



LIFELINE SYSTEMS INTERACTION AND THEIR SEISMIC PERFORMANCE ASSESSMENT

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SUMMARY

Urbanization is rapidly developing in the whole world; one of the important characteristics in this procedure is that the lifeline systems play a more important role to keep the healthy developing of the economy and society. The correlation of the function and space among different lifeline system are becoming stronger and stronger. According to earthquake survey in recent decades, the correlation and coexistence of lifeline systems are the important factor to result in their big losses. The paper presents the interaction laws among main six lifeline systems and proposes a new method to assess the seismic performance of lifeline system under their interactions. The interaction among lifeline systems is expressed as the comprehensive behavior about the interdependence on functions, the spatial coexistence, and the conditionality in recovering procedure. Three interaction coefficients are defined based on the statistical analysis of lifeline systems earthquake damage, the quantitative analysis of interaction can be done with these coefficients. To estimate the seismic performance of lifeline systems when the interaction is considered, a new method based on Fault Tree Analysis (FTA), Network Analysis (NA), and Geographical Information System (GIS) is proposed. Here, FTA is applied to build these failure models contraposing different elements or unites of all of lifeline systems, NA and GIS is used to simulate the their physical and functional structure, and GIS is also the developing and assembling platform to integrate the FTA and NA. Finally, an illustration, to assess the performance of actual lifeline systems under a scenario earthquake invading, is given to testify the reliability and precision of the new method; the result is compared with that from the present popular method, like the Flow Analysis and Earthquake Damage Matrix, it is proved that the new method is rational and owns a higher precision.

INTRODUCTION

Strong dependence on lifeline system is one of the distinctive characteristics of modern urban area. Lifeline earthquake disaster brings not only property loss, but also functional damage to urban activities and socioeconomic loss. It is well known that the performance of lifeline system during and following a destructive earthquake is the key factor for rescuing and reconstruct or rehabilitation. So, from 1970s, lifeline system disaster mitigation is being the most important aims for society. By now, the study to reduce the earthquake damage of lifeline has had a great progress; some lifeline system has good abilities to resist earthquake invading. But, in recent thirty years, some new earthquake damage characteristics are shown up, Interaction damage is one of them.

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Interaction damage means that the performance failure of a lifeline system is possibly led by malfunction of other lifeline system. Many researchers studied the performance interaction of lifeline systems under earthquake invading earlier. Hoshiya and Ohono (1985) built a system model in seismic performance assessment of electric power and water supply network. Nojima and Kameda (1991) presented a probabilistic method to evaluate the seismic risk of urban lifeline network system with emphasis on the interactive aspects of lifeline earthquake disaster; system interaction is quantified on a probability basis as a single parameter. Zhang (1992) present a *critical state* parameter to describe the interaction during the post-earthquake urban system reconstruction. Bob (1995) studied the water-power lifeline interaction by comparing the function level in three modes of operation: normal, fire and earthquake. With a general survey on kobe earthquake, Hada and Meguro (2000) presented a optimum restoration model considering interaction among lifeline system, and suggested that development of methodology for evaluating the effect of interaction be very important and should be studied. This paper develops a new quantitative analysis method to evaluate the interaction existing six main lifeline systems. The quantitative analysis is very important to identify the reason of lifeline system malfunction and prioritize the important performance parameters of the lifeline systems for a retrofitting purposes and building in future.

EARTHQUAKE DAMAGE CHARACTERISTICS OF LIFELINE SYSTEM INTERACTION

The earthquake damage characteristics of lifeline system interaction can be observed from earthquake events. In Miyagiken-oki earthquake (1978, Japan), the interruption of water supply lasted 20 hours due to the power system function failure. Water treatment plant can't operate without supplement of power. Four cable of telecom hung on the bridges were damaged because of the bridge damage. In Kobe earthquake (1995, Japan), telecom function had been interrupted for 6 hours because power system was damaged. Malfunction of power had led that the traffic information lamps can't function, so, the transport was severely crowded. In San Fernando earthquake (1971, U.S.A), A central telecom building was inundated due to the crack of a main water-transmitting pipeline in Newhall, and the telecom was interrupted. In Sylmar-San Fernando, flood that was led by rupture of main water pipeline interrupted the leakage checking and repairing of Gas system. In the crossroad of state 5th and 210th highway, the elevated bridge was damaged; the damaged bridge obstructed the railroad that passes through under the elevated bridge. During Loma Prieta earthquake (1989, U.S.A), in Santa Cruz, gas explosion due to electricity ignition and recovery work arrangement with power system, water pump stopped without power supply; in San. Francisco, power failure due to gas leak inspection and no water, no power for water supply repair work; telecom can't normally function due to power service diminishes; because the bridge was damaged, no transporting machinery can be provided for rescuing. In Mexico earthquake (1985) the metros that there was no any physical damage itself couldn't function with the support power function failure. During the Izmit earthquake (Turkey, 1999), the interruption of telecom resulted in the traffic jam.

