OPTIMUM POST-EARTHQUAKE RECOVERY OF LIFELINE SYSTEMS BY IMPORTANCE ANALYSIS

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SUMMARY

Based on concepts of probabilistic importance, a methodology is developed to prepare rational countermeasures for seismic damage to lifeline systems. Various measures can be applied to evaluate the order of importance for system components. A case study is made for a water supply system in Sendai City, Japan. Time-dependent behavior of system performance with a progress of repair works is examined on basis of theoretical formulation of stochastic process. The method is capable of considering the system properties, the system operating strategies and the repair process.

INTRODUCTION

Serious damage to lifeline systems was observed in the 1971 San Fernando earthquake and the 1978 Miyagiken-oki earthquake, etc. Much experience has been obtained from these earthquakes, especially on the restoration of deteriorated serviceability of lifeline systems (Ref. 1). It is important for engineering purposes to investigate efficient and practical post-disaster strategies. Some papers have been published with an attempt to provide information on the system serviceability based on the damage restoration model in a comprehensive manner (for example, Ref. 2).

For lifeline systems in a modern urban area, necessity of predisaster planning and preparedness, including accurate damage estimation for future earthquake disaster, has been widely recognized. Hence, optimum countermeasures for the restoration process must be established as well as accurate estimation of seismic damage. Emphasis should be placed on the general restoration process of these systems in addition to the damage inflicted on each component of structures. Most studies, however, furnish hardly practical information required for the establishment of importance concepts for improving system reliability, diagnosing seismicity, and generating repair checklist, etc.

In this paper, a methodology based on concepts of probabilistic importance is developed to prepare effective countermeasures for the restoration process of seismic damage of lifeline systems. Various measures can be applied to evaluate importance rankings of system components and cut sets in fault trees. Several illustrative examples are solved to examine the usefulness of the method. The restoration process of a water supply system is examined with a progress of repair works.

THEORETICAL BACKGROUND FOR IMPORTANCE ANALYSIS

Birnbaum's Measure on Importance

Birnbaum's importance is defined as the rate at which system reliability

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improves as the reliability of the i-th link improves (Ref. 3). This importance is expressed as follows:

$$I_i^B(t) = \frac{\partial g(q(t))}{\partial q_i(t)} \quad\quad \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where g and q_i represent the unreliabilites of the system and the i-th link, respectively. $I_i^B(t)$ is the probability that the system is in a state at time t in which the functioning of the i-th link is <u>critical</u>; i.e., the system functions and fails when the i-th link functions and fails, respectively.

In this study, Birnbaum's measure of importance and the unreliability of system connectivity are computed using the upper bound by minimum cut set (Ref. 4). In order to calculate $I_i^B(t)$, the following notations are introduced.

K_i^i ; union of all minimum cut sets containing the i-th link
NK^i ; number of cut sets that contain the i-th link
$P(K^i)$; probability that the i-th link is contributing to system failure under the condition that a cut set containing the i-th link has failed

$$P(K^i) = 1 - \prod_{j=1}^{NK^i} (1 - \prod_{i,l \in K_j} q_l(t)) \quad\quad \cdots\cdots\cdots\cdots\cdots (2)$$

$P_1(K^i)$; probability of occurence for any of cut sets containing the i-th link when failure of the i-th link is occuring

$$P_1(K^i) = 1 - \prod_{j=1}^{NK^i} (1 - \prod_{i \in K_j, l \in K_j - \{i\}} q_l(t)) \quad\quad \cdots\cdots\cdots\cdots\cdots (3)$$

Assuming statistical independence of every cut sets, Birnbaum's measure of importance can be calculated as follows:

$$I_i^B(t) = \frac{1 - g(q(t))}{1 - P(K^i)} P_1(K^i) \quad\quad \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

Criticality Importance

Birnbaum's definition of importance is a conditional probability of the system under the state of the i-th link being fixed. The probability that the system is in a state in which the i-th link is critical and has failed by time t is

$$\{g(1_i, q(t)) - g(0_i, q(t))\} q_i(t) \quad\quad \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

