Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Lifeline interaction and post-earthquake urban system reconstruction

R. H. Zhang
Department of Civil Engineering, State University of New York at Buffalo, N.Y., USA

ABSTRACT: An approach is proposed in this paper to take into consideration the interaction among lifeline systems in studying the strategies for urban system service restoration after destructive earthquake. The restoration of each lifeline system is modelled as a Markov process. The degree of effect that certain lifeline has on the restoration of some other lifeline is a function of its *critical state* and its current expected state. Acomputer simulation is carried out to show the feasibility of the approach. Results from the simulation show significant effect of interaction on the speed and cost of the urban system reconstruction.

1. INTRODUCTION

The restoration of service of urban lifeline systems after destructive earthquake is a very important issue because the normal functioning of these systems is vital to many aspects of people's life who reside in the area. Urban system consists of several important lifeline systems, such as, electric power, telecommunication, water supply line, gas line, highway system, and et al. When considering emergency response policy, the planner should consider the various lifeline systems as a complete system in order to have a comprehensive restoration policy to optimally allocate limited rescue resource.

Most of the studies conducted to date on the restoration of lifeline systems have been concerned with the restoration of some individual lifeline. For example, Noda et al. studied the restoration of water supply system, where the process was treated as Markov Chain(Noda, et. al., 1981). Isoyama, et. al., Iwata and Iwata et. al. discussed the post-earthquake restoration of city gas systems(Isoyama et. al., 1985, Iwata 1985 and Iwata et. al. 1988).

Recently, attention has started shifting to the study of various lifelines together as a system. Some researchers used a systematic approach for the study of urban systems reconstruction, where the urban system is considered as a collection of several lifeline systems (Zhou, 1989, Kozin and Zhou 1990), each competing for the limited rescue resource with the others. Each individual lifeline is treated as a subsystem of the urban system. The evolutionary restoration process of each of these subsystems is modeled as Markov chain. By assigning a common serviceability index, namely, the immediate *economic return* vector, the problem of optimally distributing limited rescue resource among these subsystems was addressed. One important factor which was not addressed in their study, however, was the effect of interactions among various lifeline systems. In fact, interactions do exist among different lifeline systems, e.g., it is not hard to imagine that the malfunction of electric system will affect the water supply and communication system. The problem is how can the interaction be properly introduced. The interaction problem later studied by Eo (Eo, 1990). Based on the systematic approach advanced by Kozin and Zhou, Eo introduced the *total system states* and state transition probability matrix through Kronecker algebra operation. Interactions among subsystems are considered by constructing an adjustment factor matrix for each subsystem. The problem with Eo's method is that it makes an already sophisticated problem even more complex because the size of the problem become hard to manage. Besides, there was no result to show how the interaction introduced will affect the restoration procedure in Eo 1990.

In this paper, a simpler and more straight forward approach is proposed for the interaction consideration. It is conceivable that, if subsystem a has effect on the restoration of another subsystem b, then state transition probability of b will change and, further more, the probability will be a function of the state of a and there will exist a *critical state* of a below which the restoration of b will be slowed down and otherwise restoration of b will be accelerated. By specifying such *critical state* for and knowing expected state of each subsystem, the interaction among various subsystems is introduced. A computer simulation is carried out to show the feasibility of this approach.

2. THEORETICAL DEVELOPMENT

The theoretical derivation will follow the same approach developed in Kozin and Zhou 1990. To facilitate the discussion, the systematic approach used therein is briefly described below followed by the presentation of the proposed approach.

2.1 Systematic approach of urban reconstruction

As mentioned earlier, an urban system consists of several lifeline systems, or subsystems for the purpose of this study. When considering the restoration of service of these subsystems, some important factors need to be considered.

First, the capacity states of each subsystem , $S_n(t_i)$, $i=0,1,2,...,T$, this include the initial damaged state and the evolution of these states during the restoration. Figure 1. shows a typical restoration curve for subsystem n. These subsystem states should be considered as random processes, because, at any stage of the restoration they can not be determined with certainty. Furthermore, since the present state may depend on the state at one step previous in time and is independent of other previous time, they can be represented as a discrete-state, disceṛte-time Markov process(Markov chain).

