SEISMIC PERFORMANCE ASSESSMENT OF WATER-SUPPLY SYSTEM CONSIDERING INTERACTIONS WATER-ELECTRIC SYSTEMS

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ABSTRACT :

Not only in daily living, but also in seismic rescuing, water-supply system is one of the most important lifeline systems; its performance plays an key role on the post-earthquake rescuing, reconstructing and rehabilitating of daily production and living. The paper presents one methods to calculate the earthquake damage of the water-supply system considering the interactions between water-electric systems during earthquake. To assess the interaction between water supply and electric system, the graph theory (GT), network analysis (NA) is applied. Based on the GT and NA, both of water supply and electric systems are consisted of nodes and links, and the nodes are farther divided into two types: simply and complicated. The simply nodes mean that their seismic performance will not be affected by the performance of electric system, but the complicated nodes will be done. The interactions between water supply and electric systems are considered in complicated nodes through the definition of several parameters based on the statistic analysis. The links are applied to describe the pipeline element and electric transmitting elements, and their performance levels are estimated considering the effect of the fault movement, ground displacement, and peak ground acceleration. Based on the reliability of nodes and links, the water-supply systemic reliability is calculated by use of GT and NA. Lastly, compared with seismic performance of water supply in one actual earthquake in China, one illustration is given to test the reliability of the proposed method in this paper.

KEYWORDS: Seismic performance assessment, water-supply system, Power system, Interaction

1. INTRODUCTION

The interactions among lifeline systems mean the function of one lifeline system will depend on functions from others lifeline systems, or its performance will be affected when other lifeline systems are damaged. This kind of earthquake damage phenomena is usually found in almost all of damage earthquake. Among them, the interactions between water supply and electric power system are particularly important, because they play an important role in the emergency rescuing and restoration of living and production and it has been proved that the interaction of water-supply and electric power lifeline is easily observed. Hoshiya and Ohono (1985) proposed a system dynamic model to assess seismic performance of electric power and water supply network. Bob (1995) studied the interaction of the water-power lifeline system in San Francisco Bay Area when they were in normal, fire and earthquake. Shinozuki and Tanaka (1995) proposed a quantitative analysis method to study interaction of water supply and electric power transmission systems in Memphis, Tennessee and the results will be used to identify and prioritize important performance parameters of the lifeline system for the retrofitting purposes. Hada and Meguro (2001) had put forward an optimum restoration model considering intersection among lifeline system. Tang and Wu (2004) studied the interaction of water-power system in Daqing City using Geographic Information System (GIS) and Network Analysis. Based on works by these and other specialists, this paper proposes a new method using the Graph Theory (GT) and Network Analysis (NT) method to evaluate reliability of the water supply system post-seismic performance considering interactions between water supply and electric power system; the interaction of water supply and electric power system in Daqing City under a scenario earthquake is regarded as one illustration for testing reliability of the proposed method.

2. MODEL OF WATER SUPPLY AND ELECTRIC POWER SYSTEM IN DAQING CITY

Daqing City is the important center of oil production and the biggest taxpayer in China. Because Daqing City is at risk from earthquake originating in the highest earthquake intensity zone in Heilongjiang, where produced the largest earthquakes (Ms=6.0, in 1940) in the recorded history of the Heilongjiang Seismic Zone. According the seismic forecasting result, an earthquake larger than 6.8 will take place in Daqing during the next 50 years. So, a series of programs has been set up to reduce the earthquake risk in Daqing, particularly the lifeline systems seismic risk mitigation. The water supply system is managed by Water Supply Company of Daqing (WSCD, Fig. 1), and is responsible for 7 districts with a population of over 200,000.The Electric Power Company of Daqing (EPCD, Fig.2) manages the electric power system, which provide for the 7 districts in Urban area of Daqing and is also the electric power transmitting center of its affiliated 5 counties.
According to the survey, in study area, the interaction model of water-supply system and electric power system has been setup (Fig.3). And details of seismic and geological environments have also been built up. In order to simplify the analyzing procedure and find out the most vulnerable and key elements, the water supply network system is abstracted as following figure (Fig.4).

