

# STUDY EFFECT OF LIFELINE INTERACTION UNDER SEISMIC CONDITIONS

Baohua YAO<sup>1</sup> Lili XIE<sup>2</sup> Enjie HUO<sup>3</sup>

#### SUMMARY

The mechanism of lifeline interaction is analyzed. The method and its corresponding result for categorizing the lifeline system interaction are presented. Various methods for the different kind of interaction are reviewed in this paper. For the function interaction of the lifeline system, an all-round study method is recommended. A WebGIS based aided decision-making method for the post-earthquake restoration of multi-lifeline system is also presented. Meanwhile, some key-points for the lifeline interaction are discussed.

### **INTRODUCTION**

The lifeline interaction is the mutual effect between a lifeline system and other lifeline systems in the same district under seismic conditions. In other words, the reliability of a lifeline system, in addition to system oneself earthquake resistant performance, still depends on the reliability of other lifeline system which have functional connections or physical proximity with the lifeline system. For example, the function of water supply system also relies on the function of power supply system; the bridge collapse in transportation system results in the breakage of the correspondence electric cables fixed on the bridge. Obviously, the lifeline system interaction will directly affect the earthquake damage forecasting, post-earthquake loss estimation of lifeline systems, earthquake resistant reinforcing strategy, earthquake resistant standard, post-earthquake emergency operation deployment of the lifeline engineering system, and secondary disaster controlling strategy and disaster reduction resources allocation.

Since San Fernando earthquake in 1971, earthquake resistant problem of the lifeline engineering system has been paid attention to by researches. Thus, it became one of the research directions in the earthquake disaster reduction in large cities; a lot of achievements have been obtained. However, these researches laid emphasis on individual lifeline system. In middle of 1980', some researchers in Japan and the United States started to study the lifeline system interaction. In 1991, Kansai Chapter of the Japan Society of Civil Engineers established Committee of Lifeline System Interaction Studies and Development of

<sup>&</sup>lt;sup>1</sup> Senior Engineer, Tongji University, Shanghai China. Email: bhyao@sbsn.net

<sup>&</sup>lt;sup>2</sup> Professor, IEM, China Seismological Bureau, Harbin China. Email: llxie@public.hr.hl.cn

<sup>&</sup>lt;sup>3</sup> Professor, Seismological Bureau of Shanghai, Shanghai, China. Email: ejhuo@sbsn.net

Information Management System under Urban Earthquake, to do the further research (Nojima [18], Kameda, 1991).

The national economy construction of China is rapidly developing, but currently destructive earthquakes in urban areas also occur frequently. So it is of significant to study the lifeline engineering system in detail. The interaction among lifeline systems is one of major issues of lifeline engineering system.

#### **1 MECHANISM FOR INTERACTION OF LIFELINE SYSTEMS**

In fact, the interaction of lifeline system can usually be observed under seismic conditions, especially in the destructive earthquakes such as the 1989 M=6.9 Loma Prieta earthquake (U.S. Earthquake Engineering Institute [4], 1991), the 1995 M=7.2 Kobe earthquake (China Japan-Earthquake Investigation Term[8], 1995), the 1976 M=7.8 Tangshan earthquake (LIU[2], 1986) and the 1999 M=7.6 Taiwan Ji-ji earthquake (LEE[13], 1999), etc. These earthquake disasters gave a caution to us that the lifeline system interaction is of as great importance as the individual lifeline system performance.

Various phenomena that result from the interactions among several main lifeline systems are summarized as listed in Table 1 extracted from the table compiled by Kameda [17] and Nojima. The systems in the column influence the systems in the row. It is noted that malfunction of electric power and telecommunications severely reduces the serviceability of every other lifeline function and also hinders recovery efforts. Malfunction of transportation systems makes all lifelines lose the mobile power essential to the restoration process. On the contrary, during recovery work of underground facilities, road traffic systems suffer from a reduction in capacity or complete suspension of service.

