

Analysis and Evaluation Research on Road Damage of Post-Earthquake Using Generalized Information Diffusion Model

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ABSTRACT: Timely and effective estimation of road damage degree can provide scientific and reasonable support for emergency rescue. In this paper, we shall first briefly introduced a generalized information diffusion model to evaluate the damage degree of roads. Since the road earthquake loss system is influenced by many factors, which has some characters such as smaller and random sample size, the excessive features and nonlinear, etc. Based on it, several measured indicators of road damage were selected as key impacting indicators to estimate the failure grade, including the damage degree of road and bridge x_1 , damage degree of subgrade and pavement x_2 and damage degree of roadside environment destruction on road x_3 . Moreover, the fuzzy diffusion and interpolation mapping for sparse data points has been defined by the fuzzy mapping theory. Next, the heterogeneous information diffusion from limited data point information to its adjacent area points was implemented. In this procedure, the fuzzy approximate reasoning and information centralization of road rupture width are also has been estimated. The numerical results show that the Generalized Information Diffusion (GID) model can reasonably approximate and extend effective information for incomplete data samples, which also can be applied to treat the nonlinear relationship between road damage degree of post-earthquake. Finally, an example is given to illustrate the effectiveness and feasibility of the method.

KEYWORD: Road Damage, Generalized Information Diffusion (GID) Model, Asymmetric Model, Post-Earthquake Loss

1 INTRODUCTION

Road system is an important part of urban lifeline system, which directly affects the transportation capacity of urban road system for post-earthquake. When an earthquake take place, road system often cause different degrees of damage, which can seriously affected the efficiency of emergency response to earthquake disaster relief. In recent years, many big natural disasters have been accrued in China, such as M_s 8.0 WenChuan earthquake, more than 200 main roads and 6000 bridges were damaged in the disaster area [1]. The destruction to bridges and main roads such as provincial road S318 and county road Z210 were more seriously damaged in M_s 7.0Ya'an earthquake. Similarly, the Jiuzhaigou M_s 7.0 earthquake has also caused massive damage of provincial road S301 and county road Z120 in the hardest hit areas, thus, the damage point distribution map of road in M_s 7.0 Jiuzhaigou earthquake can be shown in Fig.1. The figure shows 110 obvious damages in the study area, among them, more than 32 obvious damages points in provincial road S301 and approximately 78 damages points in county road Z120 [2, 3, 4], which brought great difficulties for emergency rescue and post-earthquake reconstruction. It can enable decision-makers to allocate various transportation resources rationally and formulate

effective disaster relief plans through evaluating quickly and accurately the damage degree of road system in disaster area. Therefore, it is significant to evaluate scientifically and rationally the damage degree of road system for relief and reconstruction efforts after strike.

At present, it has made great important progress in related fields of road damage for post-earthquake. Many scholars have conducted the related research theoretically, and draw lots of valuable conclusions and theories. For instance, Zhao provided the fuzzy comprehensive evaluation method to predict road damage caused by earthquake, combing with earthquake-resistant requirements for road systems [5]. Liu proposed a road damage assessment model based on fuzzy neural network, furthermore, the functions of model are also verified and analyzed in his research study [6]. Additionally, more than 1400 survey data caused by earthquake to the roadbeds in WenChuan earthquake were collected and analyzed statistically by Liao [7]. Wang established a practical algorithm of seismic risk index for lifeline engineering based on attribute hierarchy model and mathematical statistics method, so as to explain the mechanism of road damage and coupling model analysis from a fresh perspective[8]. Similarly, A spatial decision support system for road network seismic based on model base as the drive core is established by Jia [9]. Different from above research-

es, Ma built an assessment model of road connectivity effectiveness for post-earthquake in view of indicator-network efficiency in the complex network theory. The above research is of important engineering value to earthquake prevention for lifeline system [10].

Throughout the earthquake assessment theory of existing research results, however, it can be easily noticed that many related researches are confined to the authoritative data collection and reasonable weight coefficient allocation and originality of evaluation models. Previous models rarely consider incomplete characteristics of data samples in the actual assessment process. Following the outcome, considering the possible of complex structures and significant differences between data samples. In addition, there may be some asymmetric structures or rules among the incomplete samples. This paper has carried on the discussion to the evaluation method for road damage of post-earthquake based on generalized information diffusion theory [11, 12, 13, 14], which can improve the prediction precision for the case of the above and is of great value for engineering applications.