Then, criticality importance of the i-th link is defined as follows (Ref. 5):

$$I_i^{CR}(t) = \frac{q_i(t)}{g(q(t))} I_i^B(t) \quad\quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

Fussell-Veselly's Definition of Importance

It is possible that when system failure is observed, two or more cut sets could have failed. Restoring a failed link to a normal state with repair work doesn't necessarily mean that the system is restored to a normal state. It is possible that failure of a link during earthquake can cause system failure without being critical. The i-th link will contribute to the system failure if a cut set containing the i-th link fails.

Supposing that the system has failed by time t, the probability that the i-th link is contributing to system failure is given by using Eq.(2). The Fussell-Veselly's definition of importance (Ref. 6) is as follows:

$$I_i^{FV}(t) = \frac{P(K_i)}{g(q(t))} \quad\quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (7)$$

Fussell-Veselly's Cut Set Importance

Cut set importance is defined as an analogy to methods that determine the

importance of the i-th link. Now, Q_{K_i} is the probability that cut set K_i is contributing to system failure. Then, the importance of a cut set K_i is given by

$$I_{K_i}^{FV}(t) = \frac{Q_{K_i}}{g(q(t))} \quad , \quad Q_{K_i} = \prod_{l \in K_i} q_l \quad \cdots\cdots\cdots\cdots (8)$$

ASEISMIC DIAGNOSIS AND OPTIMUM IMPROVEMENT OF SYSTEMS ON THE BASIS OF IMPORTANCE RANKINGS

Importance analysis is performed for four measures. Case studies are made for a simple network model and a water supply system in Sendai City, Japan.

Model Network Used for Case Study

A simple model (Fig.1) which forms a macroscopic part of lifeline system is surveyed extensively. The numbered circles represent branch nodes. The damage probabilities are assumed to be the same for all links. Damage to the nodes are not considered.

Because the lack of the practical point of view, four measures of importance are qualitatively examined. Fig.2 is drawn with probability of unconnectivity between supply node 1 and demand node 6 on the abscissa.

The importance rankings obtained by various methods show the following characteristics: 1)Because I_i^B can give significance to a relatively insignificant event, I_i^B can't be practically applied for upgrading reliable systems, 2) I_i^{CR} implies that it is more difficult to improve the more reliable links than to improve the less reliable links, and 3)When a link contained in cut set K_i is not replicated in other cut sets, this always assigns more importance to a cut set of a lower order than a cut set of a higher order when failure probability of each link is equal.

The importance measures are strongly affected by those definitions. Fig.2 shows that links 1 and 6 (or cut sets 1 and 2) are more important. It is also observed that variation of importance measures differs from link (cut set) to link (cut set), depending on the redundancy of the network between the supply and demand nodes. Increasing the probability of system unconnectivity, importances for I_i^{FV} and $I_{K_i}^{FV}$ increase gradually. On the other hand, the relation for importance I_i^{CR} is in reverse. For I_i^{FV}, the rate of the change of importance is much greater in the range of g (=prob. of unconnectivity) > 0.5 than that in the range of $g < 0.5$. This tendency is especially evident for the links near center of the network. Birnbaum's importance I_i^B in system unreliability near the value of 0.5 is almost similar to or higher than that of other values. These results are naturally influenced by the properties of the particular system considered.

From these results, it may be concluded that the methods dealt with herein are quite stable against the change of system unreliability. In order to evaluate the more critical behavior of the local system performance, it is necessary to subject the network to more critical conditions.

Monte Carlo simulations on system connectivity are performed. The results of 10000 simulations are shown in Fig.3 for terminal reliability (in other words, reliability of system connectivity) between source node 1 and demand node 6. At first, simulations are carried out with a constant reliability of 0.5 for all links. As a result, terminal reliability is 0.3952. The change of terminal reliability is also examined with the change of reliability of each link from 0.5 to 0.9 or 0.1.