In China, the lifeline interactions are also a common earthquake damage of lifeline serviceability failure. The interaction is summed in table 1.

According to statistical laws of the lifeline system earthquake damage, the forms of interaction among lifeline system can be classified into three types. Firstly, the functions of a lifeline system depend on other lifeline system. For example, a water-supply system can't function when the supply of electric power is interrupted due to a severe earthquake. A telecommunication system can't normally function when the supply of electric power and water supply is malfunction. Secondly, interactions will occur during the procedure of recovering and rescuing. Functional failure of the transportation system significantly impedes post-earthquake emergency response for all of lifeline system including itself; shortage of power will impede repair operation for other lifeline system. Thirdly, radiation or propagation of damage, this means that malfunction of a lifeline system will result in function failure of other lifeline system. Because the construction of some lifeline system is correlative in space, this forms of

interaction is common. For example, the pipeline for transmitting water, oil or gas hung to the bridge will be damage when the bridge is damaged. Always, some different lifeline systems are built in a limited space, when one of them is damaged, the other lifeline will also be damaged. The Northridge earthquake (1994) had witnessed such a case. In This case, there are 9 kinds of lifeline to be constructed in same ditch, the damaged power and damaged gas pipeline encountered and an explosion bursts out, all of the 9 lines, in addition to other 2 line above surface, were damaged.

Table 1. Lifeline interaction in China earthquakes during recent times

Earthquake	Power supply	Gas-supply	Water-supply	Road traffic	Railway	Telecom
Haicheng earthquake (1975)		22cm-diameter gas pipeline was broken by damage bridge	9 hours of water stopped without power		The crack of water pipeline destroyed the roadbed of railroad	Capacity diminished due to no power
Tangshan Earthquake (1976)	Power stopped due to telecom function failure	Leakage of gas interrupted water-traffic	4 days water stopped without power support	Damaged bridge broke oil-pipeline and power pole	Roadbed liquated due to inundation of broken water pipe	poles were damaged by slip of bridge
Baotou Earthquake (1996)		Water inundation made the gas-tank tile	Capacity diminished due to malfunction of power	The landslide of reservoirs damaged traffic in downstream		Capacity diminished due to no power
Taiwan Jiji Earthquake (1999)	Recovery of power was delayed due to telecom failure	The settlement s of roadbed damage gas-pipe	The settlement s of roadbed damage water-pipe	Collapsed bridge damaged gas-pipe and water-pipe, the break of PVC pipe result in road settlement		Function failure due to no power
Jiashi Earthquake (26, Feb. 2003)	Foundation failure induced Water-pipeline broken	pipeline Broken due to liquefaction induced Water-pipeline broken		Foundation failure and pavement fracture induced Water-pipeline broken		Interruption without power supply

PARAMETERS FOR EVALUATING LIFELINE SYSTEM INTERACTION

In order to quantitatively evaluate the lifeline system interaction, some parameters are defined. In the paper, three parameters are presented.

Definition of Single Direction Interaction Factor

The interactions among lifeline system possess characteristics of vector and strength. Some lifeline system can affect other lifeline in a great degree, but no vice versa. The Single Direction Interaction Variable is defined to describe the direction of interaction. The definition is the influencing or limited level that a certain lifeline system (demand system) is affected by function failure of other lifeline systems (supply systems). The equation of definition is expressed as following:

$$e_{AB} = \eta_{AB} \times p_B \quad (1)$$

Where e_{AB} is the Single Direction Interaction Variable that B system (supply systems) acts on the A system (demand system or affected system); η_{AB} means the physical join relationship between A system and B system, named physical join coefficient, the value is evaluated according to the actual relationship including the function and space (table 2) between supply system and demand system; P_B is the failure potential of B system (supply system), its value is calculated by following equation (2~4).

