Reinforce-Optimization of regional network seismic based on connectivity reliability

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Abstract: Road traffic is an important access for emergency service and disaster relief after the earthquake. In this paper, a reinforce-optimization model for road network seismic is established in combination with the analysis results of the seismic reliability of road segment and the importance of road segment. The model is aimed at the lowest cost of reinforcement and optimization, ensuring the asseismic reliability of the road segment and the system to reach the lowest limited value after the reinforcement and optimization, and the highest reliability of the system is mainly considered after the reinforcement and optimization. The orthogonal enumeration method is used to solve the scheme which satisfies the model condition, and a design method for seismic reinforcement and optimization of road network is given. Finally, it confirms the feasibility of this method with an example.

1. Introduction
The probability of the earthquake, especially the destructive earthquake, is low, but it is devastating. It not only has a certain influence on the national economy, but also has a profound influence on the social stability and human psychology, which has attracted wide attention from all over the world. The data shows that China is one of the most serious countries which has ever suffered from earthquakes. Since 2013, there are 184 earthquakes of more than 5.0 degree in our country.

Although most cities have developed road networks in China, they lack relatively fast response capabilities in earthquake emergency response. Thus, through the evaluation of the seismic reliability of the traffic system composition unit, estimating the post-earthquake state of the traffic system scientifically, putting forward improvements of the reinforcement and optimization measures of various composition unit, improving the overall connectivity of the traffic system after earthquakes, and transforming the emergency repair of the unit after the earthquake into the reinforcement and optimization before earthquakes are urgent task for us at present and have certainly guiding significance in engineering.

2. Literature review
Reliability was regarded as a subject for professional research. It first appeared during World War II. Since 1970s, the research of reliability has entered a mature era and has made rapid development. Reliability has infiltrated into all aspects of people's life. The information and complication of civil products have greatly promoted the improvement of reliability research.

The reliability research of road network system started relatively late, and it has only been several decades since the concept was put forward. Road network reliability is an important index to measure the performance of urban road network, especially for traffic system under unexpected events. The
reliability evaluation of road network is one of the effective methods to analyze the uncertainty and randomicity of the road network. Its function is to evaluate the probability of the road traffic network to reach a certain level of service[1], that is, to reach a certain level of traffic service. Researches of Evaluation index and evaluation method are key technology of road network reliability evaluation. It has been developing rapidly since 1990s.

Mine and Kawai first proposed the concept of connectivity, which reflected the probability of maintaining connectivity between two nodes traffic network. Generally, only 0, 1, two states of a section or node are studied, that is, connectivity or disconnection[2]; Iida and Wakabayashi further expanded connectivity from two points to k points and road network[3]; Nicholson used graph theory and the Floyd algorithm to calculate terminal reliability[4]. Asakura and Kashiwadani first put forward the concept of travel time reliability, pointing out that the volatility of travel time can be used to represent the reliability of traffic network, that is, the reliability of travel time[5]; Lida[6] defined the travel time reliability as the probability that travellers can reach the destination within a specified time range. On this basis, Yin, et al.[7] estimated the travel time change caused by traffic demand change by sensitivity analysis; Chen[8] proposed the concept of road network capacity reliability for the first time, and then put forward a method to evaluate the reliability of urban road network capacity[9]; Yang and Bell[10] put forward a two-dimensional graphical reliability analysis method based on the overall consideration of road network capacity reliability and travel time reliability; Sumalee and Kurauchi[11] calculated the reliability of urban road network capacity under different conditions by changing traffic management control measures, analyzed it with Monte Carlo method and verified it in a small experimental network.

