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SPA Model on Repair Priority for Earthquake-damaged Transport Infrastructures

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Abstract

Sequence is an important mission and performance in such repair decision-making operation for the earthquake-damaged transport infrastructures. Through introducing Set Pair Analysis ideology, the decision-making model was established for earthquake repair sequence of transport infrastructures. Then, the SPA comparing space was built, the association identity, contrary and difference degree parameters were calculated for repair projects, the relative SPA proximity was determined for each repair project, as well as the repair sequence was given. Meanwhile, the integration of Efficiency Coefficient method and Information Entropy to determine the index weights, improved the reliability of repair sequence. Finally, Case showed a typical evaluation index system and model application, which provided a scientific, simple and suitable method on the repair priority decision-making operation for the earthquake-damaged transport infrastructures.

Keywords*: repair, transport infrastructure, sequence, Set Pair Analysis (SPA), earthquake*

1. Introduction

Transport infrastructure is the foundation of the traffic system, whose earthquake damage directly affected the stability and reliable operation [1], and extended or zoomed out the earthquake risk [2], such as the Airport Runway [3], Harbor Infrastructure [4], and Highways [5]. Therefore, the urgent repair requirement to the fragmented transport infrastructures, is the important content and basic condition in earthquake emergency management and hazard mitigation measures [6].

Aiming at the characteristics of earthquake disaster, which was sudden, emergent, diversity, spatial and temporal coupling, and chain distribution [7], Reference [8] established the earthquake damage prediction model for mountainous urban transport system, and this paper [9] demonstrated the earthquake reliability analysis of transport system, which showed that the transport infrastructure repair under earthquake action was a typical complex, fuzzy, timely and risky system engineering.

Under the actual heavy situation of restoration and reconstruction task, much project is limited to the resources or time constraints in earthquake emergency, so a project management system and a management model [10] would be the principle requirements and trends, which could ensure the reconstruction progress and maximize the performance of rescue emergency. Reference [11] established a two-stage fuzzy evaluation level from the value coefficient perspective, which determined the relative value coefficient among projects and repair sequence. Reference [12] proposed a decision-making model for emergency events, which was based on the earthquake cases and preparatory emergency plans. Earthquake is occasional, and case was lack, so this model was difficult to guide the repair decisions.

Set Pair Analysis model [13], evaluated the the repair decision-making structure for such transport infrastructure from the entire and part view, which tried to solve the various uncertainty and uncertain complex structure within the repair decision-making operation. It was significant for improving repair decision-making capacity of transport infrastructure after earthquake.

2. Set Pair Analysis Model for Engineering Projects Sequence

2.1. Foundation of Set Pair Analysis Model

SPA model was proposed by Chinese scholar in 1989 [13]. The core mathematical method of SPA is to dialectically analyze and deal with the certainty and uncertainty within the system structure. And, "Identity" and "Contrary" reflects the certainty, while "Difference" reflects the uncertainty condition.

In the context of specific issues, when Set A and Set B had some relations, SPA model combined Set A with Set B as one pair of $H = h(A, B)$, and H has n characteristics. Of all these characteristics, l number of characteristics are common namely identity, g number of characteristics are opposite, namely contrary, and s number of characteristics are neither opposite nor common. Here, s, g and l was defined as follows in Formula (1).

$$s + g + l = n \qquad (1)$$

Then, establish the identity, difference and contrary degree expressions under the background of the specific issue, as the following Formula (2), denoting the above common, opposite and other conditions.

$$f(\mu) = \frac{l}{n} + \frac{s}{n}\vec{\alpha} + \frac{g}{n}\vec{\beta} = a + b\vec{\alpha} + c\vec{\beta} \qquad (2)$$

Where, $f(\mu)$ denotes the specific index weight condition for such SPA decision-making operation. And, $a = l/n$ is the identity degree, $b = s/n$ is the different degree, $c = g/n$ is the contrary degree. $\vec{\alpha}$ is called Different Coefficient, $\vec{\alpha} \in [-1,1]$, and $\vec{\beta}$ is called Contrary Coefficient, defined $\vec{\beta} = -1$.

2.2. Decision-making Model about Project Sequence

Let Q as the decision-making problem about the repair sequence or priority on transport infrastructures after earthquake, which could be expressed formally as the following Equation (3).

$$Q ::= < E, C, \mu, D > \qquad (3)$$

Where, $E = \{E_i\}$ ($1 \le i \le m$) is the set of Transport Infrastructure Projects, $C = \{C_j\}$ ($1 \le j \le n$) is the index set of Repair Priority, the index weight is $\mu = (\mu_1, \mu_2, ..., \mu_n)$, $D = \{d_{ij}\}_{m \times n}$ is the Decision-making Matrix, and d_{ij} is the measurement of Project E_i according to Index C_j.

