STUDY ON THE POST-EARTHQUAKE CONNECTIVITY OF TRANSPORTATION SYSTEM NETWORK

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ABSTRACT:
This paper introduces the seismic reliability of transportation system components in earthquake, and the damage grade and its definition of the transportation system network in earthquake. According to the property of transportation system network, combined with graph theory and network analysis theories and methods, the transportation system network connectivity analysis model was constructed. The Warshall algorithm was used in the fuzzy mathematical manipulation, and the adjacency matrix was transformed, and the reachability matrix was obtained, so the connectivity of transportation system network can be decided by the reachability matrix, the detailed realization procedure and an illustration example were presented. The Monte Carlo stochastic simulation method for network reliability analysis was fully introduced in this paper. The network analysis for a given transportation network was conducted by using this method, and the system reliabilities with different earthquake excitations are obtained. The results provide a technical method for enhancing the transportation system earthquake resistance reliability, optimizing post-earthquake transportation system and determing post-earthquake emergency recovery plan and so on.
KEYWORDS: Transportation system, Network analysis, Connectivity; Reliability; Monte Carlo Method

1. INTRODUCTION

The municipal transportation system is a widely ranged network system, and extremely easy to suffer the destruction of earthquake disasters, which bring enormously difficulties for post-earthquake emergency recovery work, and result in direct or indirect severe life losses and property damages. With the development of modernized city, the transportation network system has already become the essential condition for people’s life, and was also the important constituent of lifeline project system. The transportation system is not only the goods transportation channel, but also route for emergency evacuation, and post-earthquake disaster area personnel resettlement, the rescuing group and the engineering troop entering in as well as the rescue and transferring of casualty. It is a matter of life and death earthquake relief lifeline (Zhao Cheng-gang 1994).

Recently, during several dozens years, the global disastrous earthquakes bring about economic loss up to 10 billion, even over 100 billion US dollars. Its common characteristics was, the transportation system’s destruction shut off the seismic region transportation, rescuing work had to be at a standstill, making the disaster more heavily, and result in gigantic indirect economic losses. The bridge collapses and the road destroys, traffic breaks off, the whole city sinks into the paralysis, therefore, the connectivity and reliability analysis of post-earthquake the transportation system are of great importance (Liu Chun-guang 1999).

The connectivity and reliability in transportation system network field have already got series of achievement abroad, various methods and improved algorithms were emerges one after another incessantly, take connective research aspect for example, colored graph method that based on breadth-first search and depth-first search, reachability judgment method based on transitive closure. Reliability research aspects, complete condition enumeration method, inclusion-exclusion principle, minimal paths set non-intersect sum, approximate calculation and numeric simulation method and so on (Lu Ming-sheng 2001). Scholar has also done large amount of jobs in these two aspects in our country, but the research on post-earthquake transportation system network was not so much.

An actual transportation system network is extremely complicated, so we are impossible to get various facilities' failure or reliable probability accurately and also causes the whole system's earthquake resistance reliability analysis to be extremely difficult. This paper is in the hypothesis of corresponding principle foundation. Firstly, transportation system component's reliability analysis for earthquake resistance was carried on, which mainly contains such as road, bridge and tunnel. Then, the relational matrix transmission and transitive closure (Liu Xi-hui 1991) was used to analyze the connectivity of entire system network, and the corresponding C++ algorithm was given out of. Based on this foundation and through Monte Carlo stochastic simulation technology, a network with 44 points and 114 edges was applied to take 2,000 stochastic simulations, and the city's transportation system's reliability will be obtained in the future earthquake of different intensity. The weak links which exist in the transportation system will be discovered, and also parts and road sections which need to be reinforced, bridge components and their repairing order. This work is useful for the city disaster reducing and provides the technical support and theoretical foundation for city disaster control.

2. RELIABILITY ANALYSIS OF TRANSPORTATION SYSTEM COMPONENT

In analysis of transportation system network, the analysis of component is basic step. This paper refers to road section component without bridge and bridges these two kinds of situation, and their reliability was calculated separately as follows.