It is found from Fig.3 that the links are basically divided into three groups according to the values of terminal reliability; 1)links directly

connected to the supply node 1, 2)links near the center of network, and 3)links near the demand node 6. Since nodes 2 and 3 (or nodes 4 and 5) are directly connected to the supply node 1 (or demand node 6), respectively, their service-abilities depend almost entirely on the reliabilities of the corresponding links. This would be justified from redundancy of the network which is affected by allocation of double links particularly of pipes 3 and 4.

Water Supply System in Sendai City, Japan

The main water distribution network in Sendai City is shown in Fig.4. The areas (2,3,4) marked with   are treated as supply nodes and 13-15,21,24-26 as demand nodes. Junctions of branch flows from the main distribution pipes are called branch nodes. The probability of reliability of each pipe section is represented by Table 1 (Ref.2). Fig.5 is the zoning map of soil condition and levels c_1,c_2,c_3 and c_4 are determined on the basis of correlation of various damage levels to ground characteristics.

The system connectivity at least from demand node 24 to one of the supply nodes is taken into account. The siting of the supply and demand nodes and routing of links (pipelines) between these nodes are assumed to be predetermined as shown in Fig.4. Birnbaum's importance measure of all pipes is computed. Since the lowest ranking of importance is a direct measure of the weakest links in the system, this link is excluded from the network in order to reduce the hazard potental. For repeating this procedure, the importance for a newly constructed system is evaluated by Birnbaum's analysis at each progressive step untill the system allocation is completely determined.

A typical optimization performed under this strategy is summarized in Table 2. It is noted from Table 2 that the links verified from importance rankings are grouped as follows; 1)links connected to source and demand nodes, 2)links near the center of system, and 3)links in the periphery of the system, respectively. The system shown in Fig.4 is considered the existing system upon which an increased demand on system connectivity has been imposed. A system reduced from its existing configuration under this strategy is shown in Fig.6.

System configuration is much more sensitive to the strategies based on importance. Alternatives for the network topology are considered by the possible choice of unconstructing (i.e., excluding oldest pipelines) some of the feasible links. Those routes would produce a redundancy in the system at which an obviously disproportionate cost should be considered unfeasible. In the 4-th step of the importance analysis shown in Table 2, there is not link 18 between nodes 9 and 10. It means that the construction of a pipeline between two nodes has been ruled out on the basis of infeasibility.

SYSTEM PERFORMANCE DURING RESTORATION PROCESS

Restoration of Damaged Network with Progress of Repair Works

Connectivity between the supply and demand nodes is achieved by the existence of at least one of the tie sets in network. Reliability of connectivity is a main parameter used to evaluate the restoration as the first stage after the earthquake. Many failures are assumed to occur in each pipeline. The degrees of damage and restoration progress are derived by discrete-state discrete-transition Markov process. The restoration is evaluated in terms of the expected number of the damaged locations in each link as a function of time passage. The time required for repair should depend on the location and extent of damage, etc. A conceivable strategy is used in this study. Details of analytical procedure are presented in Ref. 2.

In order to examine the capabilities of the method, the network system

shown in Fig.4 is again evaluated. The order by which the damaged links are to be repaired is preassigned. Repair works must be based on the real characteristics of the system. It is assumed that the repairs are initiated simultaneously for all the failures in the network. For this system, the strategy which gives priority to the pipe with smaller damage seems to be more favorable. Moreover, higher priority is given to the pipe located closer to supply nodes and the higher importance in the system. This strategy is able to utilize the system redundancy more effectively. Repair works will be finished in short times.

The damaged network system immediately after earthquake is simulated by a Monte Carlo approach as shown in Fig.7 (t=0). This is compared with the damage to the water supply system in Sendai City caused by the 1978 Miyagiken-oki earthquake. It may be observed that damaged locations in Fig.7, t=0 immediately after earthquake, agree fairly well with pipes of minor and major failures in the light of damage from actual earthquake.

