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Multi-Objective Optimization for Seismic Structural Investigation and Maintenance Strategies of Bridges in Service

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Abstract: With the continuous updating of seismic design codes for Bridges, the new regulations have higher requirements for the seismic structure and mechanical properties of old Bridges. In order to make the decision of seismic structure strengthening more scientifically, with the goal of optimal overall performance, minimum economic cost and minimum environmental impact, the optimal model of seismic strengthening sustainable strategy is established. Firstly, according to the results of the seismic measures of the existing Bridges, the corresponding reinforcement measures are proposed for the structural problems that do not meet the seismic measures. Then the utility evaluation of the three objectives of the existing bridge was carried out. At last, NSGA-Ⅱ algorithm was used to build a multi-objective maintenance decision optimization model of the bridge network. Combined with the weight of the decision-maker's preference, TOPSIS algorithm was used to obtain the optimal solution of the target, and decision-making suggestions were provided for the relevant departments. The results show that there are many structural problems in the new evaluation of the old bridge, and the maintenance of the structural problems are more feasible and effective than the improvement of the traditional mechanical properties. Combined with the comprehensive evaluation utility and reinforcement objective function, the maintenance decision can be better under different objectives. The reinforcement maintenance decision model has the ability to improve the comprehensive performance and sustainability of the bridge to the maximum extent within the limited budget.

Keywords: Seismic investigation of bridge (SIB), Reinforcements strategy (RS), Utility evaluation (UE), Multi-objective optimization (MOP), NSGA-Ⅱ algorithm

I. Introduction

In recent years, earthquake disasters have occurred frequently in China, such as Wen chuan earthquake in 2008, Yu shu earthquake in 2010, Ma duo earthquake in Qinghai Province in 2021, etc. These sudden earthquakes have severely affected the highway and bridge system in China [1, 2]. As a crucial component of transportation infra-structure, the seismic performance of bridges plays a pivotal role in enhancing the resilience of the entire transportation network in the event of earthquake disasters. At the same time, with the aging of infrastructure and the increasing traffic load, local structures of existing Bridges are prone to fatigue damage, making their seismic performance no longer meet the basic requirements of structural safety. In addition, since all existing highway Bridges were built before the release of the current seismic design code for highway Bridges, they are constructed according to the old version of the code. With the continuous update of the seismic design code for Bridges, the new code has higher requirements for the seismic structure and mechanical properties of old Bridges [3].

Currently, the research on the seismic performance analysis of Bridges during their life cycle has been relatively mature [4-6], but the investigation and research on the seismic structure is still in its infancy. Since 1990s, China has not issued a special seismic design code for Bridges, and has been learning and drawing lessons from foreign regulations and standards on bridge seismic design. In 1959 and 1964, China has twice compiled the draft code for building design in earthquake areas as a temporary reference for seismic construction of Bridges. It was not until 1977 that China officially promulgated and implemented the first Code for Seismic Design of Highway Engineering, which included the seismic design provisions for highway Bridges, roadbed, retaining wall and other structures. In 1989, China revised the previous specification and promulgated and implemented the revised Code for Seismic Design of Highway Engineering (JTJ 004-89), the content mainly extends the scope of application of the code to all highway projects. Since the previous specifications are not graded fortification, and the calculation of seismic performance is not comprehensive, and the seismic design of bridge structure has obviously different characteristics from other highway structures, it is necessary to carry out special design code guidance for high-way Bridges. In 2008, the Ministry of Communications issued the "Rules for the Seismic Design of Highway Bridges" (JTG/ TB02-01-2008), which subdivides the types of Bridges and improves the theories and methods of seismic design. In recent years, China has carried out a lot of scientific research on the seismic technology of bridge structure, and accumulated a lot of engineering experience. In 2020, the Ministry of

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Transport promulgated the Code for Seismic Design of Highway Bridges (JTG/T 2231-01-20), which is the current code. At this point, the seismic design of highway Bridges in China has entered a more perfect and scientific stage of development, and its design methods and practicability are more complete.

Recent studies [7, 8] have shown that more and more attention is shifting to applying multi-criteria decision analysis methods to optimize resources, strategies, and interventions. In this area, several approaches have received much attention, including Pareto Frontier, multi-attribute utility theory, analytic hierarchy Process, multi-attribute value theory, goal planning, and TOPSIS comprehensive evaluation methods, among others. Dabous et al. [9] proposed a reasonable decision-making technique for bridge management. They used the improved analytic hierarchy process to evaluate and rank bridge repair strategies. Bukhsh et al. [10] applied analytic hierarchy process (AHP), multi-attribute utility theory and objective planning to solve the maintenance plan decision problem of 22 Bridges in Dutch highway network. The research results show that although there are differences in the specific implementation of multi-criteria decision analysis methods, they produce similar results in bridge ranking results. Schaffer[11] first proposed a multi-objective genetic algorithm based on vector evaluation. Carlos et al. [12] improved the multi-objective genetic algorithm and proposed an improved multi-objective genetic algorithm in which the individual order value of the sorted population should be determined according to the number of individuals dominating it.

With the in-depth study of decision-making optimization of bridge maintenance and reinforcement by scholars at home and abroad, the research focus has changed from the single objective relationship between bridge safety and other influencing factors to the multi-objective optimization problem. Paya et al. [13] proposed a method for de-signing frame structures using multi-objective simulated annealing algorithm, taking economic cost, constructability, environmental impact and overall safety as four objective functions. Liu and Fangopol [14] combined a structural time-varying reliability prediction model to combine time-varying reliability with bridge network performance. They constructed a multi-objective decision-making framework for bridge network maintenance based on bridge performance and life cycle cost. By aiming at the lowest maintenance cost, bridge failure cost and user cost, the optimal maintenance and reinforcement decision of bridge network is selected.