2 THE EVALUATION FACTORS AGGREGATION AND DATA PREPARATION

2.1 Selection and quantification of evaluation factors aggregation traditional information diffusion model

According to actual engineering experience combined with the existing data, the road system damage for post-earthquake is huge and complex system and it is affected by many factors, which should be described by multiple states. Additionally, Considering the complex nonlinear relationship between the road damage of post-earthquake and influencing factors [5]. This article selected the road damage factors to discuss the destructive seismic situation on road: the damage degree of road and bridge x_1 , damage degree of subgrade and pavement x_2 and damage degree of roadside environment destruction on road x_3 (Full disclosure: It is more difficult to rush repair the tunnel in a short time after a major disaster. Therefore, the damage of the tunnel is neglected in the evaluation process, or rather, we integrate the tunnel damage into the above damage form). The three evaluating factors of road damage degree are all taken as the evaluation indexes according to the estimated rush repair time, and the values of each index are normalized to a number within an interval [0,1]. When the score is 0, it means no damage occurred during the evaluating process, conversely, it means that the failure is not recoverable when the score is 1. In practical evaluating process, the earth-

quake damage situation, emergency repair personnel and mechanical equipment conditions are firstly investigated by a certain number of technicians. Moreover, the rush repair time is completed to estimate the value of each indexes with any of perforated factors [6]. Therefore, the grading standard of damage degree evaluation can be gained as shown in table 1.

2.2 Data preparation

Forasmuch as the survey results of road damage after multiple earthquake disasters and the standard theoretical samples generated by computer automatic assignment. We selected 20 group experimental data as information diffusion samples. The score values of each indexes are given by experts as input data, which can be shown in table 2 [6]. The information diffusion theory is developed on the basis of traditional fuzzy mathematics. Sample data are incomplete for the parent population when the given sample cannot understand fully and accurately the probability density function of the matrix, therefore, in order to find out the probability distribution of data index, we draw the lognormal map of the data sample in the 95% confidence interval and the matrix diagram of the three indexes, which is shown in Fig.2. Thus, it can be concluded from there plots that some indexes have small differences in data partition such as x_1 (Fig.2-a), however, x_3 is the opposite (Fig.2-c). Besides, due to the small samples lead to spurious results, theoretically this understanding of parent population is not exact only with regard to the distribution of data, which could improve effectively the accuracy of GID model without increasing the other sample points. As each incomplete sample represents a collection of uncertain samples, it only provides a crumb of information on its observations. Therefore, the information contained in each incomplete sample point is generally fuzzy information. because the boundary of collection is not clear, fuzzy and flexible [15, 16, 17]. The transitivity of incomplete samples lends itself to special fuzzy uncertainty properties, which has a certain influence area at the sample points.

3 GENERALIZED INFORMATION DIFFUSION THEORY

The GID model is developed on the basis of traditional fuzzy mathematics. Suppose $\omega = \{\omega_i\}$ is evaluation index sample aggregate of model, among them, L and I_j are universe of discourse and test point of universe, respectively. Therefore, a particular distribution function $\mu(x)$ may yet exist when the sample ω to be evaluated belong to incomplete infor-

mation, thus, it is possible to spread the information with a value of 1 on the sample ω_i to the test point l_j in view of the particular distribution function $\mu(x)$. The information distribution Q obtained after dispersion can better reflect its distribution in universe of discourse L .

$$Q(l_j) = \sum_{i=1}^n \mu(x) = \sum_{i=1}^n \mu[\varphi\{\omega_i - l_j\}] \quad (1)$$

Therefore, aiming at a small sample event under incomplete information condition, we can get more information of internal correlation contained in small sample through a particular diffusion function $\mu(x)$ when the basic principle of information diffusion is adopted. In another word, the core of the information diffusion model is how to find an effective diffusion function conforming to the sample characteristics.