Zhang Yong and Yang Xiaoguang analyzed the reliability of urban road network based on complex network theory. The results show that the road network has different robustness under the two attacks of randomicity and selectivity[12]; Liu Sifeng et al. put forward the corresponding matrix algorithm and used it to build the Graph Evaluation and Review Technique model[13]; By combining the reliability theory of series system and parallel system, Zhang Jie analyzed the reliability of the road between OD points, the reliability of the emergency rescue road network, the reliability of the transportation network of the rescue materials and the seismic reliability of the medical rescue traffic network[14]; He Xuan took the influence factors into the network topology model, and further defined the relationship between the influencing factors, so as to analyze the reliability of the emergency rescue system[15]; Tian Fangshuai et al. analyzed the main factors that affect the connectivity reliability of the traffic system, offered calculation methods for the connectivity reliability of the transportation system components and the traffic network and established the seismic reliability model of the urban transportation system[16]. Based on Monte Carlo simulation method, Hou Benwei et al. established an post-earthquake connectivity reliability and traffic volume transit time analysis model, and analyzed the influence of the seismic that effect the road network support capability from three aspects of the road and bridge structure (unit), the section (line) and the network system, and compared the results characteristics and applicability of the two models[17].

3. Aseismic reinforcement and optimization of road traffic system

3.1 Reliability analysis of the road network
The road traffic network is large and complex, it has so many miscellaneous data that it is difficult to calculate accurately. In this paper, Monte Carlo simulation method is used to analyze connectivity reliability of post-earthquake traffic network. Based on the Monte Carlo simulation method for seismic reliability evaluation of road traffic system, the following assumptions are made:

①Only road sections may fail in the road network, and nodes will not fail;
②There are only two states in the road network, connectivity or failure;
③The road segments are independent of each other, and the two traffic flow reliability of road segment is consistent.

The basic idea of the seismic connectivity reliability evaluation of road traffic system based on
Monte Carlo simulation method is based on obtaining the seismic reliability of post-earthquake road segment. Through a large number of simulation experiments, this paper obtains the probability of reliable connectivity of each path, and the system seismic connectivity reliability. The process is as follows:

①Mark the node of the road network and the road segment in the study area with \( m \) nodes \((i, j)\) and \( M \) road segment (expressed in \( U \)), input the seismic reliability value \( P_{ij} \) of each road segment \((i \) is the starting mark of a road unit, \( j \) is the end point mark of a road unit).

②Set up the adjacency matrix \( U(m, m) \) between each node.

\[
\begin{align*}
0 \text{ Node } \rightarrow & \text{ do not connect} \\
1 \text{ Node } \rightarrow & \text{ connect}
\end{align*}
\]

③At each road segment, the random number \( X_{ij} \) on the \([0,1]\) interval is generated and compared with the aseismic reliability \( P_{ij} \) of the road segments, and the adjacency matrix is dealt with correspondingly.

\[
\begin{align*}
\text{When } X_{ij} \leq P_{ij} & \quad \text{The analog unit is connected, let be } u_{ij} = 1, u_{ji} = 1 \\
\text{When } X_{ij} > P_{ij} & \quad \text{This analog unit is not connected, let be } u_{ij} = 0, u_{ji} = 0
\end{align*}
\]

④By using Breadth-First Search, searching out the connected nodes gradually from the source point, and the connection path of the source point to the target node \( i \) denoted by "1", and the shortest path denoted by "2", and each unit \( u (u=1,2,...,M) \) in the shortest path denoted by \( 3u (u=1,2,...,M) \). At the same time, we record the simulation times of \( i \) from source point to different node.

⑤Repeat steps ③—④, statistic the times of "1" in all links and denote as \( t_i \), the shortest path number in the connection case denoted by \( d \), and each unit \( u (u=1,2,...,M) \) in the shortest path occurrence number denoted by \( d_u \), the number of simulations time is \( T \), thus the connectivity reliability \( R_i \) of source point O to node and the connected reliability edge betweenness \( \lambda_c \) are:

\[
R_i = \frac{t_i}{T}
\]

\[
\lambda_c (e_u) = \frac{d_u}{d}
\]

\( \lambda_c \) refers to the proportion of the number of specified edges in the shortest path of the network to all the shortest path. The higher the proportion, the greater the edge betweenness, indicating that this edge plays a more important role in the road network.