Table2. The value of physical join coefficient η_{AB}

Physical join coefficient	Complete backing	Part backing	No backing	Note
η_{AB}	1.0	0.5	0	Part reliable means the supply system owns backup systems or multi-circuit and can normally function post earthquake

The lifeline system possesses characteristics of network; the basic forms of network include series and parallels.

(1) With respect to series system, the failure probability is estimated by Wang (1998) method. The reliability of system is:

$$\Psi = \Psi_1 \prod_{n=2}^N [(1 - \mu_0) \Psi_n + \mu_0] \quad (2)$$

And system failure potential P_B is $1 - \Psi$. Where $\Psi(\cdot)$ is reliability of system or element $1 \sim N$; μ_0 is the coefficient of conditional relevance, its value is the function of earthquake basic intensity I_0 , which of the value is $7 \sim 10$. N is the number of network elements.

$$\mu_0 = 0.06 \times I_0 + 0.30 \quad (3)$$

(2) With regard to parallel system, the failure probability is

$$P_f = P_{f1} \prod_{n=2}^N [(1 - \mu_0) P_{fn} + \mu_0] \quad (4)$$

Where $P(\cdot)$ is failure probabilities of system or element $1 \sim N$. the meaning of the other parameter is same as equation (2~3), $P_B = P_f$.

Considering the single direction interaction factor, the failure potential W_{aj} of j^{th} node in A system (demand system) due to the failure of the support system B is

$$W_{aj} = (1 + e_{AB}) \times P_{aj} \quad (5)$$

Where P_{aj} is the failure potential of j^{th} node in A without interaction.

Definition of Mutual Direction Interaction Factor

The mutual direction interaction factor is used to evaluate the influencing or limited level of interaction that lifeline systems are affected each other. The formula of definition is

$$h_{AB} = \eta_{AB} \times p_B \times p_A \quad (6)$$

Where h_{AB} is the mutual direction interaction factor, meaning that A system is affected by performance of B system where the function of B system affected by A system has been considered in advance. $P(\cdot)$ denotes failure probabilities of system without interaction. So, the failure potential of j^{th} node in A system is:

$$W_{aj} = (1 + h_{AB}) \times P_{aj} \quad (7)$$

The failure potential of j^{th} node in B system is:

$$W_{bj} = (1 + h_{BA}) \times P_{bj} \quad (8)$$

Where $W(\cdot)$ denotes failure probabilities of node in system with considering mutual direction interaction; $P(\cdot)$ denotes failure probabilities of node in system without interaction. Because the η_{AB} is not certainly equal to η_{BA} , the W_{aj} is not certainly equal to W_{bj} . This is identical with the actuality. For example, there are interactions between the water-supply and power system, the influencing level is different, the water-supply will stop its function once the supported power system loses its serviceability in most of events, but, the power system won't interrupt function when the water-supply malfunctions.

Definition of Interaction Grade Factor

The strength of interaction is alterable as the different types of lifeline system, discrepant distance of construction and earthquake damage status, and so on. The interaction grade factor is used to describe the level of interaction among lifeline system. Because the interaction is complicated, it isn't easy to strictly demarcate the grade.

Referring to idea of earthquake damage grade, earthquake damage index, performance grade and ATC-13, Recurring to the statistical survey result of lifeline systems, the interaction grade factor is defined as following table.

Table3. Lifeline Interaction grade factor

Grade factor (α)	1	2	3	4	5
Description	Very slightly	Slightly	Moderately	Highly	Very highly
Single direction factor(e_{AB})	0~0.1	0.1~0.3	0.3~0.5	0.5~0.7	>0.7
Multi-direction factor (h_{AB})	0~0.1	0.1~0.2	0.2~0.35	0.35~0.5	>0.5

The interaction grade factor (α) is quantitatively determined according to the Single direction factor(e_{AB}) and Multi-direction factor(h_{AB}). The interaction grade factor should be given the greater value only when one of e_{AB} and h_{AB} lies in the limited value.

DESTRUCT MECHANISM OF MAIN LIFELINE SYSTEM

Based on the studies, the destruct mechanisms of main lifeline system can be quantitatively studied. This paper presents several typical models of interactions about the water- power system, telecom –traffic-power, and water-power-gas.