3.1 Standard normal information diffusion model

On the basis of molecular diffusion theory and mathematical method, the diffusion information obtained at a distance x from the point at which the injection point of the sample can be described as

$$\mu(x) = \frac{1}{h\sqrt{2\pi}} \exp\left(-\frac{x^2}{2h^2}\right) \quad (2)$$

It can be seen that the spread function determined by formula (2) is exactly the same as the density function of normal distribution in mathematical statistics. Thus, we could get two-dimension standard spread function through simplification and expansion.

$$q = \frac{1}{2\pi h_x h_y} \exp\left(-\frac{x^2}{2h_x^2} - \frac{y^2}{2h_y^2}\right) \quad (3)$$

While: the diffusion coefficient h_x and h_y can be determined by the maximum value b , minimum value a and the number of sample points n [14].

$$h = \begin{cases} 0.8146(b-a), n=5 \\ 0.5690(b-a), n=6 \\ 0.4560(b-a), n=7 \\ 0.3860(b-a), n=8 \\ 0.3362(b-a), n=9 \\ 0.2986(b-a), n=10 \\ 2.6851(b-a)/(n-1), n \geq 11 \end{cases} \quad (4)$$

Let be $x' = \frac{x}{\sqrt{2}h_x}$, $y' = \frac{y}{\sqrt{2}h_y}$, that is: the influence of dimension and unit will be eliminated in the procedure. Eq.(3) can be transformed into:

$$q = \frac{1}{2\pi h_x h_y} \exp(-(x'^2 + y'^2)) \quad (5)$$

Thus, the multi-dimensional normal diffusion function can be expanded as follows:

$$q = \frac{1}{(2\pi)^{\frac{m+1}{2}} h_y \prod_{i=1}^m h_{x_i}} \exp\left[-\left(\sum_{i=1}^m x_i'^2 + y_i'^2\right)\right] \quad (6)$$

It can be seen that the index part is a circle equation from Eq.(6). That is, the information on each sample point will spread evenly in all directions. Therefore, it is also known as "Circular symmetry" homogeneous information diffusion.

3.2 Generalized information diffusion model

The standard normal information diffusion function reflects a kind of homogeneous diffusion process, which is an ideal model of actual data structure. In practice, due to the complex structures and significant differences among data samples, a certain asymmetric structure or rule may exist for the elements of incomplete sample, such as irregular proportional relation among each variable, namely the dependent variable increases linearly with the independent variable [18, 19, 20]. As for these incomplete samples, diffusion velocity and diffusion way in different directions should need to be considered in information diffusion(Fig.3). Thereby, in order to describe and depict objectively and reasonably generalized non-normal and non-uniform data structures in actual sample data, we ought to consider the non-uniform generalized information diffusion model which is more approximate to reality [12].

Based on this point, the "Circular symmetry" homogeneous information diffusion can be extended to more generalized "Elliptical type" asymmetric diffusion function (Fig.3). That is, the direction of rapid propagation corresponds to the long axis of the ellipse, however, the slow direction corresponds to the short axis of the ellipse. Thereby, the "elliptical" two-dimensional generalized information diffusion function can be obtained as follows:

$$q = \frac{1}{2\pi h_x h_y} \exp\left\{-\frac{1}{1+k^2} \left[\frac{1}{\lambda} \left(\frac{x}{\sqrt{2}h_x} + k \frac{y}{\sqrt{2}h_y} \right)^2 + \left(k \frac{x}{\sqrt{2}h_x} - \frac{y}{\sqrt{2}h_y} \right)^2 \right]\right\} \quad (7)$$

Where: k is rotary coefficient, it can be defined as the slope of the long axis of ellipse, λ is expansion coefficient, which has been defined as the square of ratio between long axis with short axis of ellipse, x , y are spatial coordinate variables, m is space dimension, $h = 1.4208 / (n - 1)$.

