Flood Risk Evaluation of Railroad Line in Diffuse Flow Area Based on Coupled Synergetic Modeling

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Abstract. This study focuses on the impacts of flash floods on transportation lines, fully considers the correlation between the natural environmental system and the system of the railroad line itself on the impacts of line floods, and evaluates the flood riskiness of the Lanzhou-Xinjiang Railway in the diffuse flow area of Gansu Province based on the coupled coordination model. The results show that the design capacity of railroad bridges and culverts and the vegetation cover have a significant impact on operational safety; the flood risk of railroad lines within the Hexi Corridor section exhibits a moderately high degree of coupling coordination, especially in Jinchang City and Zhangye City, which need to be more importantly monitored; and the consistency between the degree of coupling coordination and the flood risk results verifies the validity of the assessment model. This study not only provides a scientific basis for the management of railroad floods, but also provides guidance for improving the safety precautions in the relevant regions.

Keywords: transportation line; flood; coupled coordination model; risk evaluation

1 Introduction

Flash floods are sudden floods triggered by heavy rainfall, and their impact on transportation routes cannot be underestimated. At home and abroad, a lot of research has been done in flood disaster evaluation, and the main research methods at present are historical disaster data analysis method, hydrodynamic simulation and analysis method, and index system assessment method [1]. Among them, Gao Yuqin et al [2] evaluated the risk of flooding in the urbanization level area of some administrative districts of Nanjing through ArcGIS technology and comprehensive evaluation method; Li Zongkun et al [3] evaluated the risk level of the inundation area of the dam failure through the hierarchical analysis method and TOPSIS method; and Katarina Lazarević et al [4] evaluated the risk of flooding in the Likodra watershed through the Flash Flood Potential Index (FFPI) and the hierarchical analysis method. Hazard evaluation of potential flash floods in the Likodra watershed by means of FFPI and hierarchical analysis. At present, the flood evaluation object is mainly for cities, reservoirs, and watersheds

H. Bilgin et al. (eds.), *Proceedings of the 2024 6th International Conference on Civil Engineering, Environment Resources and Energy Materials (CCESEM 2024)*, Advances in Engineering Research 253,
https://doi.org/10.2991/978-94-6463-606-2_56

more, while the flood riskiness study for transportation routes is less, and there is no targeted evaluation method and model.

Aiming at the problem of less research on flood risk evaluation of transportation lines, this paper uses the coupled synergy model to evaluate the safety of flash flood disaster of Lanzhou-Xinjiang Railway in the diffuse flow area watershed of Gansu Hexi Corridor region.

2 Overview of the Study Area

Lanzhou-Xinjiang Railway in the Hexi Corridor area has a number of sections built in the Qilian Mountains and the northern slopes of the Longshou Mountain, Haili Mountain and the southern slopes of the Horsehair Mountain hilly area in front of the mountains, the railroad direction and the direction of the mountains are almost parallel to the nearly across all the development of the slope of the diffuse flow area. However, this zone is often no obvious grooves and traces of water flow, usually no water, a drought scene, easy to be mistaken for not affected by flash floods, whenever encountered in larger rainstorms occur when the flood, often with rapid water downhill straight down from the mouth of the outflow, in the diffuse area to form a diffuse flood, then all over the diffuse flow, the Lanzhou-Xinjiang Railway is very harmful. As shown in Fig 1.