⑥To some extent, the connectivity reliability of nodes in the road network reflects the connectivity reliability. Therefore, the average value of the connected reliability of the source point to the nodes can be used as the evaluation value of the whole connectivity degree of the road network. The seismic connectivity reliability \( R_s \) of road network system is as follows:

\[
R_s = \frac{1}{m} \sum_{i} R_i
\]

⑦Improve each unit \( u (u=1,2,...,M) \) with the original seismic reliability \( Pu' \) and repeat the above steps, a new connection reliability \( R_i' \) from the source point to the node \( i \) and the seismic connectivity reliability \( R_s' \) of the road network system will be obtained. The corresponding key importance \( I_c \) is:

\[
I_c = \frac{1 - P_s}{P_u - P_u'} \cdot \frac{R_s - R_s'}{R_s - P_u}
\]

The key importance is to consider the influence of the failure probability of the road segment on the connectivity reliability of the system while considering the change of the system connectivity reliability caused by the change of the reliability of the road segment[18].
3.2 Reinforcement and optimization modeling
Considering many factors such as post-earthquake road network reliability and economic input etc., on the basis of ensuring the post-earthquake reliability of the road network, an optimization model for the lowest cost of the road network reinforcement is established in this paper. The optimization model is as follows:

\[
\begin{align*}
\min & \quad C = \sum_{i \in U} C(i) \\
\text{s.t.} & \quad P_i \geq P_{b_i} \\
& \quad I_{s_i} \geq I_{s_j} (\exists j \in A \neq i) \\
& \quad I_{s_i} = I_{s_j}, \quad \lambda(x_i) \geq \lambda(x_j) (\exists j \in A \neq i)
\end{align*}
\]

(3.7)

Where: \(C\) is the total cost of strengthening and optimizing road network, including the cost and equipment of installation engineering, the purchase cost of tools and other costs of engineering construction, all of which are determined according to the estimate rating and the national standard; \(U\) is the set of all the units in the road network; \(x_i\) is the unit, which is taken strengthening measures in the road network; \(C(i)\) is the cost of strengthen measures for unit \(i\); \(P_S(x)\) is the connectivity reliability of road traffic system after road segment is strengthened and optimized; \(P_{S0}\) is the connecting reliability limit value of road traffic system after the road segment is strengthened and optimized; \(P_i\) is the seismic reliability after the road segment \(i\) is strengthened and optimized; \(P_{i0}\) is the seismic reliability limit value of unit \(i\); \(I_{g_i}\) is the key importance of unit \(i\); \(I_{g_j}\) is the key importance of unit \(j\); \(\lambda(x_i)\) is connected reliable edge betweenness of unit \(i\); \(\lambda(x_j)\) is connected reliable edge betweenness of unit \(j\).

For the constraints of key importance, when the existing scheme cannot satisfy the constraints, we can choose the suboptimal key importance to choose the plan. For connected edge betweenness, the higher edge betweenness can be considered only at the same key importance.

4. Illustrative example

4.1 Reliability of regional road network
In this virtual network, it contains 15 nodes and 20 road segments. Select node 1 as the source point. In the earthquake, the source point can be considered as the abstract node of the disaster area, and calculate the seismic connectivity reliability with different nodes, as shown in Figure 1.

\[
\begin{align*}
\min & \quad C = \sum_{i \in U} C(i) \\
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![Figure 1. Virtual road network diagram](image)

The aseismic reliability of road segment under different intensities is calculated by seismic reliability calculation method, as shown in Table 1.
The seismic reliability of road segment under different intensities is statistically analyzed, and the reliability percentage of each section under different intensities can be obtained by analyzing the data, as shown in Table 2.