3.3 Calculation method of rotary coefficient k and expansion coefficient λ

As for two-dimensional "Elliptical type" generalized information diffusion function, rotary coefficient k is

related to the distribution of sample data in the plane x_0y which of the fastest spreading along ellipse axis. Thereby, the possibility of distribution for sample point along its long axis direction is relatively large. It can be considered that the square of the distance from each sample point (x_i, y_i) to the straight line $y = kx + b_0$ is probably minima [13], thus

$$\min Q = \sum_{i=1}^n d_i^2 = \sum_{i=1}^n \frac{(kx_i + b_0 - y_i)^2}{1 + k^2} \quad (8)$$

The parameters k and b_0 in Eq. (8) can be derived as the following formula.

$$\begin{cases} \frac{dQ}{db_0} = \sum_{i=1}^n \frac{2(kx_i + b_0 - y_i)}{1 + k^2} \\ \frac{dQ}{dk} = \sum_{i=1}^n \frac{[2(kx_i + b_0 - y_i)(1 + k^2) - 2k(kx_i + b_0 - y_i)^2]}{(1 + k^2)^2} \end{cases} \quad (9)$$

Next, let be the derivative function in above formula is equal to zero, that is:

$$\begin{cases} b_0 = \frac{1}{n} (\sum_{i=1}^n y_i - \sum_{i=1}^n x_i) \\ k = \frac{-\sum_{i=1}^n (x_i - y_i) \pm \sqrt{(\sum_{i=1}^n (x_i - y_i))^2 + 4 \sum_{i=1}^n x_i y_i}}{2 \sum_{i=1}^n x_i y_i} \end{cases} \quad (10)$$

Where: $\tilde{x}_i = x_i - \sum x_i / n$, $\tilde{y}_i = y_i - \sum y_i / n$, the two values of k are the slopes of lines a and b in Fig. 3, respectively.

In addition, from theoretical point of view, two methods can be used to determine the expansion coefficient λ :

1. It is calculated by intelligent optimization theory (such as genetic algorithm).
2. It can be expressed in this form: The square root of the ratio between the average distance from the sample point to the stub axis and the average value of the long axis [21, 22, 23, 24].

3.4 GID model—Multi-dimensional "Elliptical" asymmetric diffusion model

Based on the above analysis, the multi-dimensional "Circular symmetry" uniform diffusion function in Eq.(6) can be extended to the "Elliptic" non-uniform diffusion function by introducing expansion coefficient λ_i .

$$q = \frac{1}{(2\pi)^{\frac{m+1}{2}} h_y \prod_{i=1}^m h_{x_i}} \exp \left[- \left(\sum_{i=1}^m \frac{x_i'^2}{\lambda_i} + y_i'^2 \right) \right] \quad (11)$$

Therefore, the GID model can be obtained by which the exponential term $-\left(\sum_{i=1}^m \frac{x_i'^2}{\lambda_i} + y_i'^2\right)$ counter-clockwise rotate at a certain angle θ_i along the plane $x_i'0y$ in turn. The proposed model also can be constructed in this way [11, 12, 13].

$$q = \frac{1}{(2\pi)^{\frac{m+1}{2}} h_y \prod_{i=1}^m h_{x_i}} \exp \quad (12)$$

$$\left[- \sum_{i=1}^m \frac{1}{\lambda_i} [x_i' \cos \theta_i - \sum_{j=i+1}^m (x_j' \sin \theta_j \sin \theta_i \prod_{k=i+1}^{j-1} \cos \theta_k) + y' \sin \theta_i \prod_{j=i+1}^m \cos \theta_j - \dots \dots - [- \sum_{i=1}^m (x_i' \sin \theta_i \prod_{j=1}^{i-1} \cos \theta_j) + y' \prod_{i=1}^m \cos \theta_i]^2 \right]$$

While: $x_i' = \frac{x_i}{\sqrt{2}h_{x_i}}$, $y' = \frac{y}{\sqrt{2}h_y}$, $\cos \theta_i = \frac{1}{\sqrt{1+k_i^2}}$,
 $\sin \theta_i = \frac{k_i}{\sqrt{1+k_i^2}}$.

4 MODEL CONSTRUCTION AND ANALYSIS

In view of the above generalized information diffusion principles and methods, the finite incomplete sample data can be diffusion modeled through the proposed model by which takes x_1, x_2 and x_3 as input variables, while regard road damage degree y as output variables. Thus, an information matrix approaching the actual information distribution is obtained. Moreover, we have established an input output mapping model to estimate the road damage degree of post-earthquake.