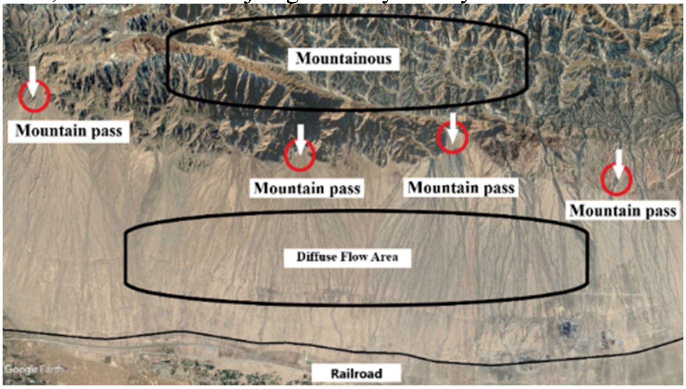


Fig. 1. Spatial distribution of railroad lines and diffuse flow areas

3 Principles of Railroad Line Flood Coupling Coordination

Coupling is originally a concept in physics that refers to the phenomenon of two or more systems or forms of motion interacting with each other through various interactions. Coupling is used to describe the degree to which systems or elements interact with each other. From the point of view of The Synergy Principle, the coupling effect and its degree of coordination determine what order and structure the system goes to when it reaches the critical region, i.e., it determines the tendency of the system from disorder to order [5].

The railroad line is divided into several units according to the railroad bridges and culverts, and the bridge and culvert units are used as the assignment objects of the coupled subsystem. The coupled coordination model includes two subsystems, which are the natural environment system and the railroad bridge culvert system. The 7 indicators of the natural environment system include rainfall data, diffuse flow area, elevation, elevation difference, slope, slope direction and vegetation cover. The two indicators for the railroad bridge system are taken from the hydrological results of the bridge, i.e., the calculated design flood level of one in 100 years and the warning rainfall are used as indicators.

3.1 Entropy Weighting Method

In the coupled system coordination model, the weights are crucial to the results of the evaluation. The current methods of assigning weights have two categories: subjective and objective, and the author adopts the entropy weight method to calculate the weights [6]. The steps of weight calculation of entropy weight method are mainly standardized data, calculation of entropy and determination of entropy weight.

Raw data standardization:

$$R = \left(r_{ij}\right)_{mn} \tag{1}$$

Where: $r_{ij} \in R_{mn}$;the raw data has a total of m indicators and n evaluation units;R_{mn} denotes normalized data.

Calculation of entropy. The entropy of the i-th evaluation metric is:

$$e_i = \sum_{j=1}^{n} p\left(x_{ij}\right) \ln p\left(x_{ij}\right) / \ln n \tag{2}$$

$$p\left(x_{ij}\right) = r_{ij} / \sum_{j=1}^{n} r_{ij} \tag{3}$$

Determination of entropy weights. The entropy weight of the i-th evaluation indicator is:

$$w_i = (1 - e_j) / \sum_{j=1}^{n} 1 - e_j \tag{4}$$

Where: $0 \le w_i \le 1$ and $\sum_{i=1}^{m} w_{i=1} = 1$.

3.2 System Coupling Synergy Model

The multi-system interaction coupling degree is obtained by generalizing from the coupling coefficient model in physics:

$$C = m\left\{(u_1 u_2 \ldots u_m) / \prod (u_i + u_j)\right\}^{\frac{1}{m}} \quad (i, j = 1, 2, \ldots, m, \text{ and } i \neq j) \tag{5}$$

Where: u_1, u_2 represent the natural system index and the railroad's own condition index, respectively. C denotes system coupling, $C \in [0,1]$. The closer the coupling degree is to 1, the more “benign” resonant coupling between subsystems is indicated, which means the higher the danger of the railroad, and the closer the coupling degree is to 0, the more the internal elements of the whole system are in a state of irrelevance, and the system develops in a disorderly manner, which means that the railroad is relatively safe. However, the coupling degree can only illustrate the strength of the interaction within the subsystem without distinguishing the advantages and disadvantages. Therefore, a comprehensive reconciliation index is introduced to construct a coupled coordination model of the natural environment and the railroad

$$T = \alpha_1 u_1 + \alpha_2 u_2 + \ldots + \alpha_i u_i \quad (i=1,2,\ldots,m) \tag{6}$$

$$D = \sqrt{CT} \tag{7}$$

Where: T represents the combined reconciliation index of the natural environment and railroad conditions, emphasizing the magnitude of the degree of coupling and reflecting the degree of goodness of the state of coordination;α_1, α_2, …, α_m denote the coefficients to be determined; D denotes the degree of coupling coordination.