Domestic and foreign scholars have made a lot of progress on the multi-objective optimization of bridge reinforcement decision-making [15-18]. However, for most Bridges, the decision-making objectives are restricted from the perspective of seismic mechanical properties of Bridges, and there is little research on the structure of Bridges. In this paper, the seismic measures of bridge structure and the multi-objective optimization of reinforcement decision are combined to establish a bridge seismic sustainable reinforcement decision optimization model. Firstly, a bridge seismic measure investigation and evaluation system is established, and then multi-attribute utility functions of bridge performance, economic cost and environmental impact are deter-mined respectively. Taking 83 existing Bridges in Xiamen City as the research object, NSGA-Ⅱ algorithm was used to solve the problem, and the optimal maintenance strategies under different objectives were obtained, which provided decision-making basis and strategies for the government and other relevant management departments, and helped to improve the seismic performance of Bridges, so as to ensure the reliability of public transportation and urban infrastructure construction.

II. MATERIALS AND METHOD

A. *Investigation and Reinforcement of Seismic Measures*

The seismic measures of 83 existing Bridges were investigated, and the Bridges with seismic structure problems were screened and evaluated to provide a basis for seismic reinforcement of bridge structures. The specific investigation steps are as follows.

The first step is to investigate the general situation of bridge engineering, including span combination, structure type, design load, seismic fortification grade, etc. Let a be the distance from the beam end of the superstructure of the simple supported beam bridge and continuous beam bridge to the cap, pier or cover beam side, as shown in Figure 1. The minimum value of a is calculated according to formula 1 in the current code and formula 2 in the old code, and should not be less than 60cm.

$$a \geq 50+0.1L+0.8H+0.5L_k \tag{1}$$

$$a \geq 70+0.5L \tag{2}$$

Where, L is the total length (m) of a combined superstructure of the bridge; H is the average height (m) of the piers of a combined superstructure, the height of the abutment is 0; L_k is the maximum single-span span (m) of a combined superstructure of the bridge. For inclined bridge and curved beam bridge, the current code gives more specific calculation rules. The calculation of inclined beam bridge is as follows

$$\frac{\sin 2\theta}{2} \geq \frac{b}{L_\theta} \tag{3}$$

$$a \geq 50L_\theta(\sin\theta - \sin(\theta - \alpha_E)) \tag{4}$$

Where, L is the total length (m) of a combined superstructure of the bridge; b is the total width (m) of the superstructure, θ is the oblique Angle, α_E is the limit falling off Angle, and the provision is 5°

The curved beam bridge is calculated as follows.

$$\frac{115}{\varphi} \cdot \frac{1-\cos\theta}{1+\cos\theta} > \frac{b}{L} \tag{5}$$

$$a \geq \delta_E \frac{\sin\varphi}{\cos\frac{\varphi}{2}} + 30 \tag{6}$$

$$\delta_E = 0.5\varphi + 70 \tag{7}$$

Where: δ_E is the amount of movement of the end of the superstructure to the outside (cm); L is the arc length (m) of the center line of a joint superstructure; φ is the center Angle (º) of the curved beam.

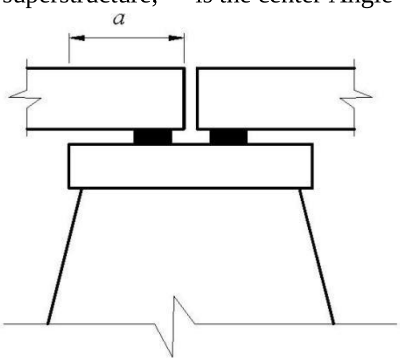


Figure 1: The minimum distance from the end of the beam to the edge of the pier, cap, or cover beam.

The second step is to investigate the situation of the bridge on the spot to determine whether its structure size is consistent with the drawing and whether there is damage in the current situation of use.

The third step, determine the technical standards of the bridge, including the design load, carriageway width, design driving speed, seismic intensity, seismic measure grade and other indicators.

The fourth step, according to the "Highway bridge seismic design Code" and "Urban bridge seismic design code", the seismic measures of the bridge structure are checked, calculated according to the evaluation system, and the bridge performance score is obtained.

The fifth step, confirm the reinforcement measures, put forward the reinforcement suggestions.

B. Multi-Attribute Utility Analysis of Bridge

The fifth step, confirm the reinforcement measures, put forward the reinforcement suggestions. This study uses an exponential utility function to obtain a utility score for each attribute, fused by weights. For single-factor utility functions, the exponential function form is generally assumed because the exponential form provides a constant risk premium under all conditions, and for alternative x, the formula for calculating the utility score for each attribute is as follows.

$$U_i(x_i) = A - B \times e^{-\frac{x_i}{RT}} \tag{8}$$

$$A = \frac{e^{\frac{-\min(x_i)}{RT}}}{e^{\frac{-\min(x_i)}{RT}} - e^{\frac{-\max(x_i)}{RT}}} \tag{9}$$

$$B = \frac{1}{e^{\frac{-\min(x_i)}{RT}} - e^{\frac{-\max(x_i)}{RT}}} \tag{10}$$

$$RT_i = \frac{-CE_i}{\ln\left(\frac{-0.5U_i(\max(x_i)) - 0.5U_i(\min(x_i)) + A}{B}\right)} \tag{11}$$

Where, U_i is the utility value of a single index; A and B are respectively shrinkage constants; $\min(x_i)$ and $\max(x_i)$ are respectively the index values when the utility of a single index is minimum and maximum; RT is the risk attitude and e is the exponential constant.