(1) Reliability analysis of road section without bridge
Road section components' passing probability is namely for entire road section passing probability.

$$P_{tr} = P \tag{2.1}$$

(2) Reliability analysis of road section with bridge
Road section component and bridge component were analyzed as a combined serial sub system. According to cascade system reliability analysis method (Jin Xing 2002), so long as a component was destroyed, then subsystem destroyed, therefore, its general passing probability should be equal to the product of reliability of road section and bridge components.

$$P_{tr} = P_r \times P \tag{2.2}$$

2.1 Earthquake Resistance Reliability Analysis of Transportation System Components

(1) Road sections' reliability calculation
After an earthquake, road sections itself come into being cranky, uplift, bulge, collapse, roadbed subsidence and so on. These damages were the direct causes to road's lower reliability. Besides, adjoining buildings along to sides of the road section were destroyed and make road blocked. An earthquake may trigger landslide, debris flow, rock-fall, earth-fall, sand liquefaction and ground fracture (etc.) geological disasters, which influence the road section's operation reliability. Take all factors effect into consideration, road sections' reliability (Jin Guo-liang 1993) of earthquake resistance can be calculated as follows:

$$P_r = \begin{cases} (1 - B/B_c)\exp(-uL) & B < B_c \\ 0 & B \geq B_c \end{cases} \tag{2.3}$$

Where B = the amount of blocking rubble caused by destroy of the buildings, B_c = the critical amounts of the blocking rocks, that may be given out according to experience, u =the number of destroyed sections per kilometer, L =the length of road sections.

(2) Bridge reliability analysis
According to Tangshan, HaiCheng, scale 7-9 of TongHai earthquake in our county, Professor Zhu Meizhen (1990, 1994) pick up 100 bridges which suffer different degree of damages as samples, with the mathematical statistic method, a seismic disaster prediction method was given, which was suitable for our country. 9 kinds

of primary factors which influence seismic disaster of bridges were selected, such as, earthquake intensity, site classification, degree of foundation failure, superstructure, supported form, pier length, pillar material, foundation form and bridge length. On the basis of this statistical analytical method, degree of bridge in different damage situation was calculated as following formula.

$$A = W_0 \prod_{i=1}^{9} \prod_{j=1}^{2,3} W_{ij}^{X_{ij}} \tag{2.4}$$

Where A= index of seismic disaster prediction, W_0 , W_{ij} = coefficient of calculation, i =number of project items， j =number of factors in project.

$$X_{ij} = \begin{cases} 0 & \text{threre is no factor } j \text{ in item } i \\ 1 & \text{other conditions} \end{cases}$$

2.2 Transportation System Network Rank Standard for Seismic Damage]

Transportation system damage condition is divided as three grades (Huang Long-sheng 1996), basic reliability, namely, road section is intact or slightly cracked, the bridge's major structure is intact or has slight deflection but non-loading bearing component has damage, the bearing capacity is not affected, and operating normally($1 \geq P_r > 0.7$).

Medium reliability, road sections crack, embankment sinks, the bridge girders deflect vertically and horizontally, abutment anchor bolt nips off, and partial steel bars leak outside of the bridge structure and slightly bend, so that must be repaired to get a normal operation ($0.7 \geq P_r \geq 0.3$).

Unreliable state, road section crack severely, crack even links up the embankment, traffic is interrupted, bridge's main load bearing component is broken, piers and abutment slipping, seriously inclines or break, span appears the remarkable change, bearing capacity greatly reduces or has lost totally, that must be overhaul or rebuild to get a normal operation($0.3 \geq P_r \geq 0$).

3. CONNECTIVITY ANALYSIS OF POST-EARTHQUAKE TRANSPORTATION NETWORK

After an earthquake, many disasters happen, according to the emergency preplan recovery, emergency rescue start immediately, and a series of questions follow, such as disaster relief commodity fast transportation, personnel evacuation, casualty's rescue, electric power and water supply security. To avoid blind action in rescue, fast evaluation of road sections, bridges and tunnel's failure grade and traffic capacity and communication line's reachability in seismic region will be the most important things that should be consider first, and this can be exact major objective for analysis of post-earthquake transportation system network connectivity.

3.1 Connectivity Model of Transportation System Network

Transportation system network is consist of multi-lines, overlapping intersection, links, and compose a vertically and horizontally interweaves and complicated municipal transportation network graph. In traffic network picture, geographical position relation among streets is pretty complicated, a street is possible intersect with or connected certain streets, and also its intersection and connected pattern are complex. In order to avoid excessively considering topology relations among streets, intersection and road section were taken out of transportation network graph as analytical object in this paper. Thus, the entire network graph is composed of intersection and road section, then, a junction is defined as a node and a road section as an edge. In a transportation system network graph, some characteristic may be obtained from natural perspective, in a 1:1,000 (or above) scale map, a road section (network side or edge) is approximately a straight line, and network topology relation is complicated, also each edge of network is usually bidirectional passable [11-14], concrete supposition as follows.