Fig.7 shows a time-dependent variation of the restoration. The restoration rate of damaged links has two phases; initial stage of slow restoration of 0.2 (steps/day) for first five days and next stage of restoration of 0.5 (steps/day), respectively. In Fig.7, T_M indicates the total time required for completing the restoration. The total number of damaged locations (N) descreases from the day immediately after earthquake (t=0) to the day of completed restoration (T_M=8 days) ; N=23,16,12,8,7,7,3,1,0 day by day. Link 36 is not easy to restore completely because of the low reliability of the pipe. As most of the pipes have not been repaired at the stage from 3 days to 5 days, the recovery of overall reliability will be not appreciable. From Fig.7, the following can be seen; 1)Some routes fail to be effective since there is no way to prevent system connectivity, and 2)Several districts selected may receive sufficient water with high efficiency, but the other areas will be completely without water.

Evaluation of System Connectivity and Serviceability during Post-Earthquake Periods

Besides importance measures representing sensitivity, two quantities related to the system performance, i.e., connectivity and functional reliability are evaluated in this study. Modes of leakages and breakages in links are taken into account to perform the conventional network flow analysis. As leakage or the number of damaged locations reduces with a progress of repair works, normal operating conditions will be recovered. The restoration will vary with the order of repair works. The normal supply is restored when all repair works are completed. Analytical method is developed to provide information on the system serviceability in probabilistic terms. The process of functional restoration and its dependence on the pattern of the order of repair works are included in a somewhat ad hoc manner (Ref. 2).

Fig.8 shows how the terminal reliability of system varies as repair works proceed. Discussions are concentrated on restoration of structural and functional damages to the water supply system. From Fig.8, two distinct differences are found for the recovery process of the structural and functional performances. In general, characteristics of restoration process are strongly influenced by how the system configuration is composed.

For the network system shown in Fig.4, system performance is evaluated by adopting two different restoration rates. Two cases take 8 and 15 days for complete restoration, respectively. Several interesting behaviors can be found from Fig.8 with respect to the recovery after the earthquake damage. In this example, it is observed from the curves of T_M=8 days that it takes about 3 days

for the 70% functional restoration, whereas the structural restoration stays at 60% level of restoration at the same time. The curves of T_M=15 days indicate that 8 days are required for the 70% functional restoration. As far as the terminal stages of restoration (after 3 days for case of T_M=8 days and 8 days for case of T_M=15 days) are concerned, the characteristics of structural restoration show no significant difference for those of functional restoration. Changes of overall reliability for T_M=8 days generally show similar tendencies to those for T_M=15 days.

System operating strategies play a very important role for the total system performance. For example, the poor performance of restoration may be explained by the following reasons. As the distances from supply node increases, the reliability of route against seismic damage descrease. Since the flow resistance increases the distance from supply nodes, this makes it difficult for water to reach these nodes. Since most of the damaged pipes are restored in day 1, serviceability curve of T_M=8 days results in a sharp increase. The curve begins to increase from the day when the pipes with the minimum repair periods are restored. After that, the recovery of overall reliability becomes very slow because of the long repair period required for the link 36 connected to demand node 24.

CONCLUDING REMARKS

The importance analysis presented herein can be applied effectively for lifeline systems ; 1)to suggest the most optimal approach to upgrade the system, 2)to find weak components in system design and operation, 3)to determine the optimal location of spatial system, 4)to make repair checklists on the basis of the importance measures, 5)to diagnose the seismicity of lifeline systems, and 6)to determine rational restoration strategies. Further study is underway for the establishment of the rational system operating strategies during restoration processes on the basis of importance analysis.