The point of no difference for decision makers is called the deterministic equivalence. Risk tolerance is calculated based on the expected value sum, where it is the average of the worst and best values of the property values. Risk attitude is calculated as follows.

$$e^{-\frac{CE}{RT}} = 0.5 \times e^{-\frac{\max(x_i)}{RT}} + 0.5 \times e^{-\frac{\min(x_i)}{RT}} \tag{12}$$

The value is selected by the expert according to the following principles [19] : when RT is negative, that is $CE > EV$, it is a risk-appetite decision; When it is 0, that is $CE = EV$, a risk-neutral decision; When it is positive, that is $CE < EV$, is a risk-averse decision. The utility function of a single indicator is summed by weighted sum to obtain the multi-attribute effect function as follows. By calculating the combined utility of each attribute utility function, a ranking of all bridge utilities is obtained.

$$U = \sum_i k_i \times U_i(x_i) \tag{13}$$

Where: k_i corresponds to the weight of the indicator utility function and satisfies the relationship $\sum_i k_i = 1$.

C. Bridge Evaluation Index

1) Bridge Performance Status: The point of no difference for decision makers is called the deterministic equivalence. Risk tolerance is calculated based on the expected value sum, where it is the average of the worst and best values of the property values. Risk attitude is calculated as follows. In order to determine the performance of each bridge, a quantitative evaluation is carried out based on the investigation results of seismic measures. The characteristics of seismic measures are quantified, and the bridge components are taken as the smallest evaluation unit. The weighted summation method is used to obtain the scores of components, span units and on-ramp bridge segments in turn. The formula is shown as follows. Since the changes of each evaluation index are different, and the degree of influence on the seismic capacity of the bridge is also different, it is necessary to convert the influence of each index on the seismic performance of the bridge into a weight.

$$P_i = \left(\left(\sum_{l=1}^{r} \sum_{k=1}^{n} \sum_{q=1}^{p} A_{ilkq} \right) \times w_i \right) \times W_i \tag{14}$$

Where, P is the performance score of the bridge, l , k , q respectively are the on-ramp bridge segment, span unit, component, r , n , p corresponding to their respective numbers, A is the quantitative score of the investigation items, w_i is the weight of the investigation items of each secondary index, and W_i is the weight of the investigation measures at all levels of the primary index.

2) Economic Cost of Reinforcement: C is the total reinforcement cost of each bridge, which mainly considers direct engineering costs, including labor costs, materials costs and construction machinery costs. According to the investigation results of the bridge seismic measures, the reinforcement measures are mainly composed of adding rubber pad, adding steel leg, adding steel seismic block, because the construction of the two measures of widening the bearing pad stone and replacing the support is difficult and not easy to achieve, and does not violate the mandatory provisions, so the reinforcement transformation does not take it into consideration. According to the construction process of the reinforcement measures, refer to the "Highway Bridge maintenance engineering budget quota", confirm the sub-quota of each bridge reinforcement measures project, and calculate the reinforcement cost according to the engineering volume of each bridge, the calculation formula is shown as follows.

$$C = C_{xk} + C_{nt} + C_{kk} \tag{15}$$

$$C_{xk} = Q_{xk} \times C_{xk} \tag{16}$$

$$C_{nt} = Q_{nt} \times C_{nt} \tag{17}$$

$$C_{kk} = Q_{kk} \times C_{kk} \tag{18}$$

Where, C denotes the total cost of reinforcement costs, C_{xk} , C_{nt} , C_{dk} respectively for a single reinforcement measure to add rubber pad block, set steel leg, set steel seismic block unit cost, Q_{xk} , Q_{nt} , Q_{dk} respectively for a single reinforcement measure engineering quantity.

3) Environmental Impact

In the process of bridge reinforcement, a series of resources and construction operations will be carried out, and harmful substances such as waste gas and waste will be generated during the construction process, which will cause damage to the environment. Carbon dioxide in the air pollutant is selected as the research object to discuss the impact of bridge reinforcement on the environment, that is, carbon emission generated by reinforcement is taken as the measurement index, and the calculation formula is as follows.

$$E_p = \sum_{i=1}^{n} S_i E_{Pi} + \sum_{j=1}^{m} M_j E_{Pj} \tag{19}$$

Among them, S_i is the amount of the first raw material used for reinforcement; E_{pi} is unit carbon emission corresponding to the first raw material used for reinforcement; M_j is the amount of the first kind of construction machinery used for reinforcement; E_{pj} is the carbon emission of the corresponding unit of the type of construction machinery used for reinforcement.

D. Reinforcement Decision Optimization

1) Optimization Model Establishment: The three factors of bridge performance state, strengthening cost and environmental impact are selected as the indicators that affect the decision making of bridge strengthening and maintenance by relevant management departments, and the corresponding objective functions are established respectively $X_i = \{0,1\}$. It is used to represent the first bridge among the existing Bridges investigated. When $X_i = 1$, at that time, the bridge is given priority for reinforcement; When $X_i = 0$, at that time, the bridge was not prioritized for maintenance. The specific objective function is shown below.