**Table 1. Analysis result of seismic reliability of road section**

| Number | Road segment | Sidewalk width (m) | Lane width (m) | Road length (m) | Five degree | Six degree | Seven degree | Eight degree | Nine degree |
|--------|--------------|--------------------|----------------|-----------------|-------------|------------|-------------|-------------|-------------|
| 1      | 1-2          | 9.0                | 24.0           | 1300            | 1.000       | 1.000      | 1.000       | 0.999       | 0.899       |
| 2      | 1-11         | 7.0                | 9.1            | 1100            | 1.000       | 1.000      | 0.999       | 0.998       | 0.895       |
| 3      | 2-3          | 4.0                | 9.0            | 380             | 1.000       | 1.000      | 1.000       | 0.996       | 0.880       |
| 4      | 2-5          | 4.0                | 9.0            | 230             | 1.000       | 1.000      | 0.933       | 0.789       | 0.459       |
| 5      | 3-4          | 9.0                | 12.0           | 1500            | 0.999       | 0.891      | 0.821       | 0.413       | 0.236       |
| 6      | 4-7          | 9.0                | 12.0           | 695             | 0.937       | 0.879      | 0.802       | 0.407       | 0.103       |
| 7      | 5-6          | 4.5                | 14.0           | 420             | 1.000       | 0.984      | 0.934       | 0.910       | 0.806       |
| 8      | 5-9          | 9.0                | 12.0           | 265             | 1.000       | 1.000      | 0.999       | 0.927       | 0.899       |
| 9      | 6-7          | 4.5                | 14.0           | 240             | 1.000       | 1.000      | 0.998       | 0.926       | 0.896       |
| 10     | 6-10         | 8.9                | 11.5           | 460             | 1.000       | 1.000      | 0.986       | 0.950       | 0.801       |
| 11     | 7-15         | 4.5                | 14.0           | 405             | 1.000       | 0.998      | 0.954       | 0.882       | 0.800       |
| 12     | 8-9          | 6.0                | 11.0           | 455             | 1.000       | 1.000      | 0.906       | 0.731       | 0.400       |
| 13     | 8-12         | 11.0               | 28.0           | 385             | 1.000       | 1.000      | 0.928       | 0.726       | 0.413       |
| 14     | 9-10         | 5.0                | 10.0           | 240             | 1.000       | 1.000      | 0.932       | 0.768       | 0.401       |
| 15     | 9-13         | 6.3                | 21.0           | 343             | 1.000       | 1.000      | 0.984       | 0.935       | 0.908       |
| 16     | 10-14        | 9.0                | 12.0           | 466             | 1.000       | 1.000      | 0.996       | 0.799       | 0.496       |
| 17     | 11-12        | 6.3                | 21.0           | 1200            | 1.000       | 1.000      | 0.996       | 0.910       | 0.898       |
| 18     | 12-13        | 6.3                | 21.0           | 600             | 1.000       | 1.000      | 0.997       | 0.978       | 0.832       |
| 19     | 13-14        | 10.0               | 12.0           | 580             | 1.000       | 1.000      | 0.991       | 0.781       | 0.430       |
| 20     | 14-15        | 6.3                | 21.0           | 740             | 1.000       | 1.000      | 0.989       | 0.913       | 0.832       |

Based on the above analysis, when the seismic intensity of the road segment is 5 degree and 6 degree, the proportion of the road segment that remains very reliable is more than 90%. The simulation process is aimed at the earthquake intensity above 7 degree or more. Monte Carlo
simulation method was used to simulate the path selection from source point to different node under different intensities, and their seismic connectivity reliability was obtained, as shown in Table 3.

