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CRITICAL COMPONENTS FOR UPGRADING SEISMIC RELIABILITY OF LARGE LIFELINE NETWORKS

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SUMMARY

For seismic reliability analysis we need an efficient algorithm that reduces the complexity of enumeration. We have developed an algorithm that has only polynomial complexity. We propose a measure for specifying critical components in lifeline networks. Using this measure the sequence that strengthens each component is defined for the upgrading of the seismic reliability of the total system. The seismic strain developed in the soil layer and liquefaction of ground are taken as dominant factors in a component's failure. Calculation of the seismic reliability of an example network and evaluation of a component's importance show that this new technique can be used with large networks.

INTRODUCTION

Enumeration of network states in a seismic environment usually has exponential complexity. We have developed an efficient procedure for assessing the seismic reliability of lifeline networks (Ref.1). For a fixed earthquake on an active fault zone, we proved that the network took at most $2n^2-2n+2$ states, n being the number of components. To show clearly the efficiency of developed algorithm, comparison of necessary computer time for several order of complexity to enumerate network state is given in Table 1. When an algorithm of 2^n complexity is applied to count out the exact number of network conditions more than 300 centuries are necessary for network with 60 elements even if we use an program to be able to enumerate all conditions of a network with 20 elements within 1 sec computer time.

Table 1 Enumeration time of subgraph

Complexity	Size of problem			
	20	40	50	60
n^2	0.0004s	0.0016s	0.0025s	0.0036s
n^3	0.008 s	0.064 s	0.125 s	0.216 s
2^n	1.0 sec	12.7 ds	35.7 ys	366 cs

s:sec ds:days ys:years cs:centuries

To develop the algorithm, we use the concept of the critical distance to the earthquake fault (Ref.2); the shortest safe distance of a component. The sphere of the radius with this distance centered at the element point defines the critical boundary for the component because it divides three dimensional space into the component of working and non-working states. The shape of the critical boundary for a node is a sphere. For a link it is a combination of a row of spheres and idealized by a circular cone with spheres at both end provided that there is linearity of the failure distances along the link. The network component will fail if the critical boundary intersects the earthquake rupture area. Taking into account the probabilistic nature of an earthquake occurring, we have defined an active fault zone. The collocation of earthquake rupture on this active fault zone is determined from a probabilistic concept. We assume rectangular areas for the active fault zone and for a rupture caused by an earthquake. The collocation of both rectangles is arranged with the axes of symmetry parallel. We define the transition area as the intersection between the critical boundary of a component of the network and the active fault zone.

To formulate network reliability, we must assume that this transition area may intersect an earthquake rupture; therefore, it is convenient to look at the positions of rupture from the center of the earthquake. Defining a simple transformation, the trace of the center of the rupture which contacts with transition area can be taken as the boundary for the component whether working or nonworking. An example of the collocation of this newly defined boundary for a simple network composed of four nodes and links is shown in Fig.1. The active fault zone is subdivided into 9 regions (defined as influence regions). The network condition changes from one region to the other.

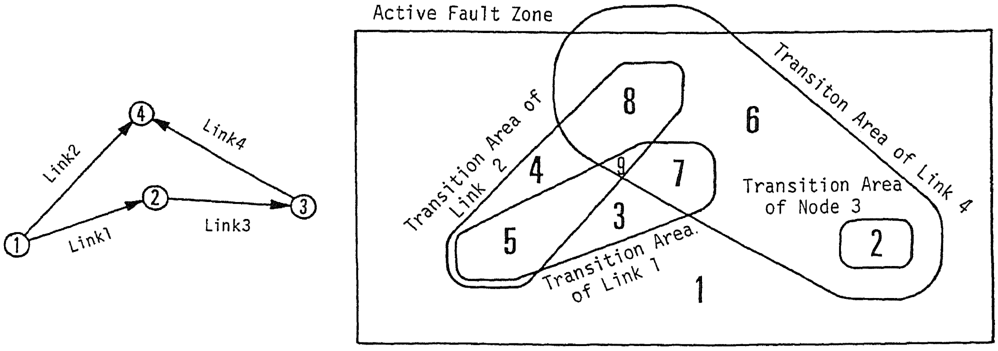

Fig.1 The collocation of the transition area for a simple network

A two-state network is here considered in order to illustrate the reliability computation. A multi-terminal reliability measure is used that is defined as the probability that a specified source node can be connected to all the other nodes in the network.