(1) Bridge performance condition score is minimized. In the case of limited reinforcement budget, the lower the performance state score of the bridge, the more structural problems it can find, and the priority should be considered for reinforcement maintenance.

$$P = \sum_{i=1}^{n} X_i U(P_i) \tag{20}$$

(2) Minimize the cost of bridge reinforcement. The lower the cost of bridge reinforcement, the less pressure on relevant departments to invest funds, and the reinforcement and maintenance that can maximize performance within a limited budget need to be given priority.

$$C = \sum_{i=1}^{n} X_i U(C_i) \tag{21}$$

(3) Minimize the environmental impact of the bridge. Carbon emissions and energy consumption are used to indicate the impact of bridge reinforcement on the environment. The less carbon emissions of the bridge, the smaller the impact on the environment, and the priority should be given to the reinforcement.

$$E = \sum_{i=1}^{n} X_i U(E_i) \tag{22}$$

The multi-objective function of the existing bridge reinforcement decision is:

$$MinF\left(P,C,E\right)$$
$$s.t.\begin{cases}\sum_i C_i \le Budget \\ i=(1,2,...i), i\ge 1 \\ X_i \in \{0,1\}\end{cases} \tag{23}$$

Budget is a budget for funds. The constraint function states that the total cost of all selected candidate maintenance activities must be less than the available budget. Set the funding budget to $1 million.

2) NSGA-II Algorithm: In the solution of multi-objective optimization, the second-generation non-dominated sorting genetic algorithm is adopted for decision optimization. It is a population that first generates a population and then iterates through variation and selection to enhance the solution. Eventually, by examining a relatively small number of possible solutions, a near-optimal solution will be obtained. The objective function must evaluate each individual in the group to find the best solution. Crossover is mutating a selected population based on the relative fitness score assigned by the objective function to produce the next population. Compared with the traditional GA algorithm, NSGA-Ⅱ algorithm has three characteristics: fast non-dominated sorting, fast crowding distance estimation process and simple crowding comparison operator (Figure 2).

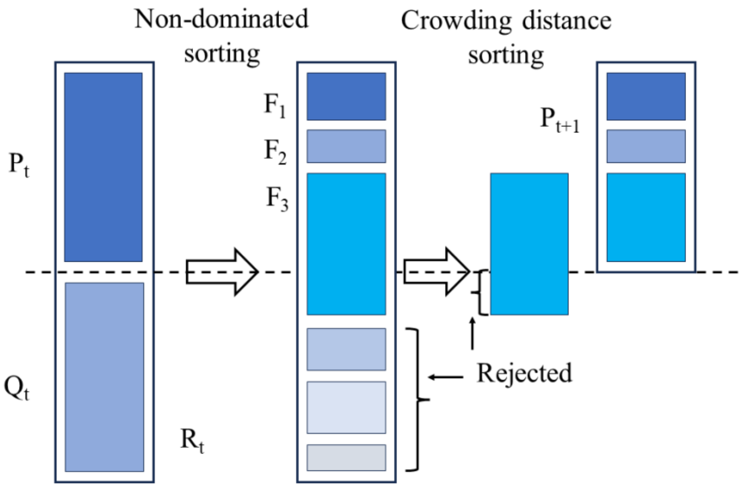


Figure 2: Non-dominated sorting flow

III. RESULTS

A. Investigation and Reinforcement of Seismic Measures

Take a bridge as an example to introduce the investigation and reinforcement process, according to the investigation and reinforcement process, the investigation results of 83 Bridges are obtained.

According to the current code for Seismic Design of Highway Bridges (JTG/T 2231-01-20), the seismic measures were investigated for the structure of G324 double-track Guanxunxi Bridge. The construction plan is shown in Figure 3.

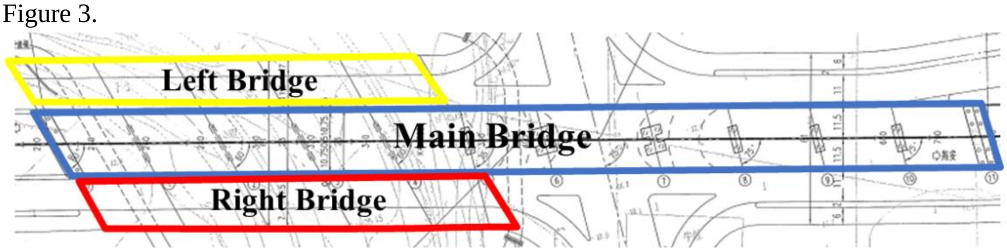


Figure 3: G324 double-track Guanxunxi Bridge

The bearing cushion stones at the abutments and over piers of the main bridge and auxiliary bridge are not aligned with the outer edges of the abutments and over piers, which does not meet the general regulations.

In the provisions of Class I seismic measures, the comprehensive data show that the main bridge does not meet the provisions of Class I seismic measures (Table 1).

Table 1: Calculation table of a value of the main bridge.

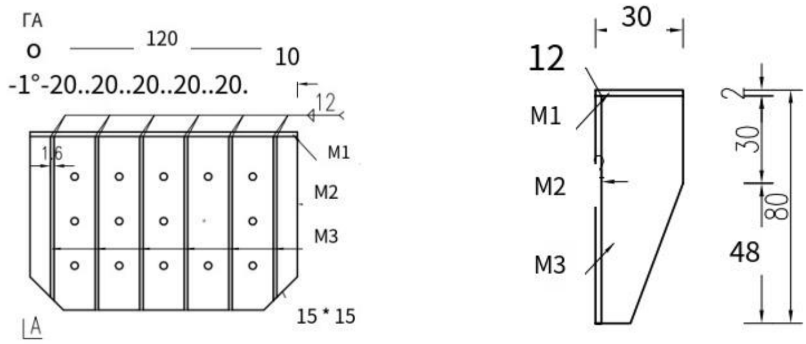
Corresponding pier		a (drawing)	L (m)	H (m)	Lk (m)	a (Formula 1)	b (m)	θ (°)	$\frac{b}{L}$	a (Formula 4)	Decision condition
1st Lien	0# Table	140	150	5.45	30	84.36	23	120	0.15	302	0.43
	5# pier	135									
2nd League	5# Pier	135	98	5.75	40	84.4	Straight section				
	8# pier	135									
3rd League	8# Pier	135	90	2.95	30	76.36	23	120	0.26	181	[illegible]
	11# station	140									

The secondary and tertiary seismic measures of the main bridge and auxiliary bridge of G324 double-track Guanxunxi Bridge were investigated. The investigation results are shown in the table 2. The results show that the main bridge does not meet the requirements of the second-class seismic measures and needs to be improved according to the structural problems (Table.2).