### 2 CLASSIFICATION AND COUNTERMEASURE OF LIFELINE SYSTEM INTERACTION

The interaction among all lifeline systems is very complicated. In order to study efficiently, the interaction must be classified according to its features. In this section, referring to damage reports on recent earthquakes and summarizing several existing classifications (Nojima[18], Kameda, 1991; Scawthorn [9], 1993), the lifeline system interaction can be classified into six categories as follows:

Type A, function interaction defined as functional disaster propagation due to failure of interdependence among lifeline systems. For example, malfunction of the electric power reduces the serviceability of the water supply system in the same area. The earthquake countermeasures for the type of interaction include necessary network redundancy and necessary backup facilities, which have better earthquake resistant performance.

Type B, collocation interaction defined as physical disaster propagation among lifeline systems. For example, the collapse of a bridge will result in disruption of telecommunication cables fixed on the bridge; water from the broken water pipe will degrade the transmission performance of the fiber-optics of telecommunication system in the proximity of the water pipe. Common duct is one of earthquake resistant structures for the type of interaction.

Type C, substitute interaction defined as influences on alternative systems. For example, failure of the gas supply system will result in the excessive requirement for the power supply system. The earthquake countermeasures for the type of interaction include necessary network redundancy and efficient emergency operation.

Table 1 Features of interactions among lifeline systems in earthquake disaster									
	Electric power supply	Gas supply	Water supply	Transportation	Communication				
Electric power supply	*	<ul> <li>Malfunction of plants, gas holders, pressure devices;</li> <li>Malfunction of centralized control system;</li> <li>No illumination</li> </ul>	<ul> <li>Malfunction of filtration plants &amp; pumping engines;</li> <li>Malfunction of centralized control system;</li> <li>No illumination</li> </ul>	<ul> <li>Traffic signal disorder;</li> <li>Malfunction of electric car &amp; urban railways;</li> <li>Malfunction of centralized control system;</li> <li>No illumination loss of power</li> </ul>	<ul> <li>Malfunction of tel. offices;</li> <li>Malfunction of centralized control system;</li> <li>No illumination;</li> <li>Malfunction of online service;</li> <li>Loss of data</li> </ul>				
Gas supply	Excessive use as alternatives,eg Hot supply	*	<ul> <li>△ Recovery</li> <li>work</li> <li>complications;</li> <li>△ Scramble for</li> <li>machinery</li> </ul>	<ul> <li>○ No passing owing to repair work</li> </ul>					
Water Supply	<ul> <li>Lack of coolant for independent power plants;</li> <li>Inundation of underground pipes and cables</li> </ul>	<ul> <li>△ Recovery work</li> <li>complications;</li> <li>△ Scramble</li> <li>for machinery;</li> <li>○ Lack of</li> <li>coolant;</li> <li>○ Lack of</li> <li>coolant for</li> <li>independent</li> <li>power plants</li> </ul>	*	<ul> <li>No passing owing to repair work;</li> <li>Lack of coolant for independent power plants;</li> <li>Flooding</li> </ul>	<ul> <li>Lack of coolant for switchboard;</li> <li>Inundation of underground cables;</li> <li>No insulation;</li> <li>Lack of coolant for independent power plants</li> </ul>				
Transpo rtation	<ul> <li>△ Battery cars unavailable;</li> <li>△ Delay in recovery work;</li> <li>○No commuting;</li> <li>○ No transportation of materials and fuel</li> </ul>	<ul> <li>△ Delay in recovery work;</li> <li>○ No commuting;</li> <li>○ No transportation of materials and fuel</li> </ul>	<ul> <li>△ Water</li> <li>wagons</li> <li>unavailable;</li> <li>△ Delay in</li> <li>recovery work;</li> <li>○ No</li> <li>commuting;</li> <li>○ No</li> <li>transportation of</li> <li>materials and</li> <li>fuel</li> </ul>	*	Telephone excessive use				
Commu nication	<ul> <li>○ Malfunction of centralized control system;</li> <li>△ No communication for recovery work</li> </ul>	<ul> <li>○ Malfunction of centralized control system;</li> <li>△ No communication for recovery work</li> </ul>	<ul> <li>○ Malfunction of centralized control system;</li> <li>△ No communication for recovery work</li> </ul>	<ul> <li>○ No passing owing to repair work;</li> <li>○ Malfunction of centralized control system;</li> <li>△ No communication for recovery work</li> </ul>	*				