3. Index Weight Calculation for Repair Priority

3.1. Standardization of Decision-making Matrix for Repair Priority

There are two types in measuring index characteristics about project repair sequence. max type denoted the higher character of the index, the bigger coefficient in the repairing preference, while min type denoted the lower character of the index, the smaller coefficient in the repairing preference. Namely, max expressed the efficient characteristics of repairing projects, and min expressed the cost characteristics.

Standardize the decision-making matrix of the earthquake-damage repairing projects under transportation infrastructure through Efficiency Coefficient Method [14]. If the repair priority index C_j showed max type, x_{ij} denoted the standardized efficient coefficient of d_{ij}, as the expression in Formula (4).

$$x_{ij} = \frac{d_{ij} - d_{min(j)}}{d_{max(j)} - d_{min(j)}}\theta + \frac{d_{ij}}{d_{max(j)}}(1-\theta) \tag{4}$$

If the repair priority index C_j showed min type, x_{ij} denoted the standardized cost coefficient about such min type environment, as in Formula (5).

$$x_{ij} = \frac{d_{max(j)} - d_{ij}}{d_{max(j)} - d_{min(j)}}\theta + \frac{d_{max(j)}}{d_{ij}}(1-\theta) \tag{5}$$

Where, θ denoted the efficacy coefficient in the repair decision-making standardization, and $0 < \theta < 1$.

3.2. Index Entropy of Repair Priority

According to the decision-making matrix D of earthquake repair projects under transport infrastructure, set X as the standardized matrix. y_{ij} is supposed as the proportion of repairing project E_i on the index C_j, then y_{ij} could be got from the following Formula (6).

$$y_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij} \tag{6}$$

Based on the calculating method of Information Entropy [15], the $Shannon$ entropy of the repairing priority index C_j could be got from the following Formula (7).

$$\rho_j = Sh(C_j) = -\frac{1}{ln(m)}\sum_{i=1}^{m} y_{ij} ln(y_{ij}) \tag{7}$$

Here, ρ_j expressed the information entropy value of the repair priority index C_j. As the greater value of such index entropy, the meaning reflects the greater internal disorder degree in the repair priority system. When $y_{ij} = 0$ showed, set $y_{ij} = 0.00001$ to replace the real $y_{ij} = 0$.

Thus, μ_j denots the weight of the repair priority index C_j, and μ_j could be calculated from the following Formula (8).

$$\mu_j = (1-\rho_j)/(n-\sum_{j=1}^{n}\rho_j) \text{ , } \sum_{j=1}^{n}\mu_j = 1 \quad (8)$$

4. Comprehensive Relationship and Sequence on Engineering Projects

4.1. Interval Comparison of Engineering Projects

With the systems information in Set Pair Analysis model and the applications [16-17], E^+ is supposed to represent the best repairing project, E^- is the worst repairing project, and $E^+ = \{x_1^+, x_2^+, ..., x_n^+\}$, $E^- = \{x_1^-, x_2^-, ..., x_n^-\}$. Where, x_j^+ and x_j^- respectively expresses the maximum and the minimum value of index C_j.

As Earthquake Repair Project E_i according to Index C_j, the value of x_{ij} has the following feature. As $x_j^- \le x_{ij} \le x_j^+$, namely, $x_{ij} \in [x_j^-, x_j^+]$ forms the interval comparison. Meanwhile, $[E^-, E^+]$ formed the interval comparison of the earthquake-damage repairing project E about transport infrastructure.

4.2. Calculating SPA Parameters of Engineering Projects

Different from Intuitionistic Fuzzy Sets and application in ranking the earthquake emergency events [18], to identify the relationship parameters of such set pair as $\{x_{ij}, x_j^+\}$ in interval $[x_j^-, x_j^+]$ of index C_j , which was the chief prerequisite of earthquake repairing decision-making SPA $h(E_i, E^+)$ and its function $f(\mu_i)$ about transport infrastructure.