Table 1. Description of coupled coordination degree and hazard classification of railroad line flooding system in diffuse flow area

degree of coupling coordination	Type of coupled coordination	Risk level	Description of a coupled coordination system for railroad lines in diffuse flow areas
0.10~0.20	Low coupling	Low	The subsystems are mutually reinforcing, with a poor degree of coordinated evolution, small weighting of the main influencing factors, and coordination leading to a low likelihood of flooding, which is negligible and maintains the status quo.
0.20~0.40	lower coupling	lower	The subsystems promote each other, the degree of coordinated evolution is poor, the weight of the main influencing factors is small, the coordination leads to the possibility of flooding is small, and the railroad bridges and culverts can be inundated on a small scale.
0.40~0.60	Moderate coupling	Moderate	The subsystems are mutually reinforcing, and the coordinated evolutionary roles and influencing

			factors are moderately weighted, but the coordinated fit is fair enough to allow for moderate scour and inundation of the railroad.
0.60~0.80	Higher coupling	Higher	Subsystem interactions are large. Systematic research intercourse is strong. Influencing factors are weighted more heavily. The coupling coordination is high and is capable of large-scale railroad linear disasters that force train stoppages.
0.80~1.00	High coupling	High	Large interactions between subsystems, strong system evolution, significant weight of influencing factors, high degree of coupling coordination, can occur large-scale washout of roadbed bridges, etc., forcing the train to stop, resulting in huge economic and property losses.

Railroad lines crossing the watershed of the diffuse flow area are affected by the watershed characteristics of the watershed underlain, such as large watershed area, steep watershed slope, weak infiltration capacity of the underlain, strong rainstorms of short duration, low vegetation cover, improper distribution of bridges and culverts in the passes, and insufficient design capacity of bridges and culverts and other complex factors, and the occurrence of scouring of the roadbed, water on the shoulders of the road and the destruction of bridges and culverts, and other water hazards; in addition, the flood capacity of the railroad bridges and culverts will also be affected by whether the upper reaches of the watershed are constructed with diversion dikes, diversion canals and other flood control facilities. Therefore, it is necessary to accurately judge the hazards and further analyze the possibility of triggering floods. According to the practical work experience and related research results in the references [7], the coupling coordination system and the degree of danger of railroad lines in the watershed of the diffuse flow area are classified into five types based on the degree of coupling coordination, as shown in Table 1.

3.3 Efficacy Functions

An efficacy function is established between the estimation of the event outcome and the judgment criterion to reflect the size of the subsystems and the degree of influence of the changes on the evolution of the total system, and the efficacy function consists of two types of efficacy, positive and negative. The positive and negative efficacy functions are:

$$x_{ij}^{'} = \left[x_{ij} - \left(x_{ij} \right)_{\min} \right] / \left[\left(x_{ij} \right)_{\max} - \left(x_{ij} \right)_{\min} \right] \tag{8}$$

$$x_{ij}^{'} = \left[\left(x_{ij} \right)_{\max} - x_{ij} \right] / \left[\left(x_{ij} \right)_{\max} - \left(x_{ij} \right)_{\min} \right] \tag{9}$$

Where: x_{ij} is the initial value of the *j*-th indicator in the *i*-th given system, x_{ij}' is the value of the efficacy function of the *j*-th indicator in the *i*-th given system, $x_{ij} \in (0,1)$.

Larger positive efficacy values indicate less favorable development of coupled synergies in the system; larger negative efficacy values indicate favorable development of coupled synergies in the system. The total degree of influence U_i between subsystems is obtained by weighting and summing the degree of influence of variable x_{ij} between subsystems.

$$U_i = \sum_{i=1}^{m} w_{ij} \cdot x_{ij} \tag{10}$$

Where: w_{ij} is the weight value of the *j*-th indicator in the *i*-th each system, and *m* is the number of factors in the system. Thus, the coupled synergistic evaluation modeling is efficacy as a basis.