4.1 Establishing asymmetric information diffusion function between the road damage degree for post- earthquake with influence factors

For demonstration purposes, the fuzzy relation matrix between x_1, x_2 and x_3 with y is established in turn by using two-dimensional generalized information diffusion function. Therefore, The sample S of road damage degree for post-earthquake can be identified as $S = \{x_{11}, x_{21}, x_{31}, y_1; x_{12}, x_{22}, x_{32}, y_2; \dots; x_{1n}, x_{2n}, x_{3n}, y_n\}$, the three variable fields are respectively.

$$\begin{aligned} \mu_{x_1} &= \{0.05, 0.22, 0.39, 0.56, 0.73, 0.90\}, \\ \mu_{x_2} &= \{0.05, 0.22, 0.39, 0.56, 0.73, 0.90\}, \\ \mu_{x_3} &= \{0.05, 0.18, 0.31, 0.44, 0.57, 0.70\}, \quad \mu_y = \{1, 2, 3, 4, 5\}. \end{aligned}$$

Suppose $x_1 = x_{1i} - \mu_{x_{1j}}$, $x_2 = x_{2i} - \mu_{x_{2j}}$, $x_3 = x_{3i} - \mu_{x_{3j}}$, $y = y_i - \mu_{y_0}$, then substitute it into three-dimensional asymmetric information diffusion function.

$$q(i, j, o) = \frac{1}{2\pi h_x h_y} \exp \left\{ -\frac{1}{1+k^2} \left[\frac{1}{\lambda} \left(\frac{x}{\sqrt{2}h_x} + k \frac{y}{\sqrt{2}h_y} \right)^2 + k \left(\frac{x}{\sqrt{2}h_x} - \frac{y}{\sqrt{2}h_y} \right)^2 \right] \right\} \quad (13)$$

Subsequently, the primary information matrix $Q = \{Q_{j,o}\}_{6 \times 5}$ can be obtained by Eq.(13), moreover, the fuzzy relation matrix $R = \{r_{j,o}\}_{6 \times 5}$ also can be generated by the primary information matrix Q , among them.

$$r_{j,o} = \frac{Q_{j,o}}{s_o} \quad (14)$$

$$Q_{j,o} = \sum_{i=1}^{j=20} q(i, j, o) \quad (15)$$

$$s_o = \max_{1 \leq j \leq 6} \{Q_{j,o}\} \quad (16)$$

Through the analyses above, the initial information distribution matrix $R_{x_1,y}$, $R_{x_2,y}$, and $R_{x_3,y}$ also can be calculated as bellow respectively.

4.2 Fuzzy approximate reasoning and information concentration

In this paper, linear information distribution is used to evaluate the influencing factors. The following formula is used for calculating μA_i [13].

1. When $a \leq \mu a_{\min}, \mu a_{\min} \in \mu A_i$, then $\mu A_i = [1, 0, \dots, 0]$,
2. When $a \geq \mu a_{\max}, \mu a_{\max} \in \mu A_i$, then $\mu A_i = [0, 0, \dots, 1]$,
3. When $\mu a_{\min} \leq a \leq \mu a_{\max}$, then $\mu A_i = \left[\max\left(0, 1 - \frac{|a - \mu a_i|}{\Delta}\right) \right]$.

While: Δ is step size.

In the process of model conformation, the probability distribution of fuzzy approximate inference level for influencing factors can be evaluated by approximate inference formula.

$$\mu B_i = \mu A_i \times R_{x_i,y} \quad (17)$$

The above formula is first-degree fuzzy approximate inference process, which can be given differences between the influence degree of each factors and road damage degree for post-earthquake, therefore, the second-degree fuzzy approximate inference should be taken into account on the basis of considering all the factors.