Table 2: Results of secondary and tertiary seismic measures

Grade	**Prescribed content**	**Check the situation**	**Meets the requirements**
Class Ⅱ seismic measures	(1) For Bridges using simple supported beams and continuous deck, it is recommended to limit the pier height to less than 40m.	Pier height is less than 40m.	yes
	(2) Add a buffer device between the abutment and the parapet, noting that the buffer pad should not limit the free expansion of the beam body in normal use.	There is no buffer device between the beam and the abutment parapet.	no
	(3) It is necessary to arrange the bridge rationally to avoid the unstable section of the bank slope or terrain mutation that may slip during the earthquake	The bridge layout is reasonable, avoiding the bank slope that may slide or the unstable terrain sudden change during the earthquake.	yes
	(4) The upper structure of the beam bridge should be set up in the cross bridge and longitudinal bridge respectively to block or seismic anchor to effectively prevent the structure from falling beam.	The pier is equipped with shock-proof block and is in good condition.	yes
Class Ⅲ seismic measures	(1) The structure adopts a reasonable limiting device to effectively prevent excessive relative displacement of adjacent components.	The bridge pier is equipped with a reasonable lateral limiting device.	yes
	(2) The design of continuous beam bridge should consider making the horizontal seismic load borne by each pier and platform to reduce the force of the fixed support pier.	The main pier supports are plate rubber supports, and the auxiliary bridge adopts basin rubber supports.	no
	(3) The design of the abutment should choose the structural type with strong integrity.	The structure type of abutment is U-shaped.	yes
	(4) When the lower part of the bridge is a reinforced concrete structure, the concrete strength grade should not be lower than C30.	The concrete grade of the bridge substructure is C30.	yes
	(5) It is recommended that the bridge foundation be set on the bedrock or hard soil layer.	The foundation is placed on bedrock and hard soil.	yes

The results show that the bridge related management and maintenance departments take the following measures to strengthen and maintain the bridge: the buffer pad is added to the abutment parapet; Longitudinal anti-fall beam facilities are set up at the position where the a value of beam end does not meet the requirements (Figure 4).



(a) Steel bull leg front schematic; (b) Side diagram of the steel leg

Figure 4: G324 double-track Guanxunxi Bridge pier limit block Multi-Attribute Utility Function Ranking

In the process of strengthening the existing bridge, different decision-making units and decision-makers have different decision-making considerations, and the decision-making emphasis on different aspects is expressed as decision-making preferences. By summarizing the degree of preference of different scholars and literatures on economy, environment and performance, four strategies are presented as the combined weights of decision makers' preferences in the table 3.

Table 3: Weight of decision preferences

	Composite weights		
	Performance status	**Cost of reinforcement**	**Environmental impact**
Biased economy	0.2	0.6	0.2
Biased environment	0.2	0.2	0.6
Biased performance	0.6	0.2	0.2
No preference	0.33	0.33	0.33

Consider preferred performance, preferred economy, preferred environment, and no obvious preference as strategies 1, 2, 3, and 4, respectively. According to the preference weights under different strategies, the target utility functions are all turned forward to obtain the comprehensive utility function of each bridge, as shown in Figure 5.