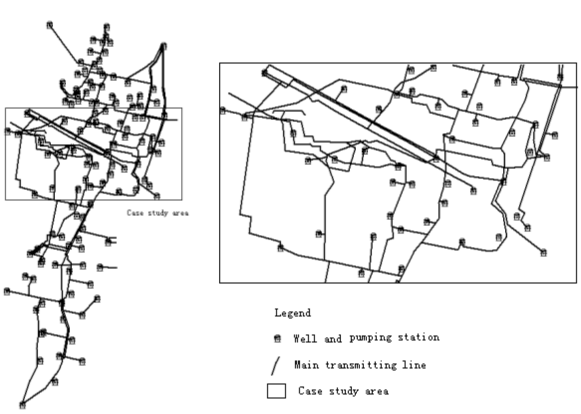

Figure 1 Water supply system in WSCD

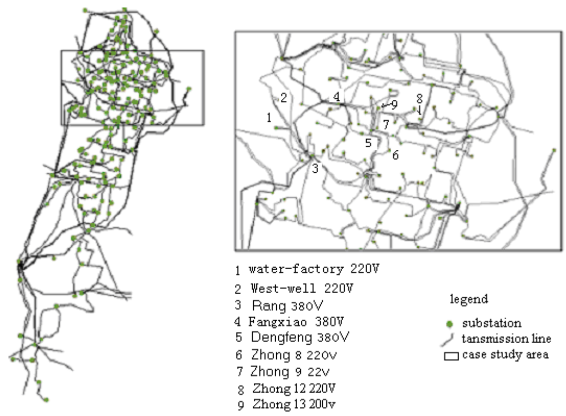

Figure 2 Electric power systems in EPCD

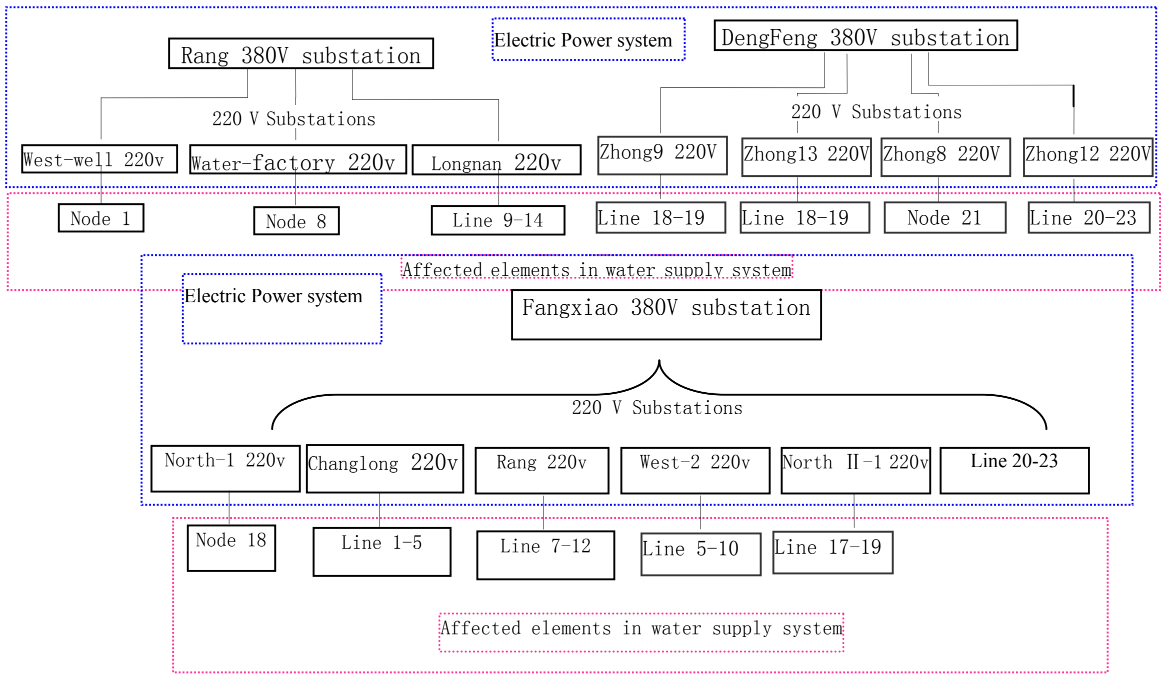

Figure 3 Physical structural model of water supply and electric power system interaction

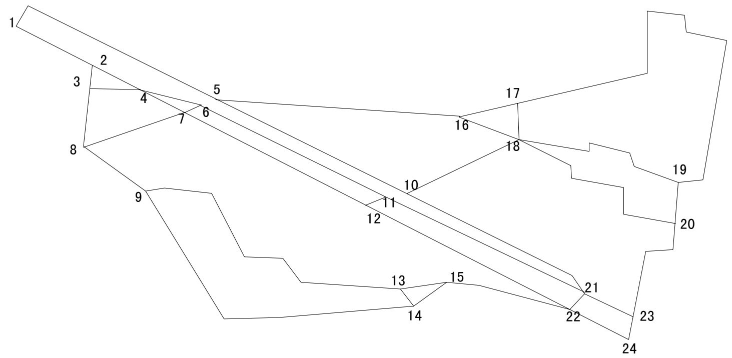

Figure 4 Simplified network of water supply system in study area

Where Node 1 and Node 8 are wellheads and the other nodes are water-fetch points and pumping stations. The Node 24 is the farthest water-fetch point. The paper will discuss how to calculate the network reliability of the water-supply system when Node 1 is only input node (single source point). When Node 1 and 8 are synchronously regarded as input nodes (multi-source point), the network reliability has also been calculated, but its analyzing procedure is not presented in this paper due to the limitation of paper length.

3. EARTHQUAKE DAMAGE FORECAST BASED ON GRAPH THEORY & NETWORK ANALYSIS