Note:  $\bigcirc$  stands for functional disaster propagation due to inter-dependence;  $\triangle$  for recovery hindrance;  $\bullet$  for physical disaster propagation; for influences on alternative systems; \* for same system.

Type D, restoration interaction defined as various types of hindrance in restoration stage. For example, there is some interference for system recovery or reconstruction between buried lifelines (water-gas, power-water, sewer-water, etc). One of solutions is to establish an optimum restoration strategy for all lifeline systems.

Type E, cascade interaction defined as increasing impacts on a lifeline due to initial inadequacies. An example is increasing degradation of water service in a conflagration due to service connections breaking as structures collapse as the conflagration grows. That is, as the conflagration increases in size, more and more structures burn and collapse, resulting in more and more broken services, resulting in greater and greater pressure loss in the water service, future impairing water supply and leading to further growth in the conflagration. The cycle then repeats itself. A similar phenomenon can be hypothesized for road transport in a conflagration. The emergency efficiency is the key to the type of interaction.

Type F, general interaction. There are the interaction phenomena between the internal components of a lifeline system such as connected electrical substation equipments (Der Kiureghian [10], et al, 1999). There are also the interaction phenomena between the main lifeline and the "facility" lifelines, the host structure or myriad of bracing and frames, whose main role is to provide structural security for the equipment and connectors of main lifeline (Felix [12], Jeremy, 1995). For example, telecommunication technology has advanced to the point where direct failure of critical equipment is unlikely in modern central offices. Failure is now more likely to be caused by collateral hazards and failure of support lifelines. To reduce the type of interaction, the "facility" lifelines must be paid attention to when the seismic design code is established. Meanwhile, the performance of existing host structure and bracing frames must be also analyzed in detail.

#### **3 RESEARCH METHOD OF THE LIFELINE SYSTEM INTERACTION**

#### **3.1 Research on the function interaction**

The function interaction of lifeline systems under earthquake conditions was studied earlier (Hoshiya [16], et al, 1984; Hoshiya [15], Ohno, 1987). They described the model of lifeline system interaction disasters in a schematic diagram.

Nojima [18] and Kameda (1991) summarized the lifeline interactions in a comprehensive table (Table 1). Based on the earthquake risk probability model of lifeline system networks, system interaction is quantified as a single parameter, in terms of the "Cross impact factor". They consider two lifeline network systems 1 and 2 (Figure 1). If system 1 fails between supply node and node N (event  $E_1$ ) or system 2 fails at node N (event  $E_2$ ), functionality of node N is unsatisfactory (event  $E_N$ ). From probability theory, the probability of the event  $E_N$  can be expressed as:  $P(E_N) =$  $P(E_1)+[1-P(E_1)]*P(E_2)*a_{2N}$ . Cross impact factor  $a_{2N}$  reflects



### Figure1 Function interaction network system

system-specific properties, which include functional dependence of node N upon system 2, the condition of disaster preparedness such as backup equipment, etc. The procedure of Fault Tree Analysis has been employed to calculate the cross impact factor.

Based on Table 1, a simple model of initial and final function states linked by a lifeline interaction matrix is presented by Scawthorn [9], that is,  $D_f = [L] D_i$ , where  $D_f$  is a vector of final functional states considering lifeline interactions,  $D_i$  is a vector of initial lifeline functional states, without consideration of lifeline interactions, [L] is a matrix quantifying lifeline interactions.

