Research on resilience recovery strategy optimization of highway network after disaster based on genetic algorithm

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Abstract. In order to effectively improve the recovery efficiency of the highway network after the disaster and make the road network quickly recover to the normal operation level, the recovery strategy of the highway network after the disaster aiming at the optimal toughness was studied and formulated. First clear the toughness in this paper the definition and put forward the two toughness indexes, then constructs the model of road network resilience restored after a disaster, in considering the time, money, resources and cost conditions, through the corresponding genetic algorithm to solve, it is concluded that the shortest road repair, restore minimum loss in the process of recovery program. Finally, an example is given to illustrate how to use the model established in this paper. The results show that from the beginning of repair to the end of repair, the repair team can achieve the expected task in a faster time, which minimizes the performance loss of the road network and saves the cost.

Keywords: Road network after disaster, resilience, genetic algorithm, recovery strategy.

1. Introduction

With the continuous development of Chinese society and the vigorous construction of infrastructure, China has formed a complex and diverse transportation network, which has greatly promoted the development of national economy and improved the spatial accessibility of transportation. Diversified transportation networks become the pillar of national and regional economic activities, and effective transportation network services provide a guarantee for the flow of social and economic activities. Among various types of transportation networks, the road network is most closely related to the daily operation activities of the public. Its characteristics of wide coverage, high density and large number of users make the road network play an indispensable role. However in recent years, the city scale expanding and the storm, typhoon, and the frequent natural disasters and accidents, such as mud-rock flow in the local road network and other infrastructure damaged, made in highway network interruption to the normal social and economic activities, but also increased the difficulty of the relief and reconstruction work, It is an urgent and important practical problem to make effective decision of road network recovery after disaster.

Due to the frequent occurrence and inevitability of disaster events, relevant researchers have realized that reliability and vulnerability indicators alone cannot well measure the road network under disaster conditions, and people are more concerned that the road network can quickly recover to the normal
operation level after accidents and natural disasters [1]. In this context, more researchers began to use resilience indicators to measure the performance of road network under major disturbance events. The definition of toughness is different in different disciplines, and its core connotation is mainly the ability of system anti-interference and disturbance absorption, as well as the ability of system to quickly recover to the expected operation level under disturbance [2-3]. In the field of transportation, many scholars believe that toughness is a composite capability with multiple characteristics, which mainly includes redundancy, robustness, rapidity and resource recovery [4].

However, at the present stage, the research on the toughness of the highway network is still in the initial stage of development. For the recovery of the highway network after the disaster, it is mainly through the rapid repair of damaged sections to restore the desired performance of the road network. At present, relevant scholars who study post-disaster highway network recovery methods and decision-making mainly take resilience, resources, time and some related variables as objective functions or constraints to establish models, so as to seek better or optimal highway network recovery methods. These problems can be classified into two directions: selection problem and scheduling problem. The selection of highway network restoration mainly focuses on determining the most favorable combination of restored sections or the optimal (better) combination of restoration measures under the condition of cost constraint, while the scheduling problem usually considers the resource constraint to study the optimal repair plan arrangement of restored sections [5].

Based on the analysis of the above problems, this paper mainly studies the optimization of road network recovery strategies with the goal of resilience, and at the same time considers the selection and planning and scheduling of road network restoration after disasters, and establishes a road network restoration strategy optimization model with road network resilience indicators as the goal. And solve it through the corresponding algorithm, and finally analyze the calculation example.

2. The state of road network changes after the disaster
This paper expresses the road network as a general undirected network topology structure graph $G = (N, A)$, where $N$ is the set of nodes, and $A$ is the set of sections in the road network. Assume that the road network performance before the disaster or accident is $\varphi(t_0)$, and when the disaster or accident occurs on the $t_e$ day, the road network performance drops from $\varphi(t_0)$ to $\varphi(t_e)$ abruptly, and then the project The repair team began to repair and restore the road network on the $t_s$ day. With the continuous advancement of the repair work, the performance of the road network is gradually recovering, and $\varphi(t)$ is gradually increasing. When the disaster is damaged on the $t_s + M$ day When the road section is repaired, the road network performance is restored to the pre-disaster level $\varphi(t_0)$. The entire road network state transformation process is shown in Figure 1.