(1) Network is defined as $N(V,E)$, where V is a set of nodes, and E is a set of edges.

(2) The whole network is a non-loop network, and no multiple edges are contained.

(3) Each edge of the network is at a two-value state, namely,

$$x_a = \begin{cases} 1 & section \;\; a \; is \; connected \\ 0 & other \; conditions \end{cases}$$

(4) Boolean matrix can be give by damage grade and according to comparing with its α cut set.

2.2 Procedure in Connectivity Analysis of Transportation System Network

(1) Form the transportation system network and label all nodes, then form a graph.
(2) Analyze each side (network component) in the graph, and calculate its reliability.
(3) According to node relation between a serial of nodes, build adjacent matrix.
(4) Refer to component reliability result and α cut set, modify the adjacent matrix.
(5) Adopt Warshall algorithm (Liu Hong-bin 2005) to use fuzzy mathematics operation as follows.

step1: mark the new relation matrix $M = A_R$

step2: here $j = 1$

step3: for all node i, if $M[i,j] = 1$, $k = 1, 2 \cdots, n$, $M[i,k] = M[i,k] + M[j,k]$

step4: $j = j + 1$

step5: if $j \le n$, go to step 3, otherwise stop, finally M is the transitive closure matrix of binary relations.

(6) According to transitive closure matrix, evaluation the reach ability of post-earthquake transportation system.

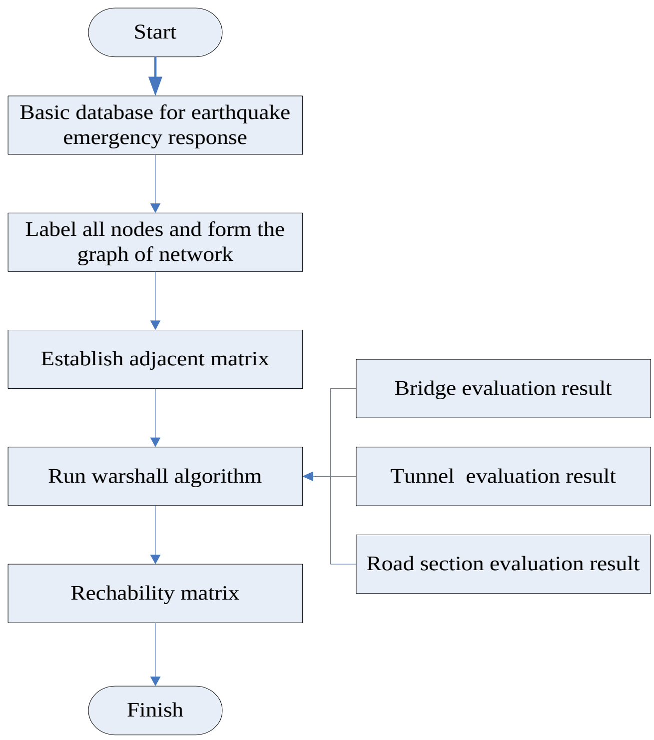

Fig 1 Methodological framework

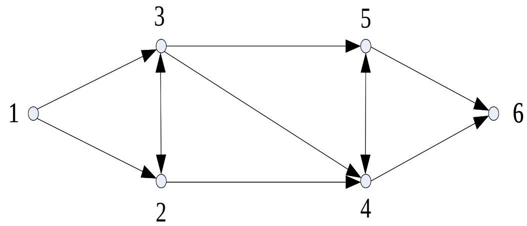

Fig 2 Classic hybrid network

$$M = \begin{bmatrix} 0\,1\,1\,0\,0\,0 \\ 0\,0\,1\,1\,0\,0 \\ 0\,1\,0\,1\,1\,0 \\ 0\,0\,0\,0\,1\,1 \\ 0\,0\,0\,1\,0\,1 \\ 0\,0\,0\,0\,0\,0 \end{bmatrix} \qquad M' = \begin{bmatrix} 0\,1\,1\,1\,1\,1 \\ 0\,1\,1\,1\,1\,1 \\ 0\,1\,1\,1\,1\,1 \\ 0\,0\,0\,1\,1\,1 \\ 0\,0\,0\,1\,1\,1 \\ 0\,0\,0\,0\,0\,0 \end{bmatrix}$$

The above transformation was completed by a c++ language program, through read-in primitive matrix data, directly output response reachability matrix. This algorithm only carried on Boolean calculation to the matrix element, and other procedures are unable to compare with because of its high calculation speed and efficiency. It is suitable for large-scale network's analysis of connectivity and the connective condition between arbitrary network nodes may be reflected.