Graph Theory (GT) and Network Analysis (NA) are one of the important tools to simulate the seismic performance states of lifeline systems at present. In GT and NA, all elements in system are regarded as nodes and links. One Graph consists of nodes and these links that link the nodes, it is an aggregation of nodes and links. In generally, one graph named G is defined as an ordered binary group, G=(V, E), herein, V is a limited non-empty aggregation, these elements in V is named as node or vertex of G. V is expressed as following: V={v1,v2 ,…,vn}. E is the aggregation of non-ordered couple (vi, vj), and its elements are called as link of G and expressed as e={ vi, vj }. In certain graph GA=(V, E), potentially, vi0, vi1,… vik $\in$V, ej0, ej1,… ejk $\in$E, if

$$e_{jt} = (v_{it-1}, v_{it}) \qquad t= 1,2, \ldots k \tag{3.1}$$

Then, μ={ v_{i0}, e_{j1}, v_{i1} , e_{j2},…, e_{jk}, v_{jk} } is defined as one link from v_{i0} to v_{jk}. If there is less than one link among arbitrary v_i, v_j, then G_A is defined as a connectivity graph. Generally speaking, G and its real function ω (v_i, v_j) that is defined for link aggregation compose one network. ω (v_i, v_j) is the weigh function of links. If the total number of nodes in G_A is n, then the following equations(Eq.2) completely expresses all possible connectivity among nodes:

$$M= E+A+A^2+ A^3+\ldots+ A^{n-1} \tag{3.2}$$

Herein, E is n x n rank unit matrix in which all of diagonal elements are 1 and the others are 0. A is n x n rank adjacency matrix and is expressed as A=$[a_{ij}]_{n \times n}$., if there is one link to connect the node i and j, then a_{ij} =1, otherwise a_{ij}=0. If M $\neq$ 0, then G_A is a connectivity graph. Table 1 describes the adjacency matrix in Figure 4. To quantitatively consider the interaction between water supply and electric power system, three parameters are included herein, which are Single Direction Interaction Factor, Mutual Direction Interaction Factor, and Grade Factor. Tang (Tang, 2004) has developed the definition of the above three parameters. According to geological and geographical conditions where this water supply system and electric power system exist, some special earthquake damages will occur induced by interaction existing in water supply system and electric power system. For example, according to result from the earthquake disaster mitigation programs in Daqing City, electric power ignited fire is easy to take place and will have a big risk on water supply system; because of existing a large area of looses fine sands layers, the water pipeline damage will induce liquefaction, lateral ground displacement, and the other permanent ground displacement (PGD), which will damage the electric power and it will in reverse act on this water supply system.

Table 3.1 Adjacency matrix in Figure 1 when Node 1 is the wellhead

i \ j			i \ j			
1	2	5	13	14	15	
2	3	4	14	15		
3	4	8	15	22		
4	6	7	16	17	18	
5	10	16	17	19		
6	7	11	18	17	19	20
7	8	12	19	20		
8	9		20	23		
9	13	14	21	22	23	
10	18	21	22	24		
11	12	21	23	24		
12	22					

4. CALCULATING RELIABILITY OF WATER SUPPLY SYSTEM UNDER INTERACTION IN SCENARIO EARTHQUAKE (MS=6.8)

4.1 Failures of Elements in Water-Supply System Due to Power Off

According to the earthquake hazard analysis in Daqing, a scenario earthquake (Ms=6.8) is designed. The intensity in epicenter is Ⅷ near the study area. Based on the seismic risk analysis, some water pipelines and pumping stations will be affected because of power cut. These affected pipelines and pumping stations are summarized into Table 2 and 3(Tab.2, Tab.3).

Table 4.1 Affected water pipelines due to power cut

Pipeline	Site patterns	220V substation	380V substation
1—5	III	Chang-long	Fangxiao
5—10	III	West-2	
5—16	III		
7—12	III	Rang	
9—13	III	Sha-zhong	Bengteng
17—19	III	NorthII-1	Fangxiao
18—19	III	Zhong-13,zhong-9	Dengfeng
20—23	III	Zhong-1	

Table 4.2 Affected Nodes (pumping station) in water-supply system due to power cut

Node	Site patterns	220V substation	380V substation
1	III	West-well	Rang substation
8	III	Water-factory	
18	III	North-1	Fangxiao
21	III	Zhong 8	Dengfeng

4.2 Reliability of Elements in Water-Supply System

The next steps will calculate reliability of the nodes and pipelines in earthquake. Herein, 24 nodes are classified into two types: complicated nodes and simply nodes. These complicated nodes mean that the interactions between water supply system and electric power system have affected themselves performance, but performance of these simply nodes can only been affected by themselves earthquake damage. In this study area, Node 1,8,18, and 21 are complicated nodes. The reliability of complicated nodes will include not only themselves physical damage, but also the effect from element's performance failure of electric power system. Based on the GT and NA, there are 35 connectivity roads from Node 1 to Node 24(Table 4). Some pipelines can't transmit water due to earthquake damage of electric power system.

Table 4 possible connectivity roads from Node 1 to Node 24

Road	Node												
1	1	2	3	4	6	11	21	23	24				
2	1	2	3	4	6	11	21	22	24				
3	1	2	3	4	6	11	12	22	24				
4	1	2	3	4	6	7	8	9	13	15	22	24	
5	1	2	3	4	6	7	8	9	13	14	15	22	24
6	1	2	3	4	6	7	8	9	14	15	22	24	
7	1	2	3	4	6	7	12	22	24				
8	1	2	3	4	7	12	22	24					
9	1	2	3	4	7	8	9	14	15	22	24		
10	1	2	3	4	7	8	9	13	15	22	24		
11	1	2	3	4	7	8	9	13	14	15	22	24	
12	1	2	3	8	9	14	15	22	24				
13	1	2	3	8	9	13	15	22	24				
14	1	2	3	8	9	13	14	15	22	24			
15	1	2	4	7	12	22	24						
16	1	2	4	6	7	8	9	14	15	22	24		

Node 1 (well, the start point of water supply) is a typical complicated node; its reliability is calculated by following steps.