3. Definition and measurement of resilience

3.1. Definition of Resilience
Due to differences in the research objects, objectives, measurement methods, and concerns of related scholars, the definition of resilience will also be different. Some scholars define resilience as the ability
of the network to recover after failure, failure or destruction, and others define resilience as the ability of the network to offset the effects of destructive accidents. Since the focus of this article is to optimize the road network disaster recovery strategy based on resilience, and when the road network is damaged, it is often necessary to use external repair measures to restore. Therefore, in this article, resilience is defined as after a natural disaster or accident, with the help of external restoration measures, the road network can be restored in the shortest time, and the road network’s performance loss during the restoration process is the smallest (the degree of restoration is the largest). The ability to return to the desired performance state in a performance state. Therefore, in this article, resilience is defined as the occurrence of natural disasters or accidents. After an accident, with the help of external recovery measures, the highway network can recover the shortest time and the performance loss of the road network during the recovery process (the maximum degree of recovery) from the destroyed performance state to the expected performance state.

3.2. Resilience index measurement
According to the definition of resilience in the context of road network in this article, resilience will be measured from two aspects. One is the shortest time for road network recovery, and the other is that the cumulative loss of road network performance is the least, that is, the degree of recovery is the greatest. The shortest time for road network restoration is to ensure that the road network can be restored to the target state at the fastest speed. When part of the road network is damaged, the performance of the overall road network will be affected. The greater the loss, the greater the impact. Therefore, a road network restoration speed index is proposed to measure resilience. The specific calculation method is as follows:

\[
\max R_r \begin{cases} 
1 - \frac{D_X}{D_{\text{max}}}, & \text{when } D_X \leq D_{\text{max}} \text{ Time} \\
0, & \text{when } D_X > D_{\text{max}} \text{ Time}
\end{cases}
\]  

(1)

\(R_r\) is the road network recovery speed and resilience index, \(D_X\) refers to the time of road network performance recovery under a certain recovery strategy, and \(D_{\text{max}}\) refers to the maximum acceptable recovery time after the road network is damaged. It can be seen from formula (3.1) that the value of the road network recovery speed toughness index \(R_r\) should be \([0,1]\). The larger the value of \(R_r\), the faster the road network performance recovery speed, the shorter the recovery time, and the better the toughness. When \(D_X = 0\), \(R_r = 1\) means that the road network instantly recovers to the initial state when it is damaged, and the road network’s recovery speed is the most resilient. When \(D_X > D_{\text{max}}\), it means that the recovery time exceeds the maximum acceptable recovery time. The minimum net recovery speed and toughness \(R_r = 0\).

The cumulative loss of network performance during the recovery process of the road network is another important aspect of measuring network performance. The less the performance loss, the better the resilience of the road network [6-7]. For the convenience of analysis, the cumulative loss of road network performance is normalized, so the road network performance loss toughness index is proposed. The specific calculation method is as follows:

\[
\max R_v = 1 - \frac{\sum_{k=1}^{K} (\varphi(t_0) - \varphi(t_k))}{D_{\text{max}} \times \varphi(t_0)}
\]  

(2)

\(R_v\) is the network performance loss toughness index during the restoration process of the road network, and \(\varphi(t)\) represents the performance of the road network. The performance before being damaged. When \(\varphi(t) = 0\), it means that the road network is completely damaged and ultimately not recovered. The value of \(R_v\) is \([0,1]\).

4. Model building

4.1. The basic assumptions
This article does not consider the changes in the characteristics of the road network at each recovery stage, as well as the changes in user selection behavior and traffic flow. The model construction in this
article is based on the following basic assumptions: ① After a certain section of the road network is damaged, its performance will be affected, but it will not affect each other with other sections, and the performance of other undamaged sections will remain unchanged. ② After a disaster or accident, the performance of the road network dropped sharply to the lowest point, and then began to gradually recover under the restoration measures, and the performance gradually increased. ③ The recovery time of the damaged section is proportional to the length of the section and the degree of damage. ④ Before the damaged section is repaired, its damage degree remains unchanged at the initial damage degree. When the repair task is completed, the damage degree of the damaged section immediately becomes 0, and the performance of the damaged section is immediately restored to the state before damage. ⑤ Each engineering repair team must completely repair a damaged section before proceeding to repair the next section. Each damaged section can only be repaired by one engineering repair team.