4.1 Model of Interaction for Water-Power

Water supply and power system are mutual direction interaction system. In past earthquakes, the phenomena of “no power, no water” is one of the common events, in the meantime, it is also one of usual earthquake damages That the broken water pipeline results in the freezing function failure in generator and other critical electrical equipment. Even, for hydropower, and heat and power system, the water supply is extremely important. So, the interaction among Water-Power system can be classed into two types: one is the mutual dependent relationship on function; the other is the failure propagation in space. The destruct models of Water-Power considering interaction can be described by use of the following diagram (Figure 1).Where mutual direction function support among water and power system means that the water-supply system provides the services of freezing for critical electrical equipments and water energy for Hydropower plants. Vice versa, the electrical system provides energy of operation for critical equipment. The Space juxtaposition means that the broken water pipelines or damaged water plants, reservoir and other storage equipment will produce a greater failure probability for critical electric apparatus, electrical poles or other critical structures when they are constructed near these elements of water supply system. In the meantime, interactions occur in the procedure of the water supply and electrical system recovery works. The interaction model of recovery can also be described as following diagram (figure 2).

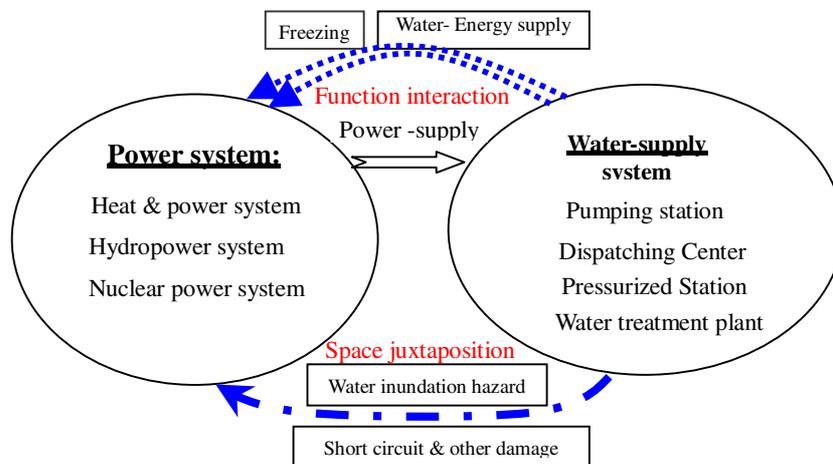
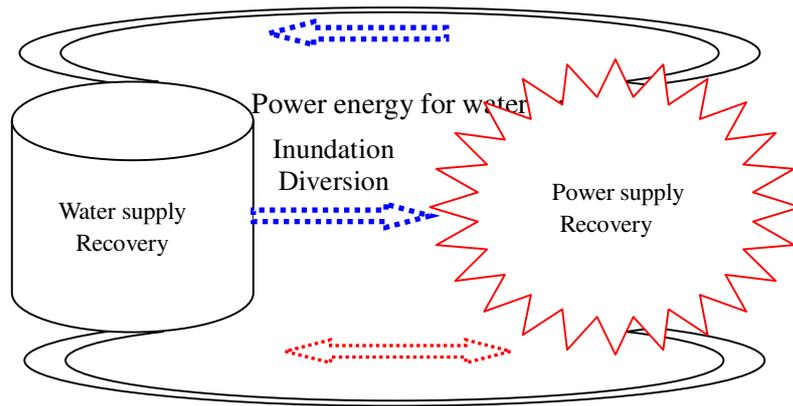