Let $I(x,y/m)$ be an indication function defined by

$$I(x, y|m)\begin{cases} 1 & \text{if the network functions after a magnitude } m \\ & \text{earthquake with a rupture centered at } (x, y) \\ 0 & \text{if the network does not function} \end{cases} \tag{1}$$

For simplicity we consider only one active fault zone in the following analysis. The reliability of the network, G, conditioned on magnitude, m, is

$$R(G|m) = \int_a^b \int_c^d I(x, y|m) f_{xy}(x, y|m)\, ds \tag{2}$$

in which a and b are the left and right ends of the active fault zone, c and d the lower and upper ends, and $f(x,y/m)$ the probability density function for the location of the center of earthquake rupture on the active fault zone.

The transition areas divide the active fault zone into some K influence regions that are mutually exclusive and collectively exhaustive regions A_i $(i=1,2,....,K)$. Each A_i region corresponds to some state of the network and

I(x,y/m) is constant within A_i, so that Eq.(2) becomes

$$R(G|m) = \sum_{i=1}^{K} I(A_i|m) \int_{A_i} f_{xy}(x, y|m) ds \qquad (3)$$

If the reliability measure for the network shown in Fig.1 is the connectivity between nodes 1 and 4, only influence regions 5, 8 and 9 do not meet this requirement, and the values of I(x,y/m) in these regions become 0. If we assume uniform distribution of f(x,y/m), R(G/m) is easily computed dividing the area (calculated by subtracting these regions from the active fault zone) by the active fault area.

The component resistance was specified by the strain induced in the pipe. For liquefaction we assumed that its component failed when the expected life after random loading became zero using S-N curve of saturated sand obtained from triaxial test results (Ref.3).

MEASURE OF COMPONENT IMPORTANCE

Because of the inherent redundancy of a network, the strengthening of various components does not have the same effect on the reliability of the lifeline. We must first distinguish the most appropriate component in the network to be strengthened in order to upgrade the serviceability of an existing lifeline system after an earthquake.

A concept was defined with which to identify critical components. We also developed a method for finding the component that has the maximum value of importance and gave the ordering of the components for reinforcement and upgrading. The fundamental value that defines the importance of a component is the rate of the network reliability improvement under a constant amount of upgrading. Assuming that the cost to reduce the unit critical distance is almost the same for each component, we define the importance of a component by the increment of reliability to an infinitesimal change in the critical distance.

If the reliability of network R is changed to R+dR by reducing the critical distance of the j-th component, r_j, with dr_j, the increment dR is

$$dR = \sum_{i=1}^{k} \{\frac{dI_i}{dr_j} A_i + \frac{dA_i}{dr_j} I_i\} dr_j/B \qquad (4)$$

in which dI_i/dr_j is 1 when I_i is changed from 1 to 0 or 0 to 1 by the change in the critical distance dr_j, otherwise 0. B is the area of the active fault zone. If the cost of reducing the unit critical distance is assumed to be the same for all the components, the value of dR/dr_j is an importance measure of the j-th component. If the change in the critical distance, r_j, is infinitesimal, the value of dI_i/dr_j can be assumed to be 0, and Eq.(4) becomes

$$dR = \sum_{i=1}^{k} \frac{dA_i}{dr_j} I_i \cdot dr_j/B \qquad (5)$$

This means that the component which gives maximum dR/dr_j is the one with the maximum $(dA_i/dr_j)\ I_i$.

dR/dr_j is obtained by calculating the seismic reliability of two network systems with different critical distances r_j and r_j+dr_j for the j-th component. The ranking of component importance is obtained by doing this calculation for all the components. A long period of computer time, however, is needed as the number of components increases. A simple method can be devised to calculate dR/dr_j that uses the data output from the reliability analysis of a network system with a critical distance of r_j. Information about the size of the critical distance, the dimensions of the transition area, the indication function that expresses the network condition, and the coordinates of the corner point and the characteristics of the periphery of each influence region can be obtained from the output.