4.2. Optimization model of resilience recovery strategy of highway network after disaster

Based on the previous analysis of the characteristics and resilience of the highway network, a nonlinear programming model was established to optimize the resilience recovery strategy of the post-disaster highway network. The objective function is to maximize the resilience index of the recovery speed and the performance loss resilience index of the road network, and the 0-1 decision variable \( x_{b,n} \) indicates whether the \( n \)-th engineering repair team is going to repair the damaged section \( b \). The specific content of the model is as follows:

\[
\max R_r = \begin{cases} 
1 - \frac{D_X}{D_{max}}, & D_X \leq D_{max} \\
0, & D_X > D_{max}
\end{cases}
\]

\[
\max R_v = 1 - \frac{\sum_{k=1}^{K} (\varphi(t_0) - \varphi(t_k))}{D_{max} \times \varphi(t_0)}
\]

s.t.

\[
\sum_{b \in B} \sum_{n \in N_{max}} d_b \times x_{b,n} \leq D_{max}
\]

\[
\sum_{b \in B} \sum_{n \in N_{max}} c_b \times x_{b,n} \leq P_{max}
\]

\[
\sum_{b \in B} \sum_{n \in N_{max}} v_b^{t_e} \times x_{b,n} \leq N_{max}
\]

\[
\frac{\sum_{b \in B} \sum_{n \in N_{max}} v_b^{t_e} \times x_{b,n}}{D_{max} \times \varphi(t_0)} \geq \rho
\]

\[
x_{b,n_1} \times x_{b,n_2} \leq 0, \ n_1 \neq n_2, \forall n_1, n_2 \in N_{max}, b \in B
\]

\[
x_{b,n_1} \in \{0,1\}, b \in B, n \in N_{max}
\]

\[
d_b = m \times v_b^{t_e} \times l_b, b \in B
\]

\[
c_b = f_b + u \times d_b, b \in B
\]

The objective function (1), (2) represents the maximum resilience index, the network performance recovery speed measurement, and the cumulative loss measurement of network performance; the constraint condition (3) ensures that the repair team repairs the damaged section of the road within the maximum acceptable repair time; constraint condition (4) Ensure that the total engineering cost of repairing damaged road sections cannot exceed the maximum budget; constraint condition (5) ensure that the number of damaged edges that can be restored at the same time cannot exceed the number of engineering teams; constraint condition (6) ensure that the network performance recovery goal is restored to Not less than \( \rho \) times the network performance before the disaster. Constraint (7) ensures that each engineering team cannot repair the same damaged section at the same time.

5. Key algorithm step description

This paper uses Genetic Algorithm (GA) to solve the model.

(1) Coding method
This paper adopts the vector encoding method in the GA algorithm of parallel machine scheduling problem to encode the repair timing of all damaged road sections, and each chromosome is expressed as:

\[ Ch = [g_1, g_2, \ldots, g_{|B|}] = [b_1, b_2, \ldots, b_{|B|}] \]

\[ \text{for } i = 1, 2, \ldots, |B| \]

where \( b_i \) is the number of the damaged road section, and \( k_i \) is the number of the engineering repair team responsible for repairing the damaged road section \( b_i \).

(2) Initial population generation method

① Randomly arrange all sections of \( B \) in the damaged section set, and get \([b_1, b_2, \ldots, b_{|B|}]\) as the first row of the chromosome; ② Randomly select the engineering repair team \( k_i \) to repair the damaged section \( b_i \), and get \([k_1, k_2, \ldots, k_{|B|}]\) is the second row of the chromosome.