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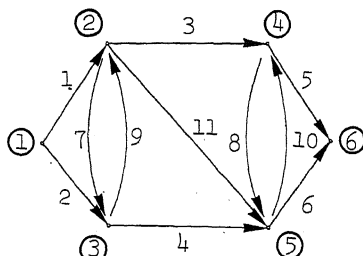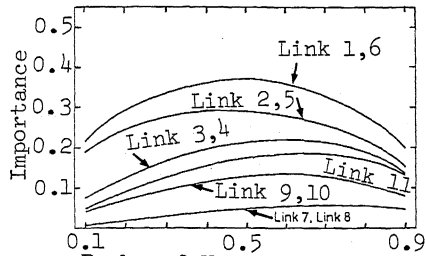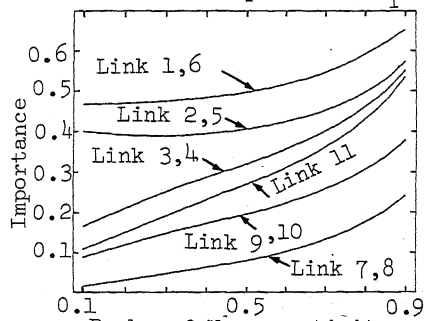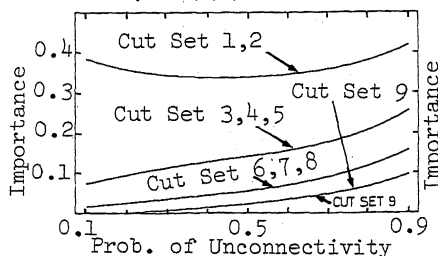
Fig.1 Network System

(a) Birnbaum's Structural Importance; I_i^B

(b) Fussell-Vesely Component Importance; I_i^{FV}

CUT SET 1 (Link 1,2)   6 (Link 1,6,9,10)
        2 (Link 5,6)   7 (Link 2,3,7,11)
        3 (Link 1,4,9)   8 (Link 4,5,8,11)
        4 (Link 3,4,11)   9 (Link 2,5,7,8,11)
        5 (Link 3,6,10)

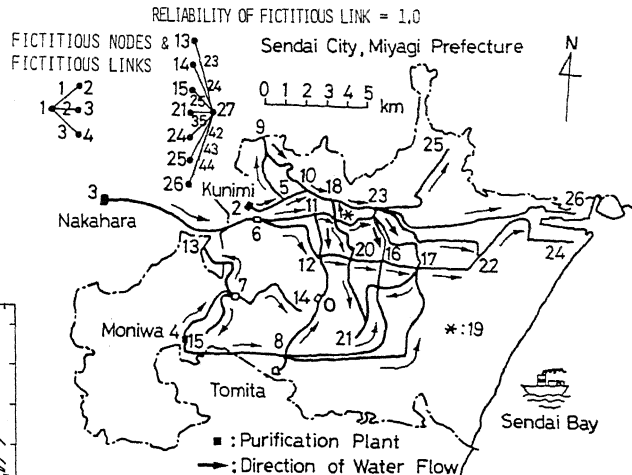(c) Fussell-Vesely Cut Set Importance, $I_{K_i}^{FV}$

(d) Criticality Importance; I_i^{CR}

Fig.2 Importance Rankings

RELIABILITY OF FICTITIOUS LINK = 1.0

FICTITIOUS NODES & 13
FICTITIOUS LINKS 14

Fig.4 Water Supply System for Sendai City, Japan

■ : Purification Plant
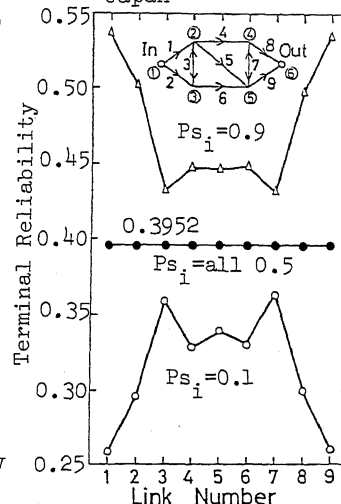➜ : Direction of Water Flow

Fig.3 Reliability of System Connectivity in Accordance with Change of Link Reliability
(10000 Simulations)