4 Railroad Flood Coupling Synergistic Risk Evaluation of Lanxin Line

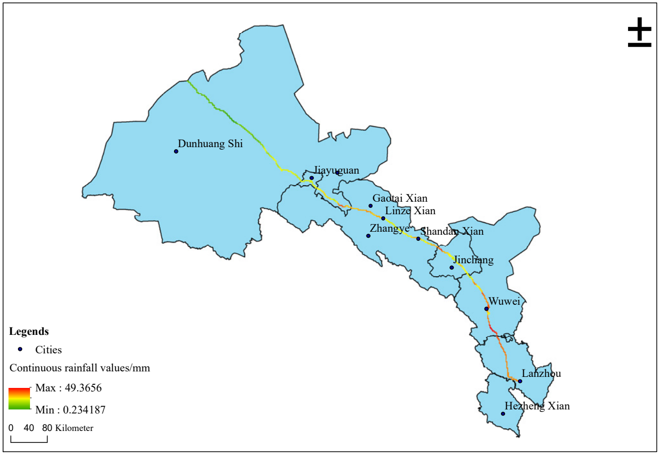
4.1 Synergy Model Subsystem Indicator Values

The values of the indicators of the 2 subsystems of the coupled synergistic model of railroad flooding on Lanzhou-Xinjiang Railway will be given in this section. The indicators of the natural environment system, including rainfall, area of the diffuse flow area, elevation, elevation difference, slope, slope direction, and NDVI, were analyzed by correlation, and it was found that there was a weak correlation between two and two of the indicators. The watershed unit was extracted by GIS means and used as the basic unit to obtain the data of seven environmental indicators in the diffuse flow area along the vicinity of Lanzhou-Xinjiang Railway as shown in Fig. 2.

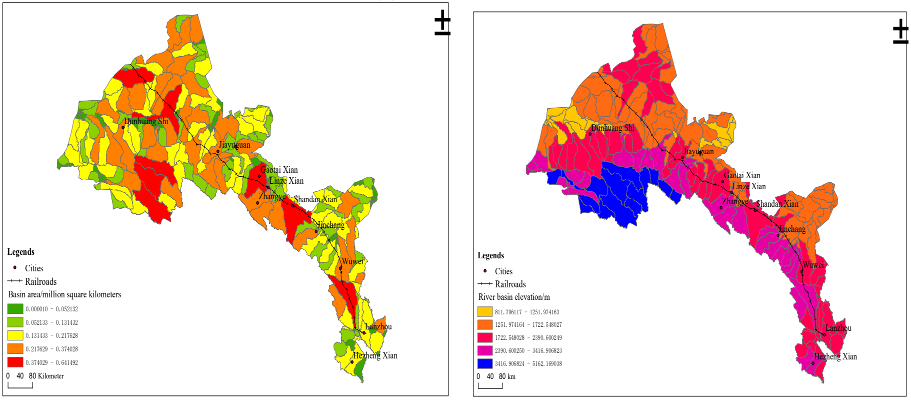
Table 2. Data table of indicators of the Lanzhou-Xinjiang Railway itself in the Hexi Corridor (partial)

serial number	center mileage	Design level of 1 in 100 years /m	Continuous 1-hour warning of rainfall /mm
1	K312.214	1.40	35.33
2	K312.927	0.73	27.20
3	K317.412	1.01	28.17
4	K325.818	0.31	48.96
⋮	⋮	⋮	⋮
190	K950.488	0.61	31.97