An example of the output from a reliability analysis of a simple network is shown in Fig.2. The periphery of the inner transition area B was drawn by reducing 10% of the critical distance of link B. We assume that the part of the periphery of transition area B which intersects the transition area C is critical. Because of the parallel nature of the outer and inner peripheries, the increment in the reliability, dR, produced by change in the critical distance of link B can be obtained approximately. The area increment, dA, of this region is calculated by subdividing the area enclosed by both peripheries into rectangles 1, 2, 3, 4 and sectors a, b, c. The error in this calculation of dA is caused by the black parts shown in the expanded view. The effectiveness of this approximation for the calculation of dR/dr_j is given in Fig.3. The reliability measure is chosen as the connectivity from node 1 to all the other nodes. Open circles obtained by approximation are in good agreement with the exact solutions represented by the full circles, and the importance of each component can be evaluated from the value of dR/dr_j. To calculate dR/dr_j for both cases, we reduced the critical distance of each component 1%. The upgrading sequence of the link number is of the order of 6, 3, 1, 2, 5 and 4.

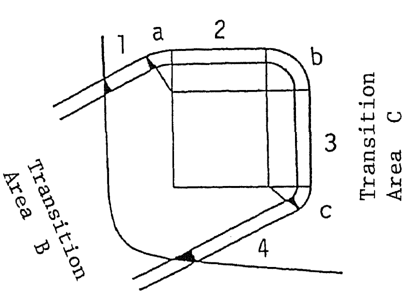

Fig.2 Expanded view of the intersection between the transition area B and C

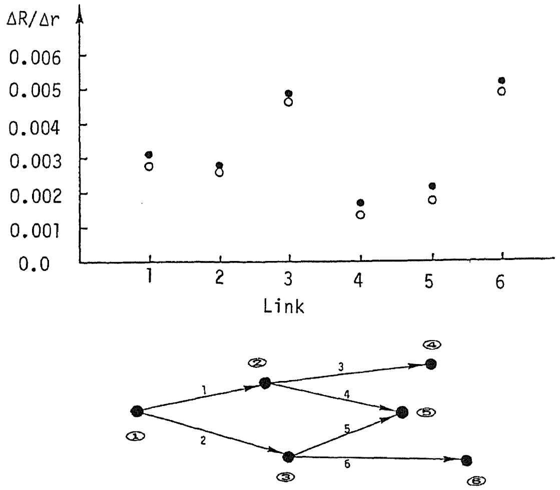

Fig.3 Importance of links in a simple network for reliability connecting node 1 to all other nodes
o, ● :approximate and exact solution

EXAMPLES

To check the applicability of our proposed method, we considered a gas supply network (Fig.4) composed of 388 nodes and 392 links. The possible directions of flow are indicated by arrows. This is by no means a detailed case study, rather it illustrates the capability of developed programs. The network shown in Fig.4 is an idealization of the southern portion of the middle pressure A line (gas pressure: $10>p>3kg/cm^2$)

Four source nodes, A, B, C and D are connected to the high pressure line through regulator stations, and 147 terminal nodes are connected to source nodes of the low pressure line through district regulators. To evaluate the reliability of this network we have chosen a simple connectivity measure, the probability that gas can reach all the termini.