| Node | Seven degree | Eight degree | Nine degree | Node | Seven degree | Eight degree | Nine degree |
|------|--------------|--------------|-------------|------|--------------|--------------|-------------|
| 2    | 1.000        | 1.000        | 0.897       | 9    | 0.991        | 0.818        | 0.627       |
| 3    | 1.000        | 0.996        | 0.711       | 10   | 0.974        | 0.832        | 0.508       |
| 4    | 0.964        | 0.889        | 0.407       | 11   | 0.961        | 0.830        | 0.807       |
| 5    | 0.995        | 0.861        | 0.690       | 12   | 0.963        | 0.843        | 0.608       |
| 6    | 0.994        | 0.811        | 0.735       | 13   | 0.964        | 0.860        | 0.714       |
| 7    | 0.997        | 0.873        | 0.881       | 14   | 0.997        | 0.875        | 0.591       |
| 8    | 0.959        | 0.833        | 0.406       | 15   | 0.993        | 0.810        | 0.758       |
| $R_s$| 0.982        | 0.866        | 0.667       |      |              |              |             |

According to the analysis of the results, the road segments are less affected when the earthquake intensity is 5, 6 and 7 degrees, all of which can remain basically reliable. Therefore, we only consider the road units under the seismic intensity of 8 and 9 degrees when analyzing the importance of the units.

### 4.2 Research on reinforcement and optimization

In the process of reinforcement and optimization, when the seismic reliability $P_u \geq 0.8$ of the road segment, such units are not considered for reinforcement. When $P_u < 0.8$, you can choose to reinforce it. In summary, the road units that need to be reinforced at 8 degree earthquake intensity are numbered 4, 5, 6, 12, 13, 14, 16 and 19 (the number of road segments to be reinforced and the 8 degree are same as 9 degree).

For each element under different states, the cost of reinforcement required for each increase 0.1 seismic reliability is different. It is assumed that the reinforcement cost of medium reliability is $a$ yuan/m$^2$, the reinforcement cost of the basic unreliable state is $2a$ yuan/m$^2$, and the reinforcement cost of the serious unreliable state is $5a$ yuan/m$^2$. The seismic reliability of the strengthened segment needs to reach 0.8 or more. If the unit is reconstructed, the seismic reliability of the reconstructed unit will be 1.000, the reinforcement cost will be $10a$ yuan/m$^2$, as shown in Table 4.

| Number | Original aseismic reliability | Aseismic reliability after reinforcement | Sidewalk width | Lane width | Road length | Reinforcement cost (yuan) |
|--------|-------------------------------|----------------------------------------|----------------|------------|-------------|--------------------------|
|        | Original base | Reconstruct | Original base | Reconstruct | Original base | Reconstruct |
| 4      | 0.789            | 0.933            | 4.0           | 9.0        | 230         | 1192a        | 11923a      |
| 5      | 0.413            | 0.821            | 9.0           | 12.0       | 1500        | 132192a      | 660960a     |
| 6      | 0.407            | 0.802            | 9.0           | 12.0       | 695         | 59297a       | 296487a     |
| 12     | 0.731            | 0.906            | 6.0           | 11.0       | 455         | 5255a        | 52553a      |
| 13     | 0.726            | 0.928            | 11.0          | 28.0       | 385         | 23953a       | 239532a     |
| 14     | 0.768            | 0.932            | 5.0           | 10.0       | 240         | 1968a        | 19680a      |
| 16     | 0.799            | 0.996            | 9.0           | 12.0       | 466         | 9915a        | 99146a      |
| 19     | 0.781            | 0.991            | 10.0          | 12.0       | 580         | 14616a       | 146160a     |
Reinforce the road segment on the basis of the importance degree and make the scheme test number in order, the seismic connectivity reliability of the original unit reinforcement and reconstruction unit are obtained after multiple simulation based on the Monte Carlo simulation method, as shown in Table 5.