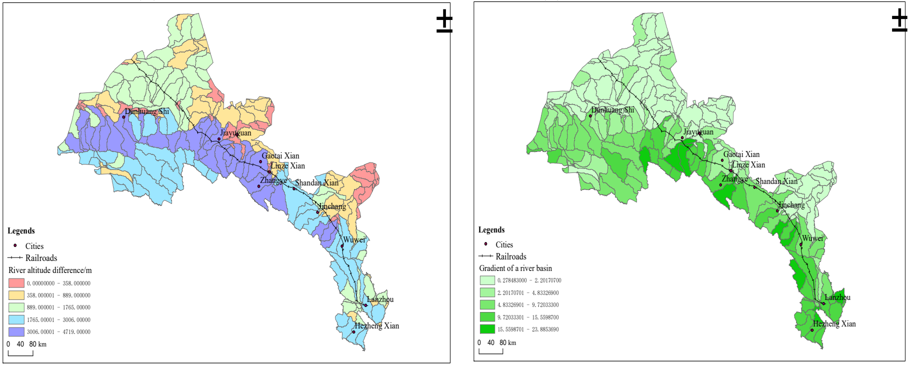
The railroad itself system indicators, including the railroad bridge and culvert one hundred years design water level and bridge and culvert disaster successive 1-hour disaster warning rainfall. The author in the article [7] using hydrological modeling combined with flash flood disaster analysis methods, has obtained the results of the railroad bridge culvert 100-year design water level and disaster warning rainfall. This result has fully considered the anti-flood disaster capacity of the railroad bridge culvert itself, of which 190 railroad bridge culverts are shown in Table 2.



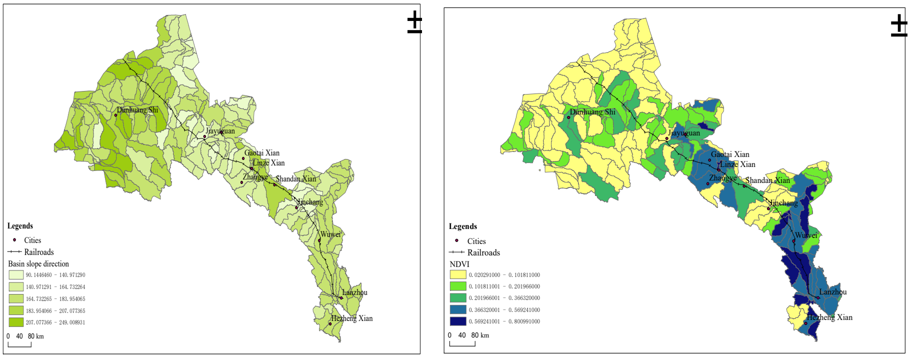
(a)Continuous rainfall



(b)Basin area (c)River basin elevation



(d)River altitude difference (e)Gradient of a river basin



(f)Basin slope direction (g)NDVI

Fig. 2. Results of data on indicators of natural environmental systems

4.2 Evaluation Process and Analysis of Results

The railroad lines within the study area were divided into subunits, and according to the spatial location of railroad bridges and culverts, as well as intersection analysis based on the natural environment indicators and railroad indicators obtained above, the railroad lines were segmented to obtain 189 railroad section subunits.

There are two subsystems in the coupled coordinated risk evaluation system, in which the number of indicators in the pipe body subsystem is 2 and the number of indicators in the natural environment subsystem is 7. The contribution value of each subsystem is calculated according to Eqs. (8) to (10), and the weights of the different indicators in each subsystem are obtained using Eqs. (1) to (4) by using the entropy weight method, and the results are shown in Table 3.

According to the coupled coordination model, the system coupling degree (C), the comprehensive reconciliation index (T), the coupled coordination degree (D) are calculated sequentially according to equations (5) to (7), in which the pending coefficients for the calculation of the comprehensive coordination index are α1 and α2, respectively, and the weights of the subsystem's contribution in the whole evaluation system are taken as α1=0.6222334 and α2=0.377666, and the final calculated results are shown in Table 4. The evaluation results of the coupled coordination model are shown in Figure 3.