Second, some probability parameters, they include the state probability vectors, $P_n(t_i)$, where,

$$P_n(t_i) = [p_{n1}(t_i)\, p_{n2}(t_i) \ldots p_{nM}(t_i)] \qquad (1)$$

and,

$$\sum_{j=1}^{M} p_{nj}(t_i) = 1.0, i = 0, 1, 2\ldots \qquad (2)$$

and,

$$T_n(x_{ni}, t_i) = \begin{bmatrix} p_{n11} & p_{n12} & 0 & \ldots & 0 \\ 0 & p_{n22} & p_{n23} & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & p_{nM-1M-1} & p_{nM-1M} \\ 0 & 0 & \ldots & 0 & 1 \end{bmatrix}$$

the transition probability matrix. Its elements, p_{njj} is the probability that subsystem n will stay at state j, and $p_{nj(j+1)}$ is the probability that the subsystem will upgrade from state j to state $j+1$.

$$P_n(t_{i+1}) = P_n(t)\, T_n(x_{ni}, t_i) \qquad (4)$$

In the above two equations, x_{ni} stands for the amount of resource put to subsystem n at restoration stage i.

Third, the immediate economic return vector is assigned to each subsystem,

$$R_n = [r_n(1)\, r_n(2) \ldots r\ (M)] \qquad (5)$$

where, $r_n(i)$, $i=1,2,...M,$, is the immediate economic return of subsystem n at capacity i. These return vectors provide a common index for comparing the efficiencies of different subsystems. Since the exact state that a lifeline system may be in is not known for certain, the expected return,

$$G_n(x_n) = R_n^T P_n(x_n, t_i) \qquad (6)$$

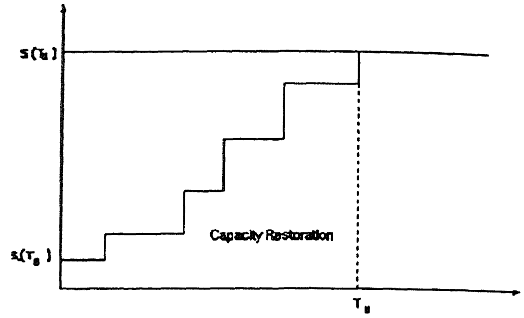

Figure1. State restoration curve

will be used, instead, to evaluate the result of allocating x_{ni}, rescue resource to subsystem n.

After knowing these parameters, a dynamic programming procedure is used to optimally distribute a given amount of rescue resource X_i at restoration stage i so that the total expected return is maximized, i.e.,

$$max \sum_{n=1}^{N} G_n(x_{ni}, t_i) \qquad (7)$$

subject to

$$\sum_{n=1}^{N} x_{ni} = X_i, x_{ni} \geq 0 \qquad (8)$$

2.2 . Consideration of interaction among subsystems

One assumption made in the above discussion is that the various subsystems are independent. This may not be true in practice. In fact, interactions do exist among different subsystems. For example, electricity shut down will affect the water supply system and other lifeline systems. It is conceivable that the abnormal or normal functioning of one subsystem may slow down or accelerate the restoration of some other subsystems. Since the parameter describe the easiness of system state transition is the state transition probability, a feasible approach to introducing interaction is to adjust the transition probability. This can be done by considering the transition probability of a subsystem as function not only of allocated resource but also of the states of the subsystems which affect its restoration, i.e.,

$$T_{ni} = T_n(x_{ni}, t_i, S_k), k = 1, 2, \ldots N \qquad (9)$$

where, S'_ks are the expected states of those subsystems. If the effect is adverse, then the probability of state transition will become smaller, otherwise, the probability will become larger.

It is also believed, regarding the interaction of one subsystem with other subsystems, that a set a *critical state*, corresponding to each of the other systems, can be specified below which the restoration of other

Table 1. Rescue resource at every stage

stage	availabel resource unit
1	11
2	13
3	16
4	15
5	21
6	27
7	36
8	36
9	36
10	36
11	34
12	33
13	30
14	30
15	30
16	27
17	27
18	24
19	23
20	23
21	21
22	20
23	15
24	27
25	27

systems will be delayed and above which restoration will be accelerated.