4. RELIABILITY ANALYSIS OF POST-EARTHQUAKE TRANSPORTATION NETWORK

The reliability of network is an important index for the performance of a network system and is an active and the sensitive topic in the system reliability research in engineering fields. City lifeline engineering network system is also the important foundation for various functions of city's regularly operation, and maintaining society economic growth. Electric power, water supply, transportation and communication network all are the complicated large-scaled network system. It is of great importance to study on these network systems, in view of transportation network:

(1) Firstly, it is synthesis reflection of overall performance of transportation network system, and also is theoretical basis of enhancement and optimization of transportation network performance, also one of theoretical basis of intelligence transportation system.
(2) Secondly, it is an important component and foundation of network system design, management, making emergency preplan.
(3) Finally, it is significant society and the economical significance for the resistance of natural calamities plan to the transportation network, emergency traffic control strategy formulation, road network potential performance excavation, secondary disaster control, reduction of the time delay under the urgent condition and indirect economic losses and so on.

At present, massive research indicates that when evaluating the performance of a network system, which may sum up as the connectivity problem about two arbitrary nodes in a network. The basic procedure to use simulating method for transportation system network reliability evaluation is as follow, the municipal transportation system is taken as a plane network, analyze each road section's reliability, and then use Monte Carlo simulation method in determining the road network connective probability of two arbitrary nodes.

In this paper, the basic thought of Monte Carlo method is damage probability of network components such as, road sections, bridges and tunnels, through massive random numbers in domain 0 to1 which produced at runtime, and compared with component damage probability, approximately reappearance of destruction state of every edge. In each simulation, connectivity of the network was checked and connective condition of source node and other distributing nodes was determined, through calculating the frequency of which is connected or is not connected each time, and thousands of times simulation, connective probability appraisal was obtained, namely, replace precise probability analysis by the approximate frequency analysis. As follows:

(1) Calculate reliable probability for every component of the transportation network.
(2) Generate random numbers in domain 0 to 1 for every component, simulate destruction state for them, compare random number with probability for every component, produce fuzzily related Boolean matrix for the network and the element of the matrix is 0 or 1.
(3) Use fuzzily related matrix and Warshall algorithm to examine connectivity of post-earthquake network. The element expresses that there is or isn't at least one passage between two arbitrarily nodes in a matrix, namely, network, that means all component between two nodes are at basic reliable or medium reliable state.
(4) Continue step (2) and step (3), after number of times' simulation (may be more than 2,000 times), the engineering demands for precision can be satisfied completely, so the reliability of whole network can be obtained.

There are 44 nodes and 114 edges (for component of the network) in the following side weighted network, if one side is bidirectional, which may be considered existing two edges. Suppose its source node is node 22, merging node is node 28, and each side's reliability was obtained by method above, also each side's failure or not is mutually independent. The following table shows the reliability between source node and merging node in different acceleration for 0.05g, 0.1g, 0.2g, 0.4g and 0.8g, and partial reliability of network in fig 3. When considering multiple sources and multiple sinks, put some reliable nodes in source set, and then calculate their reliability for new network.