If $x_{ij} > 0$, then x_{ij}/x_j^+ denoted the procimity from x_{ij} to x_j^+ , x_{ij}/x_j^- said the procimity from x_{ij} to x_j^-. Set a_{ij} as the identity degree between x_{ij} and x_j^+ , namely positive expression, and c_{ij} was the negative expression. Then, the identity and contrary level degree is calculated for the above set pair of $\{x_{ij}, x_j^+\}$, as follows in Formula (9).

$$\begin{cases} a_{ij} = \dfrac{x_{ij}/x_j^+}{1+x_j^-/x_j^+} = \dfrac{x_{ij}}{x_j^- + x_j^+} \\ c_{ij} = \dfrac{x_j^-/x_{ij}}{1+x_j^-/x_j^+} = \dfrac{x_j^- x_j^+}{x_{ij}(x_j^- + x_j^+)} \end{cases} \quad (9)$$

According to SPA association, $a_{ij} + b_{ij} + c_{ij} = 1$, the different degree is calculated for the repair SPA $\{x_{ij}, x_j^+\}$ under earthquake-damaged transport infrastructure, namely b_{ij} in the following Equation (10).

$$b_{ij} = \frac{(x_j^+ - x_{ij})(x_{ij} - x_j^-)}{(x_j^+ + x_j^-)x_{ij}} \quad (10)$$

In the interval comparision $E_i \in [E^-, E^+]$, $a_i = \sum \mu_j a_{ij}$, $b_i = \sum \mu_j b_{ij}$ and $c_i = \sum \mu_j c_{ij}$ is applied into calculating the SPA association of $h(E_i, E^+)$, as the following Formula (11).

$$a_i = \sum_{j=1}^{n} \frac{\mu_j x_{ij}}{x_j^- + x_j^+}, \quad c_i = \sum_{j=1}^{n} \frac{\mu_j x_j^- x_j^+}{x_{ij}(x_j^- + x_j^+)}, \quad b_i = \sum_{j=1}^{n} \frac{\mu_j (x_j^+ - x_{ij})(x_{ij} - x_j^-)}{(x_j^+ + x_j^-) x_{ij}} \qquad (11)$$

Here, Formula (11) is to determine a_i, b_i and c_i of such repair SPA $f(\mu)$ for earthquake-damaged transport infrastructure. And, a_i denotes the identity degree, b_i denotes the difference degree, and c_i denotes the contrary degree about the status of E_i within the repair engineering projects of E for the earthquake-damaged transport infrastructure.

4.3. SPA Proximity and Repair Sequence Decision-making on Engineering Projects

The above parameter calculation about a_i, b_i and c_i in the repair SPA function for earthquake-damaged transport infrastructures, reflected the proximity measurement from the repair engineering E_i to the best project E^+.

Set p_i as the relative SPA proximity from the repair project E_i to the best project E^+, as follows in Formula (12).

$$p_i = a_i / (a_i + c_i) \qquad (12)$$

Thus, according to SPA model and steps, such as the application on the geological disaster risk for military engineering [19], the engineering projects about transport infrastructure could be sorted or scheduled by the value of p_i. In most cases, the engineering project with maximum value of p_i is the first task under the repair sequence decision-making operation.

5. Case Study in Simulation Environment

5.1. Decision-making Index System on Road Transport Infrastructures

The diversified characteristics in the repair sequence decision-making operations, leads to hardly establish a unified, standardized evaluation index system for such earthquake-damaged transport infrastructures; On the reference and basis of the road emergency repair events and risk preplans in part damaged region in Wenchuan earthquake, the proposed index system furtherly systemized, deepened and expanded the above connotation, forming the especial index system, as shown in Table 1, including No, Identification Code, Index Name and Abbreviation.

Table 1. Decision-making Index System on Earthquake-damaged Road Transport Infrastructure

No	Identification Code	Index Name	Abbreviation
1	C_1	Destructed Status of Engineering Geology	DS
2	C_2	Safety and Quality of Engineering Slope	SQ
3	C_3	Intensity of Traffic Volume Requirements	IT
4	C_4	Impacting Coefficient of Transportation System	IC
5	C_5	Coefficient of Life-saving Value	CL
6	C_6	Survival Coefficient of Population Protection	SC
7	C_7	Feasibility of Repair Schemes	FR
8	C_8	Satisfaction Degree of Repair Resources	SD
9	C_9	Orderly Degree of Disaster Control	OD
10	C_{10}	Timeliness of Repair Disposal	TR
11	C_{11}	Flexibility of Repair Disposal	FD
12	C_{12}	Risk of Repair Environment	RR
13	C_{13}	Feasibility of Emergency Replacement	FE

With the diversified characteristics and decision-making index system on earthquake-damaged road transport infrastructure, the road transport infrastructure was taken as study object, supposed there was need to repair damaged sections of earthquake area. Through experts' demonstration, hierarchical characteristics system was established for the repair priority decision-making about road transport infrastructure, as shown in Figure 1, with the composition of Object, Rules and Task.