Fig.1. Water system and power system interaction in function and space



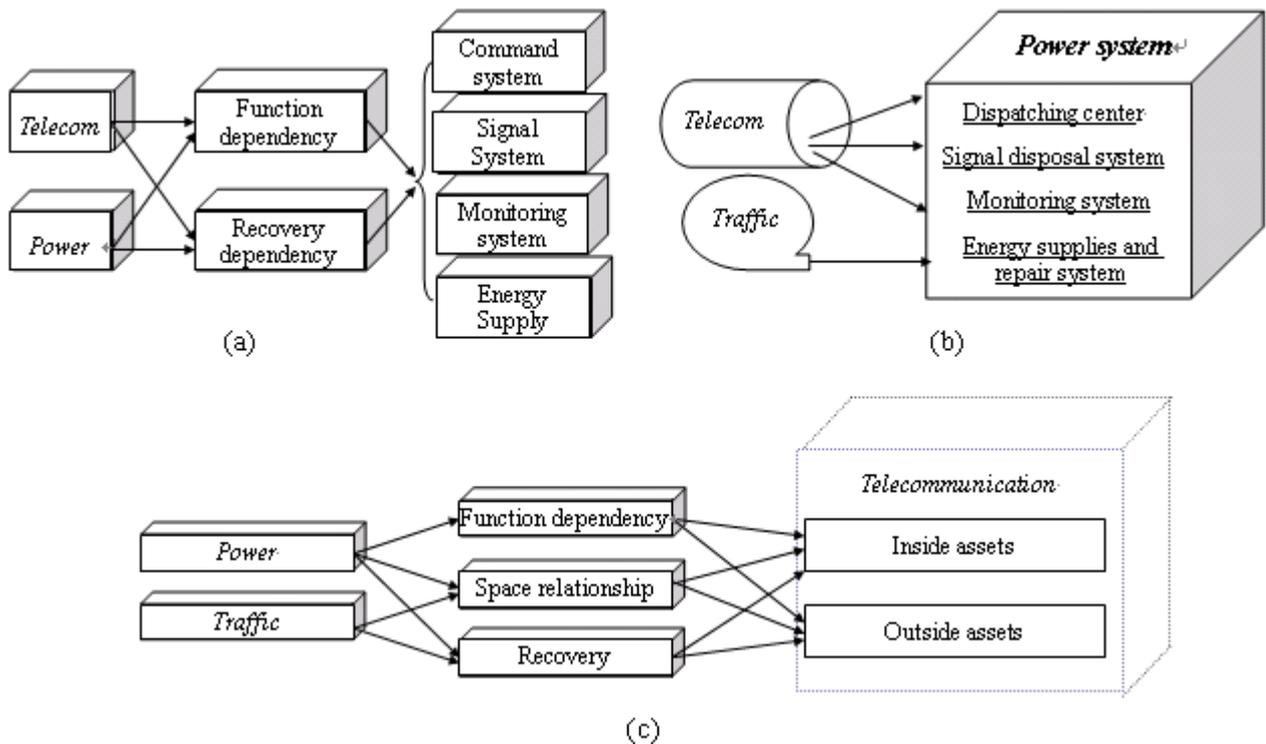
Water-electrical system synchronous check

Fig.2. Water system and power system interaction in recovery

In procedure of water recovery, the repairs need the power for operating the machines, particularly the repair of buried pipeline. To avoiding getting an electric shock, the power recovery is usually asked to do lagging the water recovery and with the same step. In inundation area, the power recovery can't be done because the power equipments or apparatus can be moist or damp, and they are easy to be burnt once the operation begins before drying out. Perhaps, if the inundation is a greater area, the power system recovery will be a more difficult job.

4.2 Model of Interaction for Telecom-Traffic-Power

Felix (1995) has pointed out that telecom technology has advanced to the point where direct failure of critical



(a) Interaction of power and transportation lifelines on telecommunication; (b) Interaction of communication and transportation lifelines on power; (c) Interaction of communication and power lifelines on transportation system.

Fig.3. the trilateral interaction of power-transportation-telecommunication

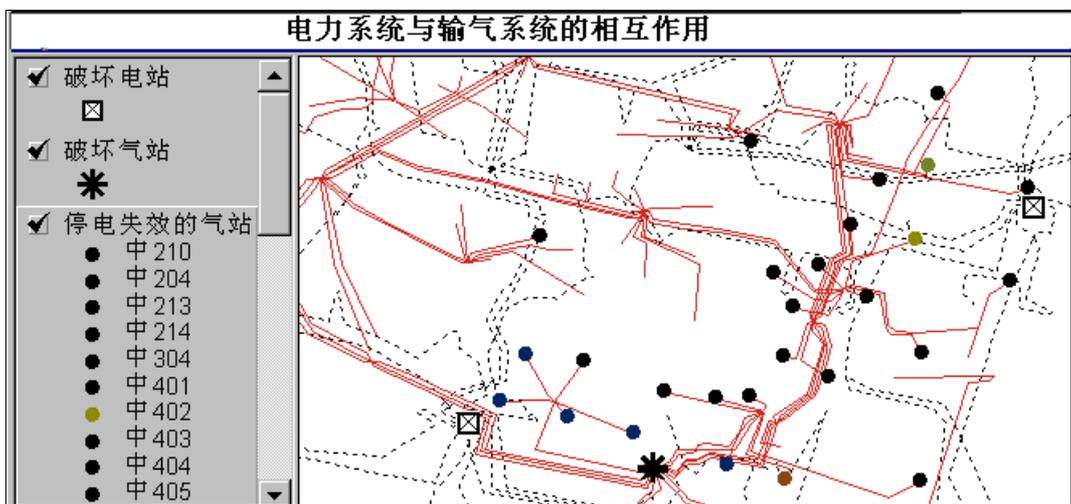
Equipment is unlikely in modern central offices. Failure is more likely to be caused by collateral hazard and failure of support lifelines. According to these results of studies and earthquake damage survey, the trilateral interaction of