Following the above discussion, we introduce two sets of factors. The first set forms a so called *interaction factor matrix* E and,

$$E = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{bmatrix} \quad (10)$$

the meaning of its elements,

e_{ij} : the effect subsystem j has on i;

$e_{ij} = 1.0$: means there is no effect from j on i;

$e_{ij} > 1.0$: means subsystem j has effect on i, and e_{ij} is assigned the *critical state value* of subsystem j corresponding to subsystem i.

From the interaction factor matrix and known expected system states, the second set of factors can be defined as the *transition probability adjustmment factor* A_n as

$$A_n = \prod_{j=1}^{N} \alpha_j \quad (11)$$

where, $\alpha_j = 1$ when $e_{nj}=1$ and $\alpha_j = s_j / e_{nj}$ when $e_{nj} > 1$.

The Transition probability $p_{nj(j+1)}$ estimated without considering interaction is now multiplied by the *adjustment factor* and becomes

$$p'_{nj(j+1)} = A_n p_{nj(j+1)} \quad (12)$$

With the transition probability so adjusted, the interaction among various subsystems can now be considered.

3. COMPUTER SIMULATIONS

The procedure discussed in the previous section is implemented into a computer program and several examples have been carried out to show its feasibility. By computer simulation, it is also possible to see the trend of how different level of interaction will affect overall system restoration procedure.

3.1. Numerical examples

The example urban system considered has 4 subsystems and each subsystem is assumed to have 10 capacity states Suppose that the service restoration is done in 25 stages, the available rescue resources at each stage are, listed in Table 1. The immediate economic returns and initial probabilities are as shown in Tables 2 and 3.

The one-step transition probability before adjustment for subsystem interaction is assumed to have the form of (Kozin and Zhou 1990),

$$p_{nj(j+1)} = a_n \{ 1 - exp(-b_n x_n (0.1j)^{1.5}) \} \quad (13)$$

where, a_n and b_n are coefficients of transition rate probability which stand for geographical and structural characteristics of subsystem *n*. Their values are listed in Table 4. It is seen that, when not considering interaction among subsystems, this probability is a function of resource put in, the geographical and structural characteristics, and the current damaged system capacity state.

If the interaction among subsystems is to be considered, the one-step transition probability should be adjusted by the adjustment factors defined in the last section. Three cases are considered as examples to show the effect of interaction.

Case 1. Without interaction

For the purpose of comparison, the first case considered is the one without subsystem interaction. Two quantities examined are the distribution of

Table 2. System economic return

subsys.	system state 1	2	3	4	5	6	7	8	9	10
1	0	10	15	30	38	50	55	65	70	75
2	0	10	10	10	10	15	16	17	19	20
3	0	15	20	20	25	35	35	38	40	45
4	0	7	9	16	18	22	30	35	45	55

Table 3. Initial probability

subsys.	system state 1	2	3	4	5	6	7	8	9	10	
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.9	
2	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
3	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.0	0.0	0.0	
4	0.0	0.0	0.2	0.5	0.3	0.0	0.0	0.0	0.0	0.0	

Table 4. Geographical and structural parameters

parameter	subsystem 1	2	3	4
a_n	0.85	0.75	0.93	0.72
b_n	0.121	0.185	0.095	0.166

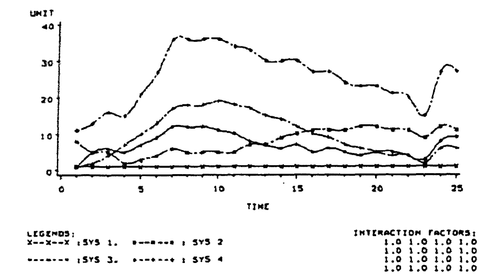

Figure 2. Distribution of resource for Case 1

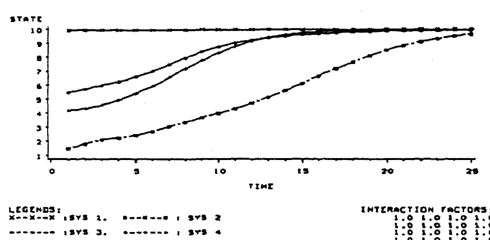

Figure 3. Evolution of expected state for Case 1

resource among subsystems and the subsystem states as function of time. The computed results are shown in Figs. 2 and 3, respectively.

