might be acceptable for local customers, the Emergency Headquarters which will attach importance to total recovery, will not think that they are the best way of proceeding.

As the actual restoration shows, when the restoration starts from the less damaged area, there is the problem that the heavily damaged area is left alone. If the number of workers engaged in repairing is limited, the most optimal strategy needs to be established.

One of the damage mitigation strategies for the gas system is the application of an extensive preset valve system, which immediately after an earthquake, could divide the distribution system into several subsisolation areas. Assuming such a system for the Sendai gas system, a simulation was made. The result indicates that the mitigation strategy would be effective on the total recovery process, as shown by the chain line in Figure 2(a).

For the electric power system, the difference between the restoration strategies have few significant effects on simulated results of the restoration curve, as shown in Figure 2(b). Since restoration during the first eight hours is dominated by the key bulk power transformer station, minor effects by the restoration strategies appear after the station is recovered and then the repair of the poles and wires start.

Therefore, it is important for the pre-earthquake aseismic
planning of the electric power system to make appropriate restrictions for the various types of damage which may be caused by an earthquake. The predicted damage to pole and wire might be obtained in a probabilistic way. As to restoration, it is desirable to design and maintain the strength of the facilities within the secondary transformer substation and the distribution substation because their damage dominates restoration of the global system. In addition, pre-earthquake planning for repair materials and workers is necessary.

The simulated restoration curve for the water supply system was not influenced by the restoration strategies as much as the electric power system. One of the major characteristics of water supply is that water service, in emergency, can continue even if there is some leakage due to damage in the system. In fact, in the Off-Miyagi earthquake, all the filtration plants operated fully, and thus, the amount of water distributed increased by about 30 percent over ordinary distribution. When the pre-earthquake aseismic planning is considered for water supply system, these findings could be used to predict damage in the filtration plants, the distribution plants and distribution pipings.

In the Sendai water supply system, from some trial water flow analyses, it became clear that some links have a greater effect than others on the water serviceability in the whole system.

In contrast to the Sendai water supply system which employs gravity flow, a water supply system which mainly depends on a pump system would be fully dominated by the electric power supply in usual circumstances and in emergencies. The chain line in Figure 2(c) demonstrates the influence of electric power outages on the restoration process of the water system in the areas of Sendai using the pump system.

Conclusions

In order to predict functional ("soft") damage to urban lifeline systems caused by a big earthquake and to take appropriate countermeasures, computer simulations based on models for the post-earthquake restoration process in lifeline serviceability were carried out. The model basically includes the recovery process from damage and the network property of each system.

Results show that the model is capable of representing the actual phenomena during the post-earthquake period for the city gas, electric power and water systems of Sendai. Furthermore, some additional simulations with varying analytical
conditions indicate that our approach can be used for pre-earthquake aseismic plannings.

The approach used by this model could be applicable to other areas if the condition of the lifeline systems within them is known and the damage rate of an earthquake is estimated.

References

Proceedings of the 7th World Conference on Earthquake Engineering
1980 Civil Engineering Aspects vol. 8.

Proceedings of the 8th World Conference on Earthquake Engineering

Sendai City Bureau of Gas

Sendai City Bureau of Water Supply

Tohoku Electric Power Company