1) Itself failure probability- $P(E_1)$

$P(E_1)$ is defined as the failure probability, which is induced by pumping equipments damage under earthquake. In general, $P(E_1)$ is 0.2 in the Ⅷ under earthquake directly invading according to the law of earthquake survey in China. Because Node 1 is in the liquefaction area, it will have a 1.5 times higher damage possibility than that in non-liquefaction area. So, the value of the $P(E_1)$ is 0.3 herein.

2) Failure probability- $P(E_N)$ considering water-electric systems interaction

At the same time, due to interaction between water-supply and electric power system, Node 1 will be affected by earthquake damage of the west-well 200 V substation, the failure probability of Node 1 depends also on the failure probability is of the west-well 200 V substation, the factual failure probability should be calculated by following equations (Eq.4.1):

$$P(E_N) = P(E_1) + [1 - P(E_1)] \times P(B) \tag{4.1}$$

Where, $P(E_N)$: the factual failure probability of Node 1. $P(E_1)$: the adjusted failure probability of Node 1 considering liquefaction effect in site soil. $P(B)$: affected factor of west-well 200V substation to N ode 1，it can be got by following equations based on network analysis(Eq.4.2):

$$P(B) = C_1 \times C_2 \times C_3 \times C_5 + C_1 \times C_2 \times (1 - C_3) \times C_4 \tag{4.2}$$

Where,

C_1: Dependency coefficient between water supply and electric power system. If there is dependency in two systems, C_1=1.0, otherwise, C_1=0. here, C_1=1.0.

C_2: failure probability of electric power system, which is got by seismic structural computation. here,2=0.445.

C_3: if there is backup electric power system in water supply system, if no, C_3＝1.0, if yes, C_3=0.1. Herein, C_3=0.1.

C_4: performance function of the backup electric power system, which related to earthquake intensity, its value changes from 1.0 (completely damaged) to 0.1. Herein, C_4=0.128.

C_5: earthquake damage rank of electric power system, it is also the function of earthquake intensity and resuming time, its value changes from 1.0（heavily damaged）~0(no damaged). here, C_5＝0.9.

From equations (3) and (4), $P(E_N)=0.3+[1-0.3]*0.09=0.363$.

Performance failure or degrading of water pipeline is due to itself physical damages-body broken, split and joint damage, which can be induced by fault motion, PGD and liquefaction etc. reliability of water pipeline elements is got according to the Seismic Code of water supply system of China.

5. SEISMIC RELIABILITY OF WATER-SUPPLY SYSTEM CONSIDERING WATER-ELECTRIC SYSTEMS INTERACTION

According to the GT, the first step is to build the adjacency matrix, which is done by Breadth First Search methods - BFS. In BFS, a top node is appointed at first, and then a path will be searched from this node to other new nodes, this search will be stopped once no any new node is found in this path, and a new search path will be re-started until all possible paths are searched. Its basic procedure is simply described as following: 1) Assuming the top node N0; 2) From N0, all adjacency nodes are orderly visited to find all possible paths from N0 to designed terminal. To realize this aim, some programs are developed. Because all paths are parallel connection, but these elements in the same path is serial connection. The reliability of every path is calculated by following equations (Eq.5.1):

$$\Psi = \Psi_1 \prod_{n=2}^{N} [(1-\mu_0)\Psi_n + \mu_0] \qquad (n=2,3,\ldots,N) \tag{5.1}$$