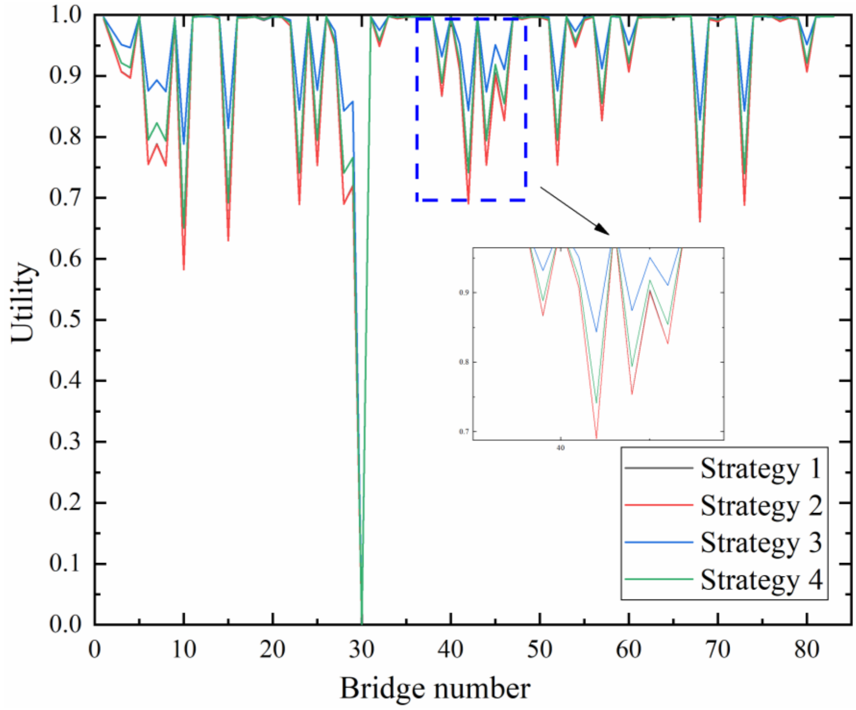


Figure 5: Comprehensive utility of Bridges with different decision strategies

Table 4: Ranking of comprehensive utility of Bridges

Bridge Number	Strategy 1 Ranking	Strategy 2 Ranking	Strategy 3 Ranking	Strategy 4 Ranking
1	45	45	43	45
2	56	56	57	56
3	62	62	62	62
4	65	65	65	65
5	4	4	5	4
6	70	70	71	70
7	69	69	69	69
8	74	74	73	74
9	49	49	52	49
10	82	82	82	82
11	33	33	33	33
12	7	7	15	9
13	1	1	8	1
14	44	44	39	44
15	81	81	81	81
16	41	41	46	41
17	42	42	48	42
18	27	27	27	27
19	52	52	54	53
20	20	20	21	20
21	29	29	26	29
22	55	55	55	55
23	78	78	76	77
24	32	32	32	32
25	72	73	70	72
26	10	10	16	10
27	57	57	58	57
28	77	77	78	78
29	75	75	75	75
30	83	83	83	83
31	14	14	12	14
32	58	58	56	58
33	6	6	10	8
34	43	43	45	43
35	31	31	31	31
36	17	17	18	17
37	30	30	28	30
38	16	16	14	16
39	66	66	66	66
40	28	28	37	28
41	60	60	60	60
42	76	76	77	76
43	12	12	7	12
44	73	72	74	73
45	64	64	64	64
46	68	68	68	68
47	24	24	30	25
48	48	48	51	48
49	35	35	35	35
50	34	34	34	34
51	51	51	42	51
52	71	71	72	71
53	11	11	17	11
54	59	59	59	59
55	50	50	38	50
56	26	26	24	26
57	67	67	67	67
58	5	5	6	5
59	23	23	29	24
60	63	63	63	63
61	40	39	44	40
62	37	37	40	37
63	36	36	36	36
64	38	38	41	38
65	25	25	11	23
66	9	9	2	7
67	8	8	1	6
68	80	80	80	80
69	46	46	47	46
70	54	53	53	54
71	21	21	22	21
72	18	18	19	18
73	79	79	79	79
74	3	3	4	3
75	2	2	3	2
76	19	19	20	19
77	53	54	49	52
78	39	40	25	39
79	47	47	50	47
80	61	61	61	61
81	22	22	23	22
82	15	15	13	15
83	13	13	9	13

Figure 5 shows that the overall comprehensive utility of the bridge is the highest when the decision is made according to the preference of strategy 3, followed by strategy 1, Strategy 4 and strategy 2. This is because the average utility of the environmental impact of Bridges is low, and Bridges in need of reinforcement and maintenance will inevitably cause different degrees of impact on the environment, while the required reinforcement cost and performance status of each bridge are highly different, so the utility value is widely distributed, and the overall comprehensive utility is higher when the weight is relatively large.

The comprehensive utility of the bridge is sorted, and the sorting results of different decision preferences are shown in Table 4 below. The interconnecting e-ramp bridge has the highest comprehensive utility, which indicates that it has good performance after seismic investigation and evaluation, and only needs to add buffer blocks for reinforcement and maintenance. Meanwhile, the bridge itself is not large, the reinforcement cost is low and the impact on the environment is small, so it ranks the highest in utility among the existing Bridges investigated. Bridges with higher comprehensive utility have the same characteristics, fewer structural problems are found, and there is no insufficient a value of beam end or possible beam fall, so the maintenance cost is low. In the comprehensive utility ranking, the Shigushan overpass ranks last, which is because the Shigushan overpass bridge segment is complex and there are many on-ramps, so there are many problems found in the investigation process, and the maintenance is difficult and the maintenance cost is high. The Bridges ranked lower in the comprehensive utility ranking are the Bridges with large scale and the possibility of falling beams, which need to be strengthened.

B. Reinforcement Decision Multi-Objective Optimization

This section will carry out multi-objective optimization of the existing bridge reinforcement decision, optimize the two influence objectives and the three influence objectives respectively, and provide reference suggestions for the decision-making of relevant management and maintenance departments. The NSGA-II algorithm is programmed in MATLABR2022a environment of Windows10 system and Intel(R) Core (TM) i5-9300H processor. After testing, the running parameters are determined as shown in Table 5 below.

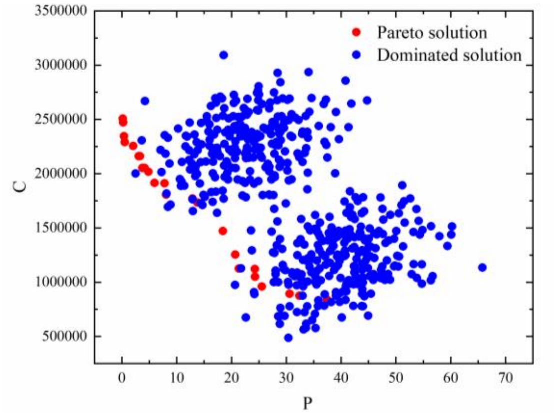
Table 5: Running parameters of the algorithm

Population size/individual	**Number of iterations/times**	**Crossover probability**	**Probability of variation**
100	200	0.8	0.2

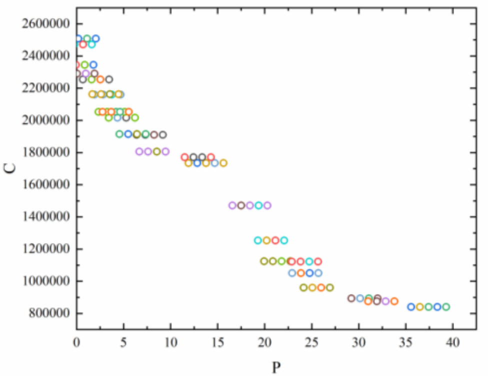
The NSGA-II algorithm is used to calculate the Pareto solution set of the multi-objective optimization model. In general, the front edge of the multi-objective genetic algorithm in the optimization process tends to generate the optimal solution set, rather than a single optimal solution. Because of the correspondence between goals and goals often become complicated. Therefore, the Pareto front must be processed to obtain the relative optimal solution. In order to obtain the optimal solution of Pareto solution set, TOPSIS method is selected for decision-making.