The result of second-degree fuzzy approximate inference is obtained through the combination of weight array $\omega_{1 \times 3}$ and fuzzy matrix U [5, 6]. At first the

matrix $U_{3 \times 5}$ is derived from the μB_i which composed from the first-degree deduction, besides, as the second-degree deduction, fuzzy relation matrix also can be calculated according to the following formula.

$$\mu = \omega \times U \quad (18)$$

Thus, the information concentration for road damage of post-earthquake after defuzzification can be expressed as bellow:

$$y_1 = \frac{\sum_{o=1}^5 \mu y_o \mu^2}{\sum_{o=1}^5 \mu^2} \quad (19)$$

While during the modelling process of generalized information diffusion model, we created a mapping from the several measured indicators such as the damage degree of road and bridge x_1 , damage degree of subgrade and pavement x_2 and damage degree of roadside environment destruction on road x_3 to road damage degree for post-earthquake y . Hence, the evaluation model for road damage degree of post-earthquake based on proposed model is established.

5 ACTUAL CALCULATION AND ANALYSIS

5.1 Data processing analysis

In view of the above theoretical analysis and model modelling, considering the statistical analysis rule of data in Table 1, in this paper, the next solves sample index weighting and simulates random course of random event using fuzzy information spread technique, therefore, based on a detailed study in the nature of big samples in normal information spread estimation, the above samples are evaluated by the proposed model, moreover, the evaluation results and the matrix diagrams for two evaluation methods are shown in Table 6 and Fig.4 respectively, it can be seen that the sample data with an asterisk* are incorrect objects. From the results of two different evaluating methods, we can easily discover that the general evaluated results are basically identical, furthermore, the prediction rate of the proposed model is higher than that of the fuzzy comprehensive evaluation method. However, It needs to be pointed out that the two evaluation models did not predict correctly the actual classification of sample 2. though, the predicted and measured values of the two models are in touching distance, which can be seen that the superiority of the proposed model in predicting incomplete sample data.

5.2 Validation analysis of road section in Wen-Chuan earthquake

The national highway 316 after WenChuan earthquake is the first highway to be repaired in the process of seismic, which has played a very important role in the process of earthquake relief work. The specific destruction of national highway 316 for post-earthquake as follows: There were 2 landslides in Liuba Road, which are 700 cubic meters and 600 cubic meters respectively, and 4 bridges and slopes are threatened. Moreover, there are more than 10 landslides and nearly 2000 cubic meters of rock fall in the section of Hantai road section. As a matter of fact there are different degrees of cracks in Hongqiao bridge in Shimen reservoir area. Additionally, the concrete is cracking on some of the highway structures and bridges along Chenggu and Xixiang roads section. Finally, we investigated the earthquake situation of Baohe reservoir area in which the earthquake caused more than 30 slopes to reach 380 cubic meters [5, 6]. Moreover, Two hills collapse along the Baohe reservoir area reach to 150 cubic meters, which can be seen that the strong earthquake damage has caused serious damage to the urban road system. In order to verify the validity and practicability of the GID model, the several evaluation models such as FNN method and traditional information diffusion model were selected to verify and analysis the usefulness and accuracy of the model, these situations prove clearly that the general evaluated results are basically identical. Therefore, the results show that the model is effective and reasonable.

6 CONCLUSIONS

1. As for the information diffusion method has strong ability to process small sample data, it is unable to get enough measured or experimental data when a short period of time for post-earthquake. Therefore, the accuracy and damage level of road damage for post-earthquake can be estimated by the information diffusion method.
2. In this dissertation, the proposed model can avoid the complex computation of membership functions and depict more generalized structural features for original data samples, compared with FNN method and traditional information diffusion model, the model also can extract and expand the structural information of the data objectively and reasonably from incomplete sample data, which can better deal with nonlinear and local minimum problems. Thereby, this study provides a new method for determining the road damage degree of post-earthquake, which pro-

vides a scientific basis for emergency rescue decision-making.

3. For the above mentioned models, the diffusion coefficient h determined by optimal window width method and entropy value method has certain influence on the calculation results. Similar rotation coefficient k and expansion coefficient λ are to be calculated fussy. Therefore, this study made the suggestion to solve the related parameters of generalized information diffusion model by intelligent optimization algorithm, which assume credibility of result of evaluation much more. However, the relevant research results will be discussed in related papers.

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