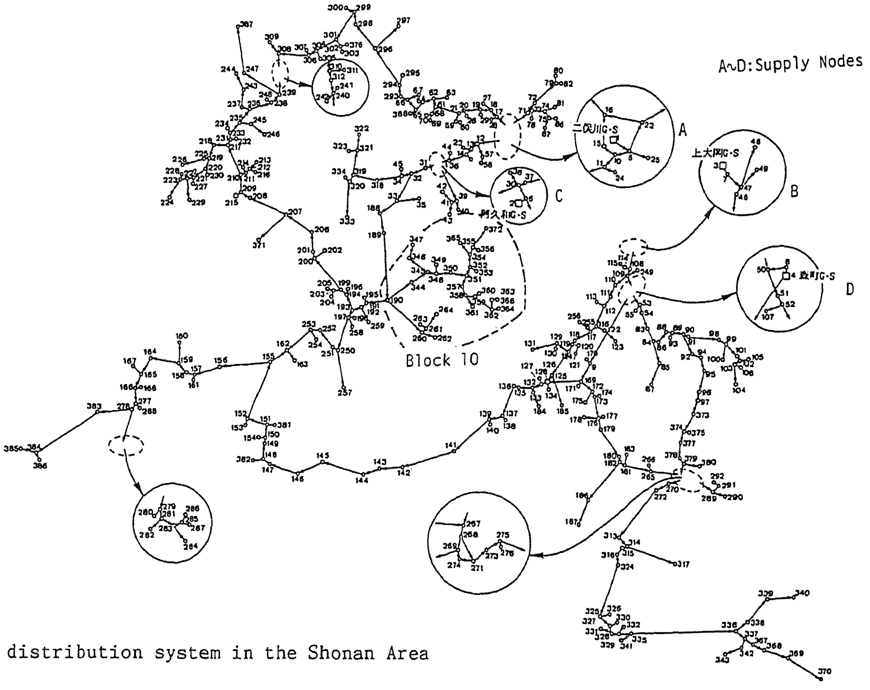

Fig.4 Gas distribution system in the Shonan Area

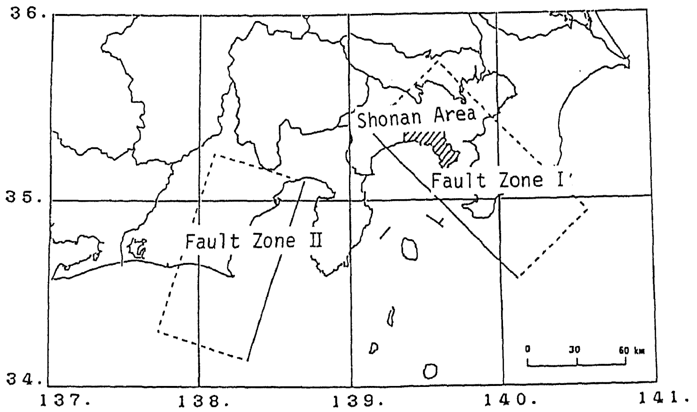

Fig.5 Active fault zones

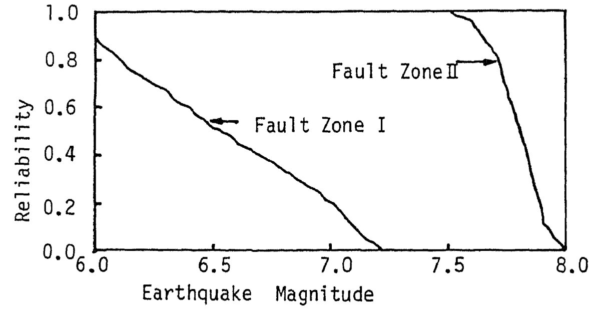

Fig.6 Network reliability for different earthquake magnitude

Two active fault zones are considered (Fig.5). Zones I and II include the fault area of the supposed Tokai Earthquake and that of the 1923 Kwanto Earthquake. The shear wave velocity and thickness of the ground at each node were calculated from the results of standard penetration tests conducted at 649 points in the area concerned. The depth of the buried pipe element is assumed to be 1.2m.

Results for the two active fault zones in terms of the reliability of the network against a random earthquake on each active fault zone are given in Fig.6. Because the expected maximum earthquake magnitude of the supposed Tokai Earthquake is 8.1, the connectivity of the network will be destroyed during such an earthquake. Zone I is very near the network, so low reliability can be seen at an earthquake magnitude of less than 6.5. Upgrading network reliability is vital for protection against earthquake occurrences in active fault zone I.

Table 2 Ordering of component strengthening for a earthquake with magnitude 7

Step	Component (Node No.)
1	275 378
2	108 148
3	95 147

Step	Component (link No.)
1	378
2	103 102
3	277
4	192
5	197

The two sequences of component numbers in Table 2 give the ordering of components for strengthening obtained by evaluating the normal importance of each component for a random earthquake of magnitude 7 in the active fault zone I. The ordering is given to the node and link separately because their failure modes differ. Because of the many terminal nodes (the reliability measure of connectivity from 4 source nodes to 147 terminal nodes), failure of any component in the network usually breaks the reliability requirement. Therefore, most outer peripheries of one or two influence regions can be detected as critical because the indication function becomes 0 in almost all the influence regions. Step 1 in the table shows that the only detectable critical components are nodes 275 and 378. A simple and efficient procedure for upgrading the network is the step-by-step strengthening of its critical components. The order of the components in step 2 in the table was obtained after all the components in step 1 were strengthened.

CONCLUSION

An efficient procedure with which to analyze the seismic reliability of a lifeline network has been presented. It uses the concept of the critical distance and an active fault zone. A simple measure was defined for evaluating important components in the network whose strengthening most improves network reliability. An efficient algorithm by which to calculate these measures also was developed. A check of the applicability of our new method was made by hypothetical seismic reliability analysis of a large gas supply network in the Southern Kanto Area.

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