Among the three objectives selected in the study, there is a contradiction between bridge performance and reinforcement cost and environmental impact. The worse the performance of bridge structure, the more need for priority reinforcement, the higher the cost of reinforcement, the greater the environmental impact, the more do not consider the priority of reinforcement. Therefore, the two objectives of reinforcement cost and environmental impact are selected. The dual objective reinforcement decision optimization model with the performance status was constructed respectively, and the NSGA-Ⅱ algorithm was used to solve it, and the distribution of all solution sets was obtained, as shown in Figure. 6.

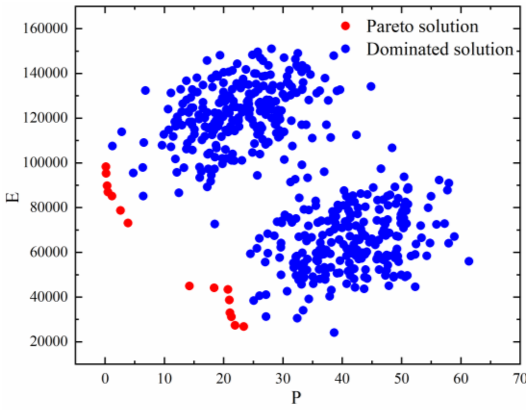
Figure 6 shows the dominant solution and Pareto solution of double-objective optimization, and the results show that the bridge performance is negatively correlated with the strengthening cost and environmental impact. According to different preferred target weights, TOPSIS method is applied to select the optimal solution biased toward the economic cost objective and the environmental decision objective in the Pareto optimal solution set. In the dual-objective decision making under different preferences, the Bridges that are preferentially strengthened are shown in Table 6 below. It can be seen that different target choices have a significant impact on the priority of reinforced Bridges. Among the two objectives of reinforcement cost and environmental impact, there are 22 Bridges that are given priority for reinforcement. Their reinforcement cost is low and their impact on the environment is small. After reinforcement and maintenance, the overall performance level of Bridges is improved.



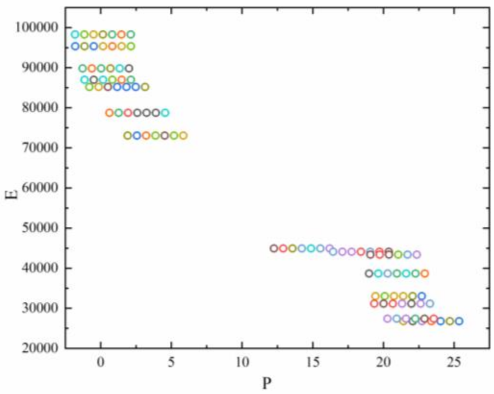
(a) All solutions of P and C



(b) P, C Pareto solu-tion set



(c) All solutions of P and E



(d) P, E Pareto solu-tion set

Figure 6: Two-objective optimization solution set

Table 6: The Bridges that are given priority for reinforcement under different preferred objectives

Target preference	**Prioritized Bridges for reinforcement**
Cost of reinforcement	3, 4, 8, 10, 13, 15, 16, 17, 19, 21, 22, 24, 26, 28, 29, 30, 33, 37, 39, 39, 41, 4, 46, 53, 57, 58, 59, 60, 61, 66, 67, 68, 72, 74, 75, 76, 78, 80, 81, 82, 83
Environmental impact	1, 3, 4, 5, 6, 10, 14, 17, 19, 20, 24, 29, 30, 33, 34, 35, 38, 39, 40, 41, 44, 46, 49, 52, 53, 54, 56, 58, 60, 61, 65, 68, 71, 1,733, 74, 75, 75, 79, 80, 81, 83

Three objectives of bridge performance, reinforcement cost and environmental impact are selected in this study, and a multi-objective reinforcement decision optimization model is established. NSGA-Ⅱ algorithm is applied to solve the problem, and Pareto solution set distribution is obtained, as shown below.

Figure 7 shows the dominant solution and Pareto solution under the three-objective optimization. According to the policy weights of different preferences, TOPSIS method is used to select the optimal solutions under different strategies in the Pareto optimal solution set.

It can be seen that the weight distribution under different preferences has a significant impact on the optimal solution of reinforcement decision (Table 7). Compared with strategy 1, the cost of strategy 2 increases by 3.15% and the environmental impact decreases by 4.32%; Compared with strategy 3, the performance of strategy 2 is reduced by 45.7%, and the economic cost is reduced by 43.68%; In strategy 4, the three goals are the most balanced among the four strategies because there is no obvious bias in decision preference.