telecom-traffic-power is the most important and the most typical. The model of trilateral interactions about them is summarized in figure 2.

The trilateral interaction of telecom-traffic-power contains the all of the three basic interaction types, which are the function, collocation in space- radiation or propagation of damage, and recovery interaction. The function dependent interaction behaves as: The traffic needs the telecom and power system to control the disciplines of traffic operation. The telecom needs the power to supply energy, and the traffic to carry the tools for repair. In interaction of space- radiation or propagation of damage, the earthquake damage of traffic elements, like bridge, retaining wall, will result in the electrical poles inclined or tumbled, and lines broken. The collapsed buildings or structures of telecom and electrical system will block the road or railway. In recovery interaction, when the traffic system is interrupted, the freight of tools and rescuing materials can't be realized. The large machines for rescuing can't work without power. With the failure of telecom system function, the earthquake damage information can't be transmitted.

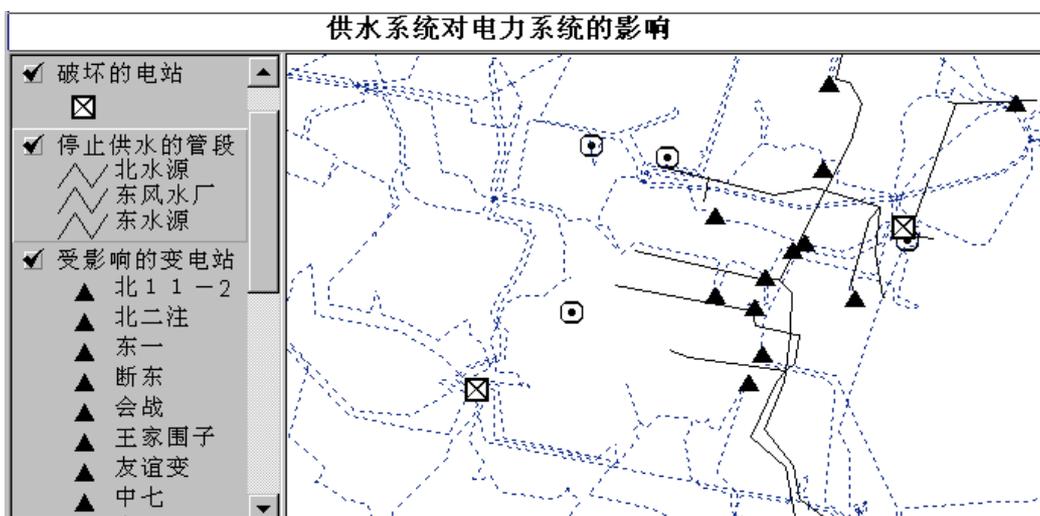
ILLUSTRATION

These above describing theory and method have been applied to assess the earthquake damage of lifeline system in Daqing Petroleum City, which is the largest oil-field in china, with a scenario earthquake. The forecasting result has also been used to improve the anti-seismic ability of lifeline system. Figure 5 is one of the forecasting results. From this figure, the weakness in the large network can obviously be found.



(Dot : Gas-supply station function failure because of the power station damage; \boxtimes :damage power station.
Dashed line: power line, hot real line: gas-supply pipeline)

Fig.4. Interactions between power system and Gas-supply system



(\boxtimes : damaged power station, \square : pumping station function stop without power.
Blue dashed line: power line, black real line: water-supply pipeline)

Fig. 5. Interaction between water delivery and power system

CONCLUSION

In this research, three parameters and several quantitative models are proposed to evaluate the destruct mechanisms due to interactions among lifeline systems based on statistical laws of earthquake damages. With these parameters and models, the quantitative analysis of interaction is possible. Certainly, these above models can't be used to assess all interaction types among lifeline systems because the problems of interactions are complicated. Systematical researches should be done in.

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