Case 2. Interaction with slowing down effect

All the parameters remain the same as in Case 1 except that interaction is considered. The interaction factors are listed in the following matrix,

$$E = \begin{bmatrix} 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 9.0 & 8.5 \\ 1.0 & 9.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \end{bmatrix}$$

The way these factors are specified means that

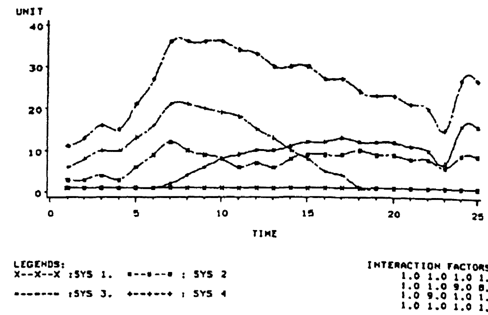

Figure. 4 Distribution of resource for Case 2

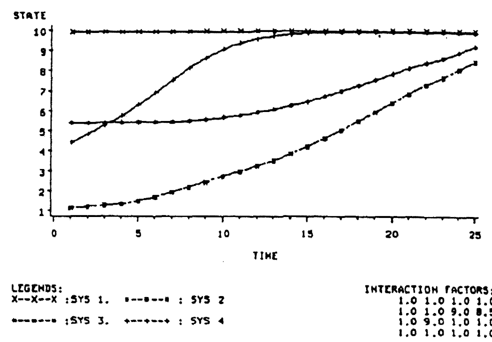

Figure 5. Evolution of expected state for Case 2

subsystem *2* is affected by the states of subsystems *3and 4* and subsystem *3* is affected by the state of subsystem *2*. If the expected state of subsystem *2* is below *9.0*, then the restoration of subsystem *3* will be slowed down or vice versa. The same is true for other subsystems whose restoration may be affected by other subsystems. Results for this case are plotted in Figs. 4 and 5. As can be seen from Fig. 5, the restoration procedure is slowed down due to the interaction because the *criical states* are rather high.

Comparing to the results from Case 1, it can be seen that the restoration processes of subsystems *2 and 3* are slowed down very significantly.

Case 3. Interaction with accelerating effect

In this case, the interaction factor values are taken to be smaller. We have E as the new interaction factor matrix. Results computed are show in Figs. 6 and 7.

$$E = \begin{bmatrix} 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 6.0 & 5.5 \\ 1.0 & 6.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \end{bmatrix}.$$

This case shows that, under certain circumstance, the restoration of some subsystems can be accelerated because of the interaction.

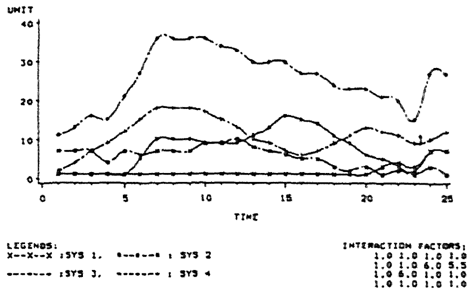

Figure 6. Distribution of resource for Case 3

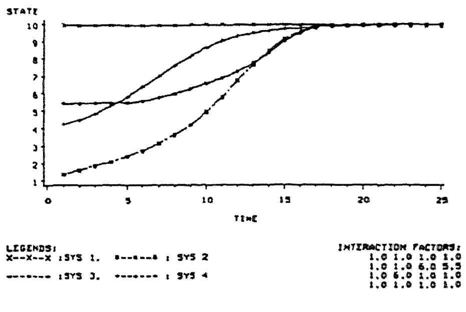

Figure 7. Evolution of expected states for Case 3

3.2 Further study on the effect of interaction

It can be seen, by comparing the three state evolution curves in Figs. 3, 5 and 7, that the interaction among subsystems affect significantly the time needed for the service restoration. On the other hand, in the above computer simulation, the restoration stage number is set before the optimization. Therefore, even when some subsystem has already reached its full capacity, resource is still allocated to it following the set procedure. One improvement which can be made to the procedure is reallocating resource, which otherwise would be put to subsystems already in full capacity states, to the other subsystems. Also, instead of presetting the number of restoration stage, the time needed for restoration of full capacity state for the whole urban system should be determined during the optimization procedure. Such improvements are added to the computer program used in previous simulation. With the improved procedure, it is possible to analyze the effect that different levels of interaction has on the time needed to restore fully the service of the entire urban lifeline system.