Utilizing GIS technology, Shinozuka [19] and Tanaka (1996) carried out the flow analysis and connectivity analysis for the water supply network under the intact and seismic-damaged conditions respectively. In Monte Carlo simulation, the interaction between the water supply system and the electric power supply system is taken into consideration by analyzing the states of pumping stations in the service area of each substation. The interaction results, such as the change states of water head and output flow ratio of each node, are showed on GIS map.

By means of the network module of the software Arc/Info, WEN [5], et al (2000) analyzed the interaction between the electric power supply system and the oil supply system, and the interaction between the electric power supply and the water supply system, etc, in the Daqing earthquake disaster reduction system.

In the analysis methods mentioned above, there is some dissatisfactory for every method. The schematic diagram by Hoshiya and Ohno (1987) is too simple; Nojima and Kameda (1991) emphasize only on the mechanism of system interaction; Scawthorn (1993) represents the concept of the interaction matrix, but he does not answer how the elements of matrix are calculated. WEN, et al (2000) discuss simply the interaction model, and the assumption that the supply nodes of network such as electric power plant always keep intact under earthquake conditions does not accord with actual fact; The method by Shinozuka and Tanaka (1996) does not consider the backup power supply in the pumping station.

By using the advantages of existing methods, a comprehensive method for the function interaction is recommended in the paper. The frame diagram of the method is showed in Figure 2. The water supply system and the electric power supply system are used as a demonstration. Based on the detailed databases, the function states of the water supply system and the electric power supply system are analyzed by utilizing the methods of the flow analysis and connectivity analysis (ZHAO [7], FENG, 1994; GAO [1], 2000). Then according to the cross impact factor analysis method, the interaction results between the two systems are calculated. Similar to Table 1, the interaction between the two lifeline systems can be calculated as:

0.83	_	0.9	0.1	0.9	Water
0.20	=	0.0	1.0	0.2	Electric

Which shows that malfunction of the electric power system directly reduces the serviceability of the water supply system. In this equation, it is indicated as follows (Scawthorn [9], 1993):

1) Without considering the system interaction, the post-earthquake remaining functionality of the water supply system can be 90%, the post-earthquake remaining functionality of the electric power supply system can be 20%.

With the system interaction, because of the effect of the electric power supply malfunction, the postearthquake remaining functionality of the water supply system becomes 83%. But the post-earthquake remaining functionality of the electric power supply system still is 20%, because the water supply system does not affect the electric power supply system in the region.

2) The matrix [L] indicates that 90% of water supply is due to the function of the water system (e.g., gravity flow) and 10% is related to electric power (e.g., power for pumps).

Similar to the method as outlined above, the interaction among multi lifeline systems can be also analyzed. When performing regional analysis, the powerful GIS function can be introduced. The final analysis results can be integrated by utilizing GIS software.



Figure 2 Analysis frame diagram of function interaction

## 3.2 Research on the recovery interaction

Zhang [21] (1992) modeled the restoration of each lifeline system as a Markov process. The degree of effect that a certain lifeline has on the restoration of some other lifeline is thought as a function of its critical state and its current expected state. A computer 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.

SU [3] and LIU (2001) analyzed the effects degree, estimated the scale of lifeline system interaction. They established the post-earthquake recovery time sequence of lifeline systems according to the effects degree sequence.

### 3.3 Research on the other type interaction

Collocation interaction. Based on the GIS technology, Felix [11] (1998) developed a system modeling tools to identify and assess the interaction between the telecommunication system and another system in the proximity of the system. INTECH Co. of the United States has studied the collocation impacts on the vulnerability of lifelines during earthquakes with applications to the Cajon Pass, California. From the

results of this study, it is found that the collocation interaction increases the vulnerability of every lifeline system, the difficulty of the post-earthquake recovery operation, and the post-earthquake recovery time.