(3) The start and end time of the repair of the damaged section corresponding to the chromosome

① Decode the chromosomes to obtain the maintenance sequence of all damaged road sections, that is, assign the engineering emergency repair team to the engineering emergency repair team for repair based on genes, and assign the engineering emergency repair team to the same engineering emergency repair team according to their arrangement in the chromosome. The positions are repaired from left to right. ② From the decoding result, the \( w \)-th damaged road section repaired by the \( u \)-th engineering repair team is recorded as \( x_{b_u,w} \).

\[ \text{Repair start time: } x_{b_u,w} = \begin{cases} t_s, & w = 1 \\ t_s + \sum_{i=1}^{w-1} d_{b_u,i}, & w > 1 \end{cases} \]

\[ \text{Repair completion time: } x_{b_u,w} + d_{b_u,w} = t_s + \sum_{i=1}^{w} d_{b_u,i} \]

6. Experimental design and result analysis

6.1. Experimental design

Figure 2 is a general undirected network topology diagram representing a road network in a certain area, which contains 64 road sections and 33 nodes. Assuming that a natural disaster or accident causes 30 road sections of the road network to fail, the damaged road section is represented by a dashed line in the road network diagram. Each road section is numbered. The end point, length of the road section connection, the damaged section, the degree of damage and the fixed cost of restoration are shown in Table 1 and Table 2. The other parameters in the model established in this paper are set as follows: \( t_s = 30, P_{max} = 4000 \) unit funds, \( N_{max} = 4, D_{max} = 250 \) days, \( m=5, u=3, \rho=0.7 \).

Figure 2. Schematic diagram of road network
Table 1. Section number and section length

| Number | Endpoint | Length | Number | Endpoint | Length |
|--------|----------|--------|--------|----------|--------|
| 1      | 1,2      | 1.74   | 33     | 15,17    | 6.52   |
| 2      | 1,3      | 4.37   | 34     | 15,18    | 3.91   |
| 3      | 1,5      | 6.15   | 35     | 16,1     | 9.10   |
| 4      | 1,6      | 1.96   | 36     | 16,17    | 4.10   |
| 5      | 2,3      | 2.80   | 37     | 17,18    | 8.40   |
| 6      | 3,4      | 10.56  | 38     | 17,29    | 4.75   |
| 7      | 3,5      | 5.24   | 39     | 18,19    | 8.02   |
| 8      | 4,7      | 6.37   | 40     | 18,29    | 5.02   |
| 9      | 4,9      | 15.75  | 41     | 19,20    | 4.75   |
| 10     | 4,12     | 15.14  | 42     | 19,28    | 8.88   |
| 11     | 5,6      | 3.22   | 43     | 20,21    | 2.81   |
| 12     | 5,9      | 18.35  | 44     | 20,27    | 8.47   |
| 13     | 5,12     | 10.72  | 45     | 21,22    | 3.43   |
| 14     | 6,15     | 8.33   | 46     | 21,26    | 3.24   |
| 15     | 6,16     | 7.33   | 47     | 22,23    | 5.33   |
| 16     | 7,8      | 6.02   | 48     | 22,25    | 6.55   |
| 17     | 8,9      | 5.01   | 49     | 22,26    | 5.18   |
| 18     | 9,10     | 5.81   | 50     | 23,24    | 3.62   |
| 19     | 9,12     | 6.21   | 51     | 23,25    | 4.42   |
| 20     | 9,22     | 5.51   | 52     | 24,8     | 3.69   |
| 21     | 10,11    | 0.54   | 53     | 25,26    | 4.49   |
| 22     | 10,13    | 1.26   | 54     | 25,33    | 3.25   |
| 23     | 10,21    | 1.20   | 55     | 26,27    | 8.52   |
| 24     | 11,12    | 2.09   | 56     | 26,12    | 5.18   |
| 25     | 12,13    | 3.88   | 57     | 27,28    | 5.30   |
| 26     | 12,14    | 6.21   | 58     | 27,30    | 5.61   |
| 27     | 13,14    | 2.11   | 59     | 27,31    | 5.44   |
| 28     | 13,15    | 2.40   | 60     | 28,29    | 2.15   |
| 29     | 14,5     | 11.99  | 61     | 28,30    | 9.33   |
| 30     | 14,15    | 10.89  | 62     | 30,31    | 9.56   |
| 31     | 14,19    | 3.47   | 63     | 31,32    | 4.95   |
| 32     | 15,16    | 5.44   | 64     | 32,33    | 5.02   |