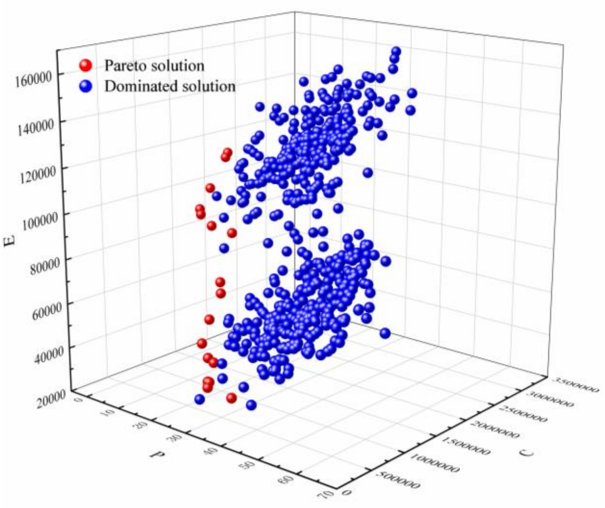


Figure 7: Multi-objective optimization solution

Table 7: Optimal solutions under different strategies

Strategies	Performance profile	Cost of reinforcement	Environmental impact
Strategy 1 (biased economy)	32.47	526747.72	30629.38
Strategy 2 (biased environment)	25.25	543315.31	29305.80
Strategy 3 (Biased performance)	17.33	964703.48	52208.43
Strategy 4 (No preferance)	21.75	724051.88	39631.33

IV. DISCUSSION

The development trend of the comprehensive utility of the four strategies is similar, because the utility difference of the performance state of the bridge is small among the objectives of bridge maintenance. Meanwhile, the effects of the preferred environmental impact and the preferred cost are similar for the comprehensive evaluation of the bridge, so the comprehensive utility value of each bridge is relatively stable. Shigushan overpass has the most problems in need of reinforcement, which also requires huge cost and has a huge impact on the environment. Therefore, in each strategy, the utility value of Shigushan overpass is a sudden change point of utility value compared with all the surveyed Bridges. In addition, several mutation points in the figure on behalf of the bridge with low comprehensive utility, are Shuangxi bridge, Zhu Cuo overpass, Shigushan overpass, Prozhou bridge, Dadeng Bridge, new shop overpass, etc., indicating that the overall situation of the bridge is poor, the problem out of more, high reinforcement cost and greater impact on the environment, in the reinforcement decision can give priority to maintenance. The results show that there is a negative correlation between bridge performance, reinforcement cost and environmental impact, while there is a positive correlation between reinforcement cost and environmental impact. This is because for existing Bridges, the more problems need to be reinforced, the higher the reinforcement cost and the greater the impact on the environment.

In this study, by incorporating environmental friendliness, social responsibility, and economic benefits into the decision-making model, we ensure that the proposed bridge seismic reinforcement solution not only creates safety and performance improvements in the present, but also continuously promotes the sustainable development of the bridge system. Through a comprehensive utility evaluation, we further ensure that the risk attitude of the decision maker is fully considered to achieve superior maintenance decisions under different sustainability objectives. This framework not only provides an effective improvement in the comprehensive performance of the old bridge, but also has the potential to maximize the improvement, providing decision-makers with both economic and environmental solutions to lead the bridge system to a more sustainable future.

V. CONCLUSIONS

This paper delves into the persistent challenges encountered by the seismic structure and mechanical properties of aging bridges, especially in light of the continually evolving seismic design codes. The overarching objective is to establish a robust decision-making model for seismic strengthening that seamlessly integrates sustainability considerations. Focusing on 83 highway bridges under the management of Xiamen City, the study introduces a decision-making framework founded on an optimal model for bridge seismic reinforcement, prioritizing overall performance optimization, economic efficiency, and environmental impact. The conclusions of this paper are as follows:

(1) A number of structural problems were found in the process of seismic measures investigation in the evaluation of the old bridge with the new code: the bearing stones of the excessive piers and abutments were not flush with the outer edges of the piers and abutments; The distance between the beam end and the edge of the pier, platform or cover beam does not meet the requirements of the first class seismic measures; There is no buffer device between beam and abutment parapet; Some Bridges lack rigid limit devices; The support does not meet the seismic needs, and there are many structural problems in the old bridge, which highlights the urgency and necessity of reinforcement and maintenance.

(2) The reinforcement maintenance is more feasible than the traditional mechanical performance improvement, mainly take the following strengthening measures: add rubber pad block, set steel leg, steel block. Compared with the traditional mechanical performance improvement, the reinforcement maintenance is more feasible to solve the structural problems, and provides a more effective way to improve the comprehensive performance of the bridge.

(3) The comprehensive utility of the bridge can fully reflect the risk attitude of the decision-maker. Through the utility assessment of the three objectives of the existing bridge, the comprehensive utility of the bridge can fully reflect the risk attitude of the decision-maker, providing a more comprehensive and objective basis for decision-making.

(4) The multi-objective maintenance decision model is effective in achieving superior maintenance decisions: The multi-objective maintenance decision optimization model of bridge network constructed by NSGA-II algorithm, combined with the application of TOPSIS algorithm, can achieve superior maintenance decisions under different objectives, and provide powerful decision-making suggestions for relevant departments. The reinforced maintenance decision model can not only effectively improve the comprehensive performance of the bridge, but also has the potential to maximize the improvement within the limited budget, providing decision-makers with both economic and environmental protection solutions.

(5) In the future, we can increase the objective factors affecting the reinforcement decision, continue to explore the bridge seismic reinforcement decision, use NSGA-Ⅲ algorithm to optimize the decision of more than four objectives, and explore the feasibility of the objectives and algorithms.

In conclusion, this study, through its scientific methods and practical maintenance strategies, successfully achieves comprehensive optimization and maintenance of old bridges. The provided strategies and decision-making basis contribute to the sustainable development and safe operation of bridges, aligning with the principles of economic efficiency, environmental protection, and long-term viability.

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