Table 1
Reliability of
Each Pipeline

link No.	Node Up	Node Down	$1-q_i$
4	2	5	0.893
5	3	6	0.834
6	4	7	0.864
7	4	8	0.893
8	5	9	0.341
9	5	10	0.901
10	6	11	0.567
11	6	12	0.403
12	7	13	0.524
13	7	14	0.211
14	7	15	0.791
15	8	12	0.918
16	8	16	0.215
17	8	17	0.475
18	9	10	0.495
19	10	18	0.918
20	11	12	0.631
21	11	19	0.779
22	12	20	0.901
26	16	17	0.797
27	17	21	0.324
28	17	22	0.211
29	18	23	0.836
30	19	18	0.870
31	19	20	0.607
32	19	23	0.573
33	20	16	0.848
34	20	21	0.318
36	22	24	0.0875
37	16	23	0.768
38	23	17	0.580
39	23	22	0.130
40	23	25	0.546
41	23	26	0.0503
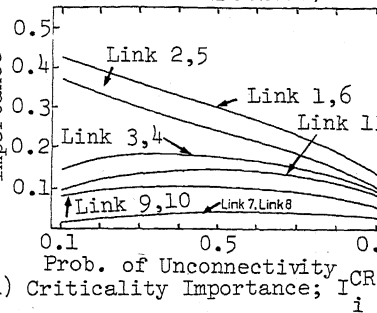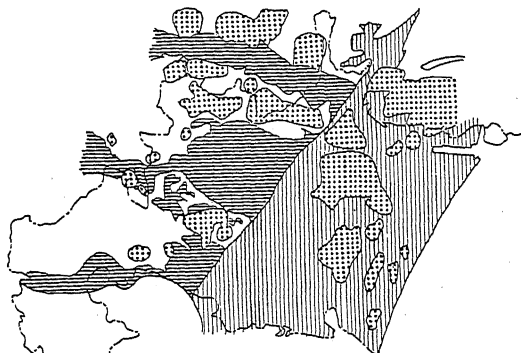
Classified Index for 4 Groups of Ground

○ GROUND OF THE FIRST KIND : $c_1 = 1$
⊜ GROUND OF THE SECOND KIND : $c_2 = 2$
⦿ GROUND OF THE THIRD KIND : $c_3 = 3$
⦂ GROUND OF THE FORTH KIND : $c_4 = 4$

Fig.5 Simplified Soil Map for Sendai City

Table 2 Scheme for Finding Optimum Topology of Links from Supply Plants 2,3,4 to Demand Node 24

No.	Birnbaum's Importance I_i^B			
	Original 1 →	2 →	3 →	4
1	28 (0.659)	28 (0.656)	28 (0.649)	28 (0.650)
2	39 (0.446)	39 (0.444)	39 (0.440)	39 (0.443)
3	36 (0.186)	36 (0.185)	36 (0.183)	36 (0.184)
4	29 (0.160)	29 (0.161)	29 (0.162)	29 (0.163)
5	4 (0.119)	4 (0.119)	4 (0.119)	4 (0.120)
6	9 (0.119)	9 (0.118)	9 (0.118)	19 (0.117)
7	19 (0.117)	19 (0.116)	19 (0.116)	9 (0.112)
8	10 (0.076)	10 (0.075)	7 (0.077)	7 (0.076)
9	26 (0.071)	26 (0.071)	26 (0.070)	10 (0.072)
10	5 (0.067)	7 (0.069)	10 (0.073)	26 (0.070)
11	7 (0.067)	5 (0.067)	5 (0.066)	21 (0.066)
12	21 (0.065)	21 (0.064)	21 (0.066)	5 (0.066)
13	17 (0.045)	17 (0.045)	17 (0.045)	17 (0.045)
14	33 (0.038)	22 (0.037)	22 (0.037)	32 (0.037)
15	22 (0.035)	33 (0.037)	33 (0.037)	33 (0.037)
16	32 (0.034)	32 (0.035)	32 (0.036)	22 (0.036)
17	38 (0.026)	38 (0.026)	38 (0.026)	38 (0.026)
18	15 (0.016)	30 (0.017)	15 (0.021)	15 (0.021)
19	37 (0.013)	15 (0.017)	30 (0.018)	30 (0.017)
20	30 (0.012)	16 (0.013)	37 (0.014)	37 (0.014)
21	16 (0.012)	37 (0.013)	16 (0.013)	16 (0.013)
22	11 (0.006)	11 (0.007)	11 (0.010)	11 (0.010)
23	8 (0.006)	18 (0.006)	18 (0.006)	
24	18 (0.006)	8 (0.006)	8 (0.006)	
25	20 (0.002)	20 (0.003)		
26	31 (0.002)			