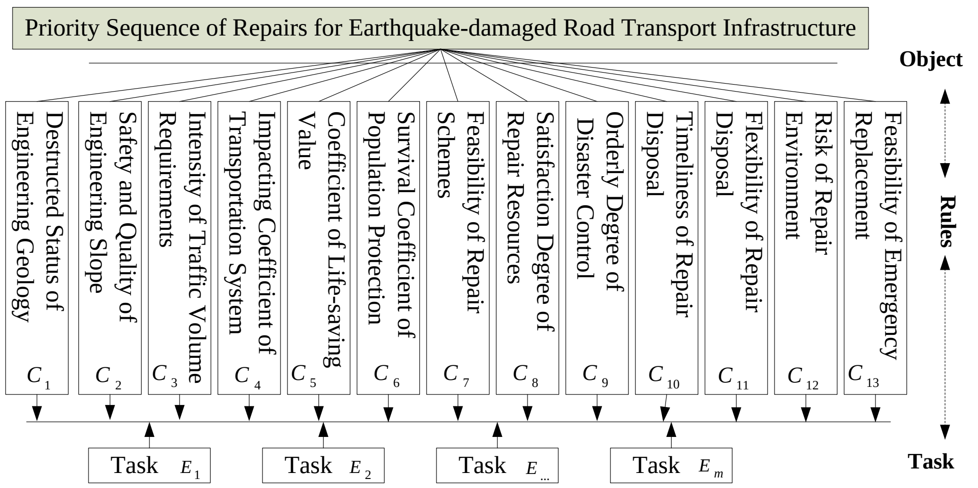

Figure 1. Characteristics of Priority Sequence of Repairs for Earthquake-Damaged Road Transport Infrastructure

With the repair decision-making simulation circumstance on road transport infrastructure, E_1, E_2, E_3, E_4, E_5, E_6 was designed as the needed repair section or task, as shown in Table 2, And, there were no logic or sequence among repair tasks. All the parameters are under the fuzzy preconditioning with Experts work and model requirements.

Table 2. Fuzzy Decision-making Matrix on the Example about Road Transport Infrastructures

	C_1 DS *min*	C_2 SQ *max*	C_3 IT *max*	C_4 IC *max*	C_5 CL *max*	C_6 SC *max*	C_7 FR *max*	C_8 SD *max*	C_9 OD *max*	C_{10} TR *max*	C_{11} FD *max*	C_{12} RR *min*	C_{13} FE *min*
E_1	0.8147	0.2785	0.9572	0.7922	0.6787	0.7060	0.6948	0.7655	0.7094	0.1190	0.7513	0.5472	0.8143
E_2	0.9058	0.5469	0.4854	0.9595	0.7577	0.0318	0.3171	0.7952	0.7547	0.4984	0.2551	0.1386	0.2435
E_3	0.1270	0.9575	0.8003	0.6557	0.7431	0.2769	0.9502	0.1869	0.2760	0.9597	0.5060	0.1493	0.9293
E_4	0.9134	0.9649	0.1419	0.0357	0.3922	0.0462	0.0344	0.4898	0.6797	0.3404	0.6991	0.2575	0.3500
E_5	0.6324	0.1576	0.4218	0.8491	0.6555	0.0971	0.4387	0.4456	0.6551	0.5853	0.8909	0.8407	0.1966
E_6	0.0975	0.9706	0.9157	0.9340	0.1712	0.8235	0.3816	0.6463	0.1626	0.2238	0.9593	0.2543	0.2511

Here, *max* and *min* described the changing trend of the risk monitoring characterizations to the repair engineering case, *max* denoted the efficiency type, and *min* expressed the cost type.

5.2. Case Study on Interval Repair Comparison of Road Transport Infrastructures

Applied with the standardization of Efficacy Coefficient Method, set $\theta = 0.8$, X is gained as the example's standardized matrix according to Formula (5).

And, the best and worst project is determined about the example in the repair engineering projects for the road transport infrastructure, whose parameters are shown in Table 3, as Row Vector of E^+ and E^-.