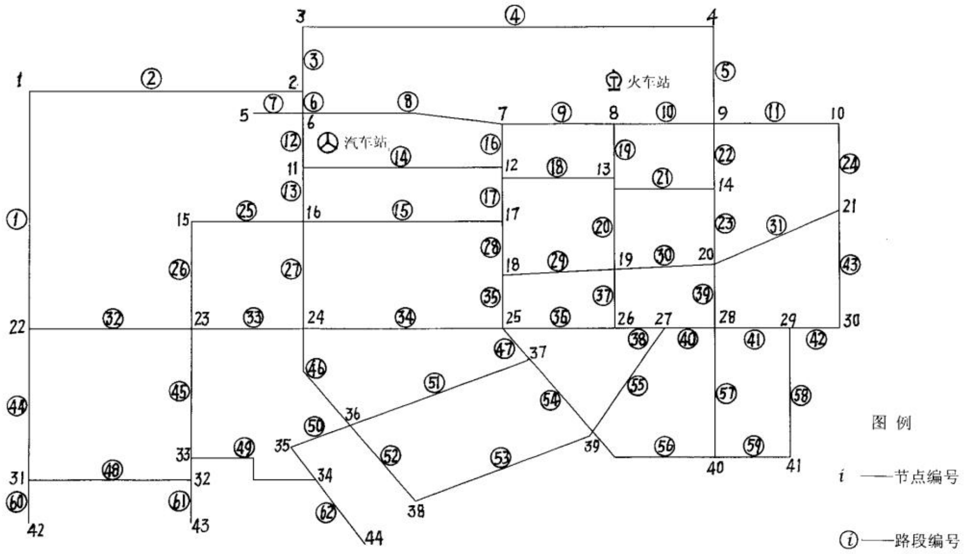

Figure 3 Network graph in a workplace

Table 4.1 Reliability of the whole network

Node \ Acc	0.05g	0.1g	0.2g	0.4g	0.8g
2	1.000	1.000	1.000	1.000	0.867
3	1.000	1.000	1.000	0.995	0.762
4	1.000	0.987	0.964	0.637	0.232
5	1.000	1.000	0.957	0.789	0.397

6	1.000	1.000	1.000	0.993	0.807
7	1.000	1.000	1.000	0.994	0.780
14	1.000	1.000	0.999	0.908	0.446
15	1.000	1.000	1.000	0.941	0.610
19	1.000	1.000	1.000	0.994	0.773
20	1.000	1.000	1.000	0.926	0.469
21	1.000	1.000	1.000	0.903	0.361
Start 1	1.000	1.000	1.000	0.998	0.895
23	1.000	1.000	1.000	0.995	0.916
24	1.000	1.000	1.000	0.995	0.853
26	1.000	1.000	1.000	0.995	0.797
27	1.000	1.000	1.000	0.979	0.692
End 28	1.000	1.000	1.000	0.994	0.742
29	1.000	1.000	0.989	0.824	0.262
30	1.000	1.000	0.997	0.866	0.305
31	1.000	1.000	1.000	1.000	0.938
32	1.000	1.000	1.000	0.994	0.897
38	1.000	1.000	1.000	0.964	0.509
39	1.000	1.000	1.000	0.987	0.623
40	1.000	0.990	0.972	0.747	0.331
41	1.000	1.000	0.988	0.737	0.205
42	1.000	1.000	1.000	0.998	0.846
43	1.000	1.000	1.000	0.989	0.809
44	1.000	1.000	0.992	0.750	0.322

Acc stands for the maximum acceleration of the earthquake and $g=9.8m/s^2$

From table 4.1, we easily find that the network system is basically reliable when the acceleration is 0.05g, 0.1g or 0.2g, and the whole post-earthquake network system is fairly good. Network system is basically reliable when acceleration is up to 0.4 g, and is already in medium reliable from source node to node 4, 5, 40, 41 and 44. When the acceleration is 0.8g, many nodes are in medium reliability and the reliability from source node to 4, 5, 21, 29, 30, 40, 41 and 44 is under 0.4, already in unreliable state. Obviously, when the acceleration surpasses 0.8 g, the connectivity from source to other nodes reduces greatly and reliability of the network system decreases dramatically, most nodes are unreachable.

5. CONCLUSIONS

The earthquake disaster inevitably brings about enormous economic losses and personnel casualties, the effective emergency recovery work is the only the powerful measure that may prevent the accident spreading and reduce consequence of the damages and highly effective emergency recovery motion in the first time, can reduce loss of the damages to a minimum in the threshold. The transportation system is an earthquake resistance and disaster relief and vital important lifeline. The transportation system network connectivity related problem research is an important topic which reduces the earthquake disasters.

In analysis of variously earthquake action and in different destruction situation, according to transportation system network's characteristic, with network analysis theory and method, an analysis of transportation network was carried out and Monte Carlo method was applied to calculate the reliability of the entire city transportation network system. The transportation system's reliability in future different intensity earthquake action was obtained, weak edges and components need to reinforce were found in transportation system, and also road network system optimization, road sections and bridges which must be repaired in a rush and its repairing order. All these measures provide technical support for earthquake resistance and disaster reduction and also provides theory basis for the city disaster damage control. The research results in this paper are of significance to transportation system in earthquake resistance and disaster reduction, and may use in GIS space research on urban planning and management, and provide references for fast disaster relief strategy, determining motion route, reducing personnel casualty and property damage and compilation of city earthquake resistance plan.

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