Importance Ranking
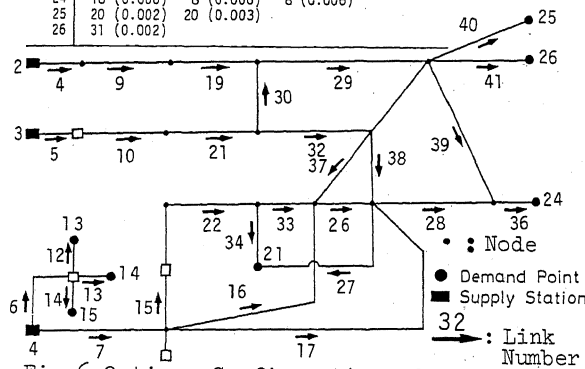
Fig.6 Optimum Configuration of System Based on Importance Analysis

• : Node
● Demand Point
■ Supply Station
32 →: Link Number

T_M =8days ——×— 39 No. of Damaged Pipeline
t=0   ×:Damaged Location
N=23   Node 26

□ A,B,C: Supply Nodes
● 24 etc.; Demand Nodes

t=1 day
N=16

t=3days
N=8

N=Total Number of Damaged Locations at Restoration Time t (days)
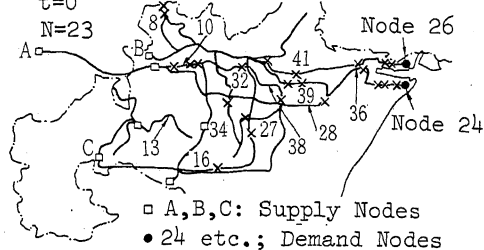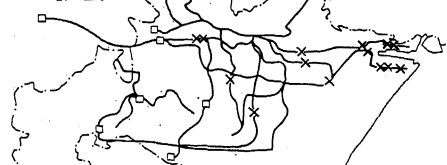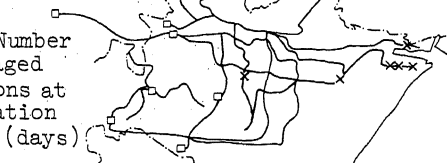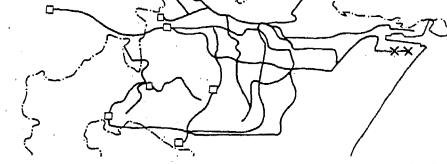
t=6days
N=3

Fig.7 Change of Damaged Locations with Progress of Repair Works
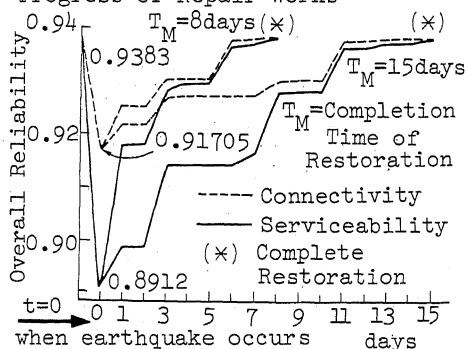

Fig.8 Change of Overall Reliability of System Connectivity and Serviceability during Restoration Process

0.94
0.9383
T_M=8days(×)   (×)
T_M=15days
0.92   0.91705 T_M=Completion Time of Restoration
0.90   ----- Connectivity
0.8912   —— Serviceability
t=0   (×) Complete Restoration
0 1 3 5 7 9 11 13 15
when earthquake occurs   days
Overall Reliability