Table 3. Matrix Standardization and Comparison Space of Such Repair Decision-making

	C_1 *min*	C_2 *max*	C_3 *max*	C_4 *max*	C_5 *max*	C_6 *max*	C_7 *max*	C_8 *max*	C_9 *max*	C_{10} *max*	C_{11} *max*	C_{12} *min*	C_{13} *min*
E_1	0.1207	0.1764	1.0000	0.8202	0.8714	0.8527	0.7231	0.9535	0.9268	0.0248	0.7203	0.3851	0.1738
E_2	0.0290	0.4958	0.4385	1.0000	1.0000	0.0077	0.3137	1.0000	1.0000	0.4649	0.0532	1.0000	0.9103
E_3	0.9246	0.9844	0.8133	0.6736	0.9762	0.3149	1.0000	0.0470	0.2264	1.0000	0.3905	0.9735	0.0423
E_4	0.0213	0.9932	0.0296	0.0074	0.4050	0.0258	0.0072	0.5215	0.8788	0.2816	0.6502	0.7722	0.7449
E_5	0.3064	0.0325	0.3628	0.8814	0.8336	0.0896	0.4455	0.4523	0.8390	0.5657	0.9080	0.0330	1.0000
E_6	1.0000	1.0000	0.9506	0.9726	0.0452	1.0000	0.3836	0.7667	0.0431	0.1464	1.0000	0.7772	0.8971
E^+	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
E^-	0.0213	0.0325	0.0296	0.0074	0.0452	0.0077	0.0072	0.0470	0.0431	0.0248	0.0532	0.0330	0.0423

Referred to mathematical method of Entropy, according to Formula (7) and Formula (8), the entropy value and index weight was calculated and obtained for the case characteristics, as shown in Table 4.

Table 4. Entropy Value and Index Weight of such Case Operations

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
Entropy	0.6923	0.8469	0.8771	0.8985	0.9000	0.6691	0.8535	0.8991	0.8761	0.8241	0.9025	0.8931	0.8649
Weight	0.1536	0.0765	0.0614	0.0507	0.0499	0.1652	0.0732	0.0504	0.0619	0.0878	0.0487	0.0534	0.0675

Here, weight calculation showed that Destructed Status of Engineering Geology (DS, C_1) is the key index of the entire road transportation repairing priority decision-making system. The impact was greater in Destructed Status of Engineering Geology, whose weight is 0.1536 for this case study; On the contrary, the impact was minimum in Flexibility of Repair Disposal, whose weight is 0.0487.

5.3. Calculating and Analyzing SPA of Repairing Sequence

According to SPA method or model of the repair priority decision-making operation about the earthquake-damaged transportation infrastructures, namely Formula (11) and Formula (12), SPA association parameters are identified for the above case to the set pair of $h(E_i, E^+)$ （$i = 1,2,...,6$）, as shown in Table 5.

Table 5. SPA Coefficients of the Repair Case Sequence

	E_1	E_2	E_3	E_4	E_5	E_6
a_i	0.5334	0.4496	0.6378	0.3225	0.4298	0.7205
b_i	0.3051	0.2026	0.2127	0.2633	0.3937	0.1368
c_i	0.1615	0.3478	0.1495	0.4142	0.1765	0.1427
p_i	0.6361	0.6894	0.7499	0.5505	0.5219	0.8404

Here, such as the engineering project of E_3, the identity degree of E_3 is 0.6378, the contrary degrees of E_3 is 0.1495, the difference degrees of E_3 is 0.2127, and the SPA coefficient is 0.7499; then, the other engineering projects could get the SPA parameters from the above Table 5.

In term of Formula (11), example's proximity degree was determined, which was shown in Table 5. Here, E_6, E_3, E_1, E_2, E_4, E_5 was the reasonable sequence. E_6 was the most priority, which should be repaired firstly. At the same time, this engineering case could be divided into different levels, for example, E_1 and E_2 was the same level, while E_4 and E_5 were the other level.

6. Conclusion

(1). Based on Set Pair Analysis, one sequence or priority decision-making model was thoroughly presented for earthquake-damaged transport infrastructures, which analyzed the relative characteristics and transformation rules.

(2). The entropy value of repairing priority decision-making index was determined with Integrated Efficacy Coefficient Method, which gained the index weight from the components and inherent relation of transportation infrastructure case.

(3). Earthquake comparison space was built fot the transport infrastructure repairing projects, and provided a new method to calculate the proximity degree and the decision-making sequence about such repair with SPA theory.

(4). Case showed, this model provided a new method for solving the similar problems in emergency decision-making operations. But the lack to data, difficult to collect data, and change to the index system, all resulted in the significant limitations in the application of SPA model. So the future applications are needed to combine with the specific circumstance, and the appropriate model is selected to solve the related problem.

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