General interaction. Der Kiureghian [10], et al (1999) studied the seismic interaction in connected electrical substation equipment. Each equipment item was modeled as a linear system with distributed mass, damping, and stiffness properties, and, through the use of a prescribed displacement shape function, was characterized by a single degree of freedom. The effect of interaction on the connected equipment item is quantified in terms of the response ratio. Felix [12] and Jeremy (1995) thinks that the host structure and myriad of bracing and frames of the communication networks can be viewed as a "facility" lifeline whose main role is to provide structural security for the equipment and connectors. The interaction among lifeline systems that include the facility lifeline was also analyzed.

For cascade interaction and substitute interaction, because their effect mechanisms are very complicated, few results are available.

In brief, there are several stages for the research of lifeline system interaction, for example mechanism analysis, model establishment, and GIS application, etc. With the development of modern information technology, it is a recommendable method to apply GIS technique and analyze in a regional scale when studying lifeline system interaction.

#### **4 LIFELINE INTERACTION AND WEBGIS**

For the restoration interaction, although researchers have got some results, there are some unresolved problems due to the poor technique at that time.

Yasunori [20] and Kimiro (2000) collected the data on actual restoration activities of each lifeline utility after the 1995 Kobe earthquake and analyzed them from the viewpoint of both time and space domains. Based on the real data, they found that there were several problems raised during lifeline restoration activities which can't be solved appropriately by individual lifeline utility with independent measures and integrated approach is very important for decreasing the total negative impact due to a disaster.

By analyzing the actual lifeline restoration process after the 1995 Kobe earthquake, Yasunori [20] and Kimiro (2000) found that the study on the course of lifeline restoration activities is important, a "Total best" of all lifeline restoration activities can be obtained by considering the interactions among lifeline systems. Therefore, the key is how to collect the data about actual restoration activities of each lifeline utility (eg: the position and restoration states of damaged items of each lifeline system). They strongly recommended that it is very important to prepare the mutual collaboration system to share and update the information so as to carry out proper recovery and reconstruction activity with strategy after an earthquake.

When compiling the guiding book on the security evaluation and restoration activities of lifeline system after an earthquake, Hang [14] (2001) realized that if the administration can in time know all data on each lifeline system and the interaction among lifeline systems, they can make the right decision. Therefore, it is suggested that integrated comprehensive disaster reduction information system, an expert information system of lifeline disaster management must be developed to control the change states of lifeline earthquake disaster, and enhance the effect of all disaster reduction.

It is a pity that for the development of these systems, they did not resolve some key problems development tool and development method, for example. With the rapid development of the internet technology,

WebGIS technology become more powerful. It is inevitable that WebGIS is used in the earthquake disaster reduction (YAO [6], et al, 2000). A WebGIS based aid decision-making method for multi lifeline system restoration was presented in the paper.

The water supply system restoration is illustrated in Figure 3. The distributing maps of each lifeline system (including the transportation system, the water supply system, the electric power supply system and the gas supply system) are integrated together in the figure. Each system is distinguished by different symbol in the map. These lifeline systems were impacted under an earthquake. The No.65 water supply pipe, signed with an arrow, must be now repaired. Besides the water supply system itself, other systems in the same region may affect this repairing activity as well: (a) the electric power supply system. The engineering machines used in the water supply system restoration activity may malfunction due to lack of power supply resulted in disruption of nearby substations; (b) The transportation system. The engineering machines used in the water supply system restoration activity can not reach the damaged location due to disruption of the road or bridges. Moreover, there is the cascade interaction between the transportation system and the water supply system; (c) The gas supply system. If the conflagration or explosion occurs due to the disruption of gas supply pipes in the proximity of the repaired water pipe, the recovery activity for the water supply system will be stopped.



Figure 3 Lifeline system post-earthquake recovery map

In order to repair the No. 65 water supply pipe effectively, it is necessary to prepare for the water supply pipe itself. Meanwhile, some information such as the damaged degrees and current states of nearby electric power lines, substations, gas supply line and road, etc, must be also known. For this purpose, using the WebGIS software ArcIMS3.1, we developed a lifeline information management system. The design process of the system is showed in Figure4.