| Number | Reinforcement on the original unit | Reconstruction unit optimization |
|--------|-----------------------------------|----------------------------------|
|        | Aseismic connectivity reliability | Variety | Cost (yuan) | Aseismic connectivity reliability | Variety | Cost (yuan) |
| 4      | 0.866                                  | 0.00%     | 1192a   | 0.873                                  | 0.66%     | 11923a   |
| 5      | 0.923                                  | 5.65%     | 132192a | 0.967                                  | 10.10%    | 660960a |
| 6      | 0.923                                  | 5.64%     | 59297a  | 0.951                                  | 8.50%     | 296487a |
| 12     | 0.867                                  | 0.08%     | 5255a   | 0.868                                  | 0.16%     | 52553a   |
| 13     | 0.867                                  | 0.07%     | 23953a  | 0.868                                  | 0.14%     | 239532a |
| 14     | 0.872                                  | 0.59%     | 1968a   | 0.880                                  | 1.33%     | 19680a   |
| 16     | 0.877                                  | 1.04%     | 9915a   | 0.886                                  | 1.99%     | 99146a   |
| 19     | 0.920                                  | 5.35%     | 14616a  | 0.921                                  | 5.49%     | 146160a |

The reliability of system aseismic connectivity calculated by the reinforcement scheme is compared, and the 4, 5, 6, 12, 14, 16 and 19 factors are selected, and the reinforcement optimization of the road network is selected based on the orthogonal enumeration method. The concrete scheme is shown in Table 6. Among them, the level figure is 2, and the "1" represents the reinforcement on the basis of the original unit, "2" represents the reconstruction of the unit.

| Test number | Factor (Element number) | Test number | Factor (Element number) |
|-------------|-------------------------|-------------|-------------------------|
| 4 5 6 12 14 16 19 | 1 1 1 1 1 1 1 | 4 5 6 12 14 16 19 | 5 2 1 2 1 2 1 2 |
| 1 2 2 2 1 2 2 2 | 2 2 1 1 2 1 2 1 |

According to the scheme determined by orthogonal enumeration method to reinforce and optimize, and the result of optimization is shown in Table 7. When the limit value of the seismic connectivity reliability is 0.800, all the schemes are satisfied. Therefore, considering the cost and the change amplitude of the network seismic connectivity reliability, the maximum increase of the connectivity reliability is No.3 and No.4. By comparison, No.4 costs the least; therefore, choose No.4 plan as the best plan and No.3 plan as suboptimal plan. So according to plan No.4, reinforce units 4, 16 and 19 on the original basis, while reconstructing the rest units.
Table 7. Reinforcement optimization index value of road segment

| Test number | Aseismatic connectivity reliability of road network | Seismic Connectivity Reliability Change of Road Network | Reinforcement cost (yuan) |
|-------------|---------------------------------------------------|-------------------------------------------------------|--------------------------|
| 1           | 0.874                                             | 0.75%                                                | 224435a                  |
| 2           | 0.870                                             | 0.39%                                                | 510220a                  |
| 3           | 0.979                                             | 11.27%                                               | 1211168a                 |
| 4           | 0.981                                             | 11.45%                                               | 1055403a                 |
| 5           | 0.918                                             | 5.14%                                                | 621612a                  |
| 6           | 0.918                                             | 5.19%                                                | 608885a                  |
| 7           | 0.910                                             | 4.34%                                                | 870877a                  |
| 8           | 0.914                                             | 4.72%                                                | 942776a                  |

5. Conclusion

Aimed at researching the reliability of the post-earthquake network, we calculated the seismic reliability of the study area under different intensities, used the Monte Carlo simulation method to analyze the system connectivity reliability under different intensities and the units with high degree of importance. The reinforcement optimization model of network is calculated by orthogonal enumeration method with the goal of strengthening and optimizing cost at least, the condition of aseismic connectivity reliability is higher, which provides a theoretical basis for seismic network reinforcement optimization. The conclusions are as follows:

1) Based on Monte Carlo simulation method, we analyzed the seismic connectivity reliability of simple road network and it was proved to be feasible.

2) Established the aseismic reinforcement optimization model of road network by minimizing the cost of reinforcement optimization of road segment as the objective function, the minimum value of the overall road network connectivity reliability that meets the set criteria after optimized, and importance height of road segment optimization as constraints. Orthogonal enumeration method is used to solve the reinforcement optimization scheme, and the optimal reinforcement optimization scheme is selected by analyzing the example.

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