Table 2. Damage degree of damaged road section and fixed cost of repair

| Number | Damage | Cost |
|--------|--------|------|
| 9      | 0.5    | 170  |
| 10     | 0.5    | 170  |
| 12     | 0.5    | 190  |
| 13     | 0.5    | 150  |
| 17     | 0.5    | 140  |
| 18     | 1      | 120  |
| 19     | 1      | 90   |
| 20     | 1      | 130  |
| 21     | 1      | 80   |
| 22     | 1      | 110  |

6.2. Analysis of results

This article uses MATLAB R2016a to program the model and algorithm. The value of the algorithm is set as: population size=200; number of iterations=150, crossover probability=0.6, bit mutation probability=0.05, exchange mutation probability=0.05. In the case of the set value, it is stipulated that within 250 days and the total budget is 4000 units of funds, a maximum of 4 engineering repair teams
shall be arranged to repair the road network, and the performance of the repaired road network shall be at least the initial road network. 70% of net performance. The final road network repair work schedule is shown in Table 3, and the resilience measurement index is shown in Table 4.

Table 3. Optimal recovery strategy for road network

| Engineering team number | Repair section | Repair time/day | Total funds spent |
|-------------------------|----------------|-----------------|------------------|
| 1                       | 17, 20, 27, 22, 27 | 86              |                  |
| 2                       | 24, 28, 43, 47, 18 | 85              | 2786             |
| 3                       | 21, 25, 49, 53, 56 | 83              |                  |
| 4                       | 23, 31, 41, 45, 46 | 81              |                  |

Table 4. Resilience index results

|                    | $R_p$ | $R_v$ | Total budget utilization | Total repair time/day |
|--------------------|-------|-------|--------------------------|-----------------------|
| result             | 0.656 | 0.9172 | 69.65%                   | 86                    |

From the results obtained, it can be known that when the four engineering repair teams carry out road network repair work, it takes a total of 86 days, which is shorter and the repair work speed is faster. The performance loss of the network is small, the performance of the road network is restored to a high degree, and the total cost of the repair project is also well controlled. Therefore, such a post-disaster road network restoration strategy is relatively excellent and in line with reality.

7. Concluding remarks

In this paper, the performance recovery strategy of the highway network after the disaster is optimized based on the toughness measurement index. The core idea is to optimize the toughness of the highway network as the goal, and obtain the best post-disaster recovery project arrangement strategy of the highway network through the genetic algorithm, which improves in many aspects and conforms to the reality. However, based on the hypothesis in this paper, optimization analysis can be carried out in a more in-depth way. For example, due to the different characteristics of each stage of recovery, the recovery target may be different, or the user's behavior choice and traffic flow in the road network can be included in the analysis. Therefore, there are still a lot of research work to be carried out and perfected in the future.

References

[1] FATURECHI R, MILLER-HOOKS E. Measuring the performance of transportation infrastructure systems in disasters: a comprehensive review [J]. Journal of Infrastructure Systems, 2015, 21(1): 1-15.
[2] ZHOU Y M, WANG J W, YANG H. Resilience of transportation systems: concepts and comprehensive review [J]. IEEE Transactions on Intelligent Transportation Systems, 2019, 20(12): 4262-4276.
[3] PATRIARCA R, BERGSTRÖM J, GRAVIO G D, et al. Resilience engineering: current status of the research and future challenges [J]. Safety Science, 2018, 102(2): 79-100.
[4] Ouyang, M., Dueñas-Osorio, L., Min, X., 2012. A three-stage resilience analysis framework for urban infrastructure systems. Struct. Saf. 36–37, 23–31.
[5] MORSHEDLOU N, GONZ LEZ A D, BARKER K. Work Crew Routing Problem for Infrastructure Network Restoration [J]. Transportation Research Part B: Methodological, 2018, 118(12): 66-89.
[6] ZHANG W, WANG N. Resilience-based Risk Mitigation for Road Networks [J]. Structural Safety, 2016, 62(9): 57-65.
[7] NOGAL M, O’CONNOR A, CAULFIELD B, et al. Resilience of traffic networks: from perturbation to recovery via a dynamic restricted equilibrium model [J]. Reliability Engineering and System Safety, 2016, 156(1): 84-96.