Here, Ψ_n is the reliability of each elements in this path， Ψ is the reliability of this path. μ_0 is corrected factor, which is the function of intensity and can be got by following equations(Eq.5.2):

$$\mu_0 = 0.06 I_0 + 0.30 \qquad (I_0= \text{Ⅶ},\text{Ⅷ},\text{Ⅸ},\text{Ⅹ}) \tag{5.2}$$

Systemic reliability of all paths is calculated by following equations (Eq.5.3)

$$P_f = 1 - p_{f1} \prod_{n=2}^{N} [(1-\mu_0)P_{fn} + \mu_0] \tag{5.3}$$

Where, P_f is the systemic reliability；P_{fn} is failure probability of possible paths. The following example shows how to calculate the reliability of every possible path. For example, path 1 consists of these nodes: Node 1－2－3－4－6－11－21－23－Node 24, then its reliability is(Eq.5.4-5.6)

$$p_1 = \Psi(1) \times \psi' \tag{5.4}$$

Herein

$$\Psi' = \prod_i [(1-\mu_0)\psi_i + \mu_0)] \tag{5.5}$$

Then

$$p_1 = \psi(1) \times \prod_i [(1-\mu_0)\psi_i + \mu_0)] \tag{5.6}$$

Where $\mu_0 = 0.78$ (I_0=Ⅷ), according to equations (3) and (4), $\Psi(1)=P(E_N)=0.363$, $\Psi_{2,3,4,6,11,23,24}=0.2$, Ψ_{21}.=0.3, then $p_1 = 0.2025$. Following the same procedure, the reliability of other paths can be calculated, these results are summarized into table 5(Tab.5).

Based on connectivity reliability of every path, considering the failure pertinence between every path and interactions existing water supply system and electric power system, the systemic reliability of entire water supply network can be got by following equations (Eq.5.7-5.8)

Table 5 the reliability of all possible paths from Node 1 to Node 24 considering interactions

Path	Nodes in path													Connectivity Reliability
1	1	2	3	4	6	11	21	23	24					0.2025
2	1	2	3	4	6	11	21	22	24					0.1882
3	1	2	3	4	6	11	12	22	24					0.2068
4	1	2	3	4	6	7	8	9	13	15	22	24		0.1235
5	1	2	3	4	6	7	8	9	13	14	15	22	24	0.1083
6	1	2	3	4	6	7	8	9	14	15	22	24		0.1147
7	1	2	3	4	6	7	12	22	24					0.2012
8	1	2	3	4	7	12	22	24						0.2294
9	1	2	3	4	7	8	9	14	15	22	24			0.1307
10	1	2	3	4	7	8	9	13	15	22	24			0.1408
11	1	2	3	4	7	8	9	13	14	15	22	24		0.1235
12	1	2	3	8	9	14	15	22	24					0.1700
13	1	2	3	8	9	13	15	22	24					0.1831
14	1	2	3	8	9	13	14	15	22	24				0.1605
15	1	2	4	7	12	22	24							0.2616
16	1	2	4	6	7	8	9	14	15	22	24			0.1307
17	1	2	4	6	7	8	9	13	15	22	24			0.1408
18	1	2	4	6	7	8	9	13	14	15	22	24		0.1235
19	1	2	4	6	7	12	22	24						0.2294
20	1	2	4	6	11	12	22	24						0.2358
21	1	2	4	6	11	21	23	24						0.2309
22	1	2	4	6	11	21	22	24						0.2146
23	1	2	4	7	12	22	24							0.2616
24	1	2	4	7	8	9	14	15	22	24				0.1491
25	1	2	4	7	8	9	13	15	22	24				0.1605
26	1	2	4	7	8	9	13	14	15	22	24			0.1408
27	1	5	10	21	22	24								0.2640
28	1	5	10	21	23	24								0.2841
29	1	5	10	18	17	19	20	23	24					0.1813
30	1	5	10	18	19	20	23	24						0.2067
31	1	5	10	18	20	23	24							0.2423
32	1	5	16	17	19	20	23	24						0.2173
33	1	5	16	18	19	20	23	24						0.2033
34	1	5	16	18	17	19	20	23	24					0.1734
35	1	5	16	18	20	23	24							0.2318

$$p_f = p_{f1} \prod_{n=2}^{35} [(1-\mu_0) \times p_{fn} + \mu_0] \tag{5.7}$$

$$p_s = 1 - p_f \tag{5.8}$$

where, $p_{fn} = 1 - p_n$, n=1, 2, …35. P_s is systemic reliability of entire water supply network, herein, $p_s = 0.8095$.