Using the same example urban system and its parameters, the effect of different values of interaction factors on the time required for restoration is computed. The results are shown graphically in Fig. 8. In these computations, the resources available at different stage are assumed to be constant. According to Eo (Eo 1990), this is the optimal way of distributing a given total amount of resource to different stage of restoration.

The interaction factor matrix has the following form, with f varying from *1 to 9.0* at a step of *0.5*,

$$E = \begin{bmatrix} 1.0 & 1.0 & 1.0 & 1.0 \\ 1.0 & 1.0 & f & f \\ 1.0 & f & 1.0 & 1.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \end{bmatrix}$$

General conclusion about the effect that different levels of interaction have on the restoration time can only be drawn after elaborated parametric study. Some preliminary observation, however, can be made about the effect from the results of this example. It is seen from Fig. 8 that The time required for full restoration in the worst case, i.e., $f=9.0$ is not very much different from the case where no interaction is considered. However, the overall range of change is relatively large. For example, in the flat curve range, f from *2* to about *6*, time needed for full restoration is significantly less than the case of no interaction.

DISCUSSIONS AND CONCLUDING REMARKS

In the study of urban reconstruction policy after destructive earthquake, the interaction among different lifeline systems is introduced by adjusting the state transition probability. The approach is easier to implement than the previously suggested method and the factors used have clear physical meanings.

From the results of computer simulations, it is seen that interaction among subsystems causes dramatic change in the restoration of system serviceability and the pattern of resource distribution to the subsystems.

When the time required for total capacity restoration of the entire urban lifeline system is concerned, results show that, under minor to moderate damage, time needed for total restoration keeps roughly the same value and is considerably less than the case with independent subsystems. Under major damage, the required time is not dramatically different form the case with independent subsystems.

It should be mentioned that the procedure discussed can be useful only when the various parameters and probability values are in agreement with the real urban system that is to be restored. Extensive studies are yet to be conducted to establish data bases from the available practical lifeline reconstruction experiences and interpret them into parameters that can be used in the systematic procedure.

Furthermore, since the experiences in lifeline restoration are still very limited, they may not be enough for all the parameters needed for the systematic procedure. Therefore, some parameters may have to be assumed from engineering judgement. In these cases some parametric sensitivity study may be helpful in establishing the confidence range of the parameters that are taken from engineering judgements.

ACKNOWLEDGEMENT

It is a great honor for the author to express his deep appreciation to Professor M. Shinozuka for introducing him to this very interesting research topic, for constant encouragement and very constructive discussions.

REFERENCES

Eo, Hajoon (1990). " Computer Oriented System Formulation For Urban System Due to Catastrophic Earthquake," Ph. D. dissertation, Polytechnic University, New York.

Isoyama, R., Iwata, T., and Watanabe, T.(1985). " Optimization of post-earthquake Restoration of City Gas Systems,"Proceeding of the Trilateral Seminar-Workshop on Lifeline Earthquake Engineering, 43-57, Taipei, Taiwan.

Iwata, T.(1985). " Restoration Planning System for Earthquake-Damaged Gas Pipeline Network," Proceeding of the Trilateral Seminar-Workshop on Lifeline Earthquake Engineering, Taipei, Taiwan.

Kozin, F. and Zhou, Huakang(1990). "System Study of Urban Response and Reconstruction Due to Earthquake," J. Engr. Mech., ASCE, Vol. 116, 1959-1972.

Noda, S., Yamada, Y. and Iemura, H.(1981)." Restoration of Serviceability of A Pipeline System,",Lifeline Earthquake Engineering, Proceeding of the 2nd. Specialty Conference of Technical Council on Lifeline Earthquake Engineering, 241-256, Oakland, CA.

Zhou, Huakang(1989). "System Study of Urban Response and Reconstruction Due to Catastrophic Earthquakes," Ph. D. dissertation, Polytechnic University, New York.