Applying the information system, the integration and the analysis on multi-lifeline system date can be carried out distributedly. The processing steps are as follows:

(1) Using the software ArcIMS, the WebGIS functions are developed on the website of every lifeline utility, the data on the real-time system recovery is all published in the form of digital maps, and the data is updated in time.



Figure 4 The design process of a lifeline information management system

(2) Using a general browser such as Internet Explorer, the repairing division of every lifeline system can access the website of the other lifeline system, and can load the needed maps to perform distributed integration of multi lifeline map on the spot. Figure 5 is used as an example of the integrated map.



Figure 5 Distributing integration with other lifeline systems

(3) Utilizing the integrated map, the query and analysis for the important data that is useful for the repairing activities can be done, for example the query of real-time transportation, buffer analysis (Figure 6), and distance measure, etc. Then, the analyzed results can be used as reference materials for the decision-making of lifeline post-earthquake recovery operations. For example, the states of substation decide whether repairing operation for pipes in the proximity of the substation can be done; the states of road decide whether the road can be selected as the path used by the repairing division.

(4) Using the digital map, the information communication and the information feedback can be realized among users.

Utilizing the above procedure, the information sharing among all lifeline systems can be realized. Therefore, the lifeline interaction can be analyzed; a more proper lifeline recovery time order can also be established. Thus it will beneficial for us to obtain the "Total best" of all lifeline system restoration. Moreover, according to summary of the post-earthquake restoration activities of lifeline system, the following experiences can also be used for reference:



Figure 6 Buffer analysis

(1) Owing to the complexity of factors affecting post-earthquake restoration activities, we should first consider the main influence factors. For example, the higher priority can be provided to the power supply system, because the functionality of power supply system can be more quickly recovered, the restoration of electric power supply will be helpful to recover the other lifeline systems. Figure 7 shows the restoration process of each lifeline system after the 1995 Kobe earthquake (SU[3] and LIU,2001). It can be seen from the figure that the recovery of the electric power supply was started from the first day after the earthquake.



Figure 7 Restoration curves of lifeline systems after the 1995 Kobe earthquake

(2) When selecting the repairing priority of pipelines, both the repairing necessity and the repairing convenience should be considered. The repairing necessity depends on the damaged agree of the lifeline system and the user number served by the pipeline. The repairing convenience depends on the number of damaged point on the pipeline and the interference degree of the other lifeline system.

#### **5** CONCLUSIONS AND SUGGESTION

(1) The complex lifeline system interaction can be classified into six categories. For each type of lifeline interaction, there is the corresponding study method.

(2) With WebGIS, the share, query and analysis of the real time information between multi-lifeline systems can be all carried out. Therefore, the WebGIS technology provides a basic ways to study the restoration interaction and establish the efficient post-earthquake lifeline restoration strategy.

(3) At present there exhibit several trends for the lifeline system interaction as described as following: (a) The actual earthquake disaster experience of lifeline systems attracts more attention, and the lifeline interaction is analyzed in both time and space domains; (b) The GIS technique is widely used. With the systematic management of GIS technology, the interaction among lifeline systems can be easily identified, and various types of analysis methods can be used for the lifeline interaction study; (c) More interests focus on the global optimization method for post-earthquake restoration of all lifeline systems.

(4) There are still some unresolved key points for the analysis on lifeline system interaction. For example, collecting the detailed basic data of all lifeline system in the studied region is difficult; there are not definite fragility models for the components of lifeline systems.

According to the current states of lifeline system research in China, it is suggested that using the American experiences from the study in Memphis city for reference, we should choose a proper city or region as research base, and unite various related organizations (eg: earthquake institutes, universities, emergency management agencies and lifeline utilities) to carry out a multidisciplinary, comprehensive study for multi lifeline system. Otherwise, by simplified analysis, the mechanism of lifeline interaction cannot be found. The earthquake countermeasure and emergency planning drawn in this way are also unsatisfactory.

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