6.CONCLUSIONS

The interactions among lifeline systems are usually found in almost all of damage earthquake. In Modern society, interlinks in spatial distance and performance among different lifelines are changing more closer, so, interaction among lifeline systems will possibly encounter the higher earthquake risk. It is necessary to explore interactions among lifeline systems to improve their reliability. According to results in this paper, it is proved that systemic connectivity of water supply system with considering effects from electric power system obvious falls; the maximum value is 38.24%. A comparative result is summarized in table 6(Tab.6).

Table 6 Connectivity reliability with and without interactions

Path	Connectivity reliability		Path	Connectivity reliability	
	Interaction	No interaction		Interaction	No interaction
1	0.2025	0.2257	19	0.2294	0.3004
2	0.1882	0.2257	20	0.2358	0.3004
3	0.2068	0.2633	21	0.2309	0.2574
4	0.1235	0.1512	22	0.2146	0.2574
5	0.1083	0.1333	23	0.2616	0.3426
6	0.1147	0.1521	24	0.1491	0.1978
7	0.2012	0.2633	25	0.1605	0.1978
8	0.2294	0.3004	26	0.1408	0.1735
9	0.1307	0.1735	27	0.2640	0.3348
10	0.1408	0.1735	28	0.2841	0.3348
11	0.1235	0.1521	29	0.1813	0.2257
12	0.1700	0.2257	30	0.2067	0.2574
13	0.1831	0.2257	31	0.2423	0.2936
14	0.1605	0.1978	32	0.2173	0.3004
15	0.2616	0.3426	33	0.2033	0.2574
16	0.1307	0.1735	34	0.1734	0.2257
17	0.1408	0.1735	35	0.2318	0.2936
18	0.1235	0.1521			

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REFERENCES

Bob L., John M.E.(1995). Water-Power Lifeline Interaction. *Proc. Of the fourth U.S. conference on Lifeline Earthquake Engineering*, 541-548.

Felix S.W., Jeremy I.(1995).Effects of lifeline interaction on seismic performance of communication networks. *Lifeline Earthquake Engineering*, *ASCE*, 557-565.

Hoshiya.M. and Ohono, T(1985). A System dynamic model in seismic performance assessment of electric power and water supply network. *Proc. of Trilateral seminar-workshop on lifeline earthquake engineering*, Taipei,181-189.

INTECH Inc (1997).Collocation impacts on the vulnerability of lifeline during earthquake with applications to The Cajon Pass, California (FEMA 226), Potomac,MD.

M.shinozuki, Tanaka,S.(1995).Effect of lifeline intersection under seismic condition. *11th World Conference of Earthquake Engineering (WCEE)*, Mexico, paper ID: 348.

O'Rourke T.D.(1996).Lessons learned for lifeline engineering from major urban earthquakes.*11th WCEE*, Mexico, paper No.2172.

Tang A.P., Ou J.P, Wen A.H, and Tao X.X(2004).Lifeline System interaction and their seismic performance assessment. 13th WCEE, Vancouver, Canada, Paper-ID: 3437.

Wu Y.X(2004). The interaction of water-power system under earthquake condition, Master thesis of Harbin Institute of technology, Harbin, China. (In Chinese).

Y.Hada, K.M.(2001). Optimum restoration model considering intersection among lifeline system –interaction among restoration activities of lifeline utilities. *12th WCEE*, New Zealand, Paper-ID: 1742.