The results of the study show that the railroad line system has a higher weight in the two subsystems, with the 100-year design flood level having a higher weight, indicating that the design capacity of railroad bridges and culverts has a greater impact on the normal operation and maintenance of railroads. The NDVI in the natural environment system has the highest weight, i.e., the railroad line crosses a large watershed in the diffuse flow area, and the NDVI data has a high degree of dispersion, indicating that the vegetation coverage has a more obvious influence on whether the railroad line is normally operated or not. According to the results of the coupling coordination degree, it is concluded that the railroad lines within the Gansu section have a moderately high degree of coupling coordination within the Hexi Corridor region, in which the coupling coordination degree of the Jinchang and Zhangye areas is higher, which should be monitored and prevented to avoid the occurrence of the diffuse flood disaster that affects the normal operation and maintenance of the railroad.

Table 3. Railway Evaluation Indicator System and Indicator Weight Table

Subsystems	Evaluation indicators	Weights
Natural environmental systems	Rainfall	0.220126
	Area	0.100035
	Altitude	0.044242
	Altitude difference	0.049142
	Elevation	0.058121
	Slope direction	0.051113
	NDVI	0.477221
Railroad line systems	Design level of 1 in 100 years	0.671557
	Continuous 1-hour warning of rainfall	0.328443

Table 4. Table of Evaluation Results of Lanzhou-Xinjiang Railway Lines (Partial)

Railroad No.	U_1	U_2	C	T	D	risk level
11	0.284	0.142	0.997	0.230	0.479	Middle
25	0.178	0.269	0.980	0.212	0.456	Middle
82	0.221	0.188	0.962	0.209	0.448	Middle
123	0.697	0.164	0.785	0.495	0.624	Relatively high
150	0.148	0.318	0.931	0.212	0.445	Middle
168	0.367	0.467	0.993	0.405	0.634	Relatively high
189	0.435	0.185	0.970	0.340	0.575	Middle

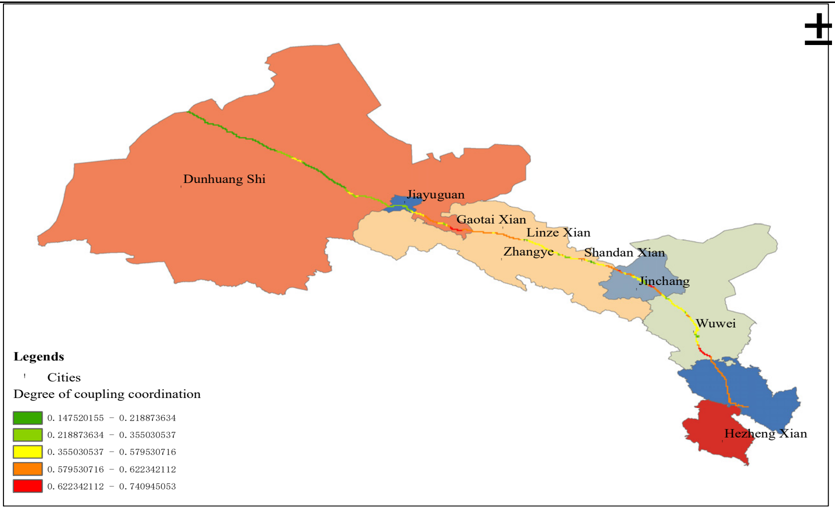


Fig. 3. Evaluation results of the railroad line coupling coordination model

Table 4 lists the coupling synergy D ranking of the study objects as No.168.> No.123.> No.189.> No.11.> No.25.> No.82.> No.150., which, based on the relationship between the coupling coordination degree and the degree of risk, indicates that the risk of diffuse flooding within the railroad line section of No.168. is the highest, followed by No.123., No.189., No.11., No.25., and No.82, No.150.; this result is similar to the results of risk ranking in literature [7]. Its comparison results are shown in Fig. 4, the evaluation results of the two methods can keep good consistency, which indicates that the flood risk evaluation model of railroad line in diffuse flow area based on the coupled synergetic model can quantify the size of the danger more accurately, and it has good applicability, which provides a new method for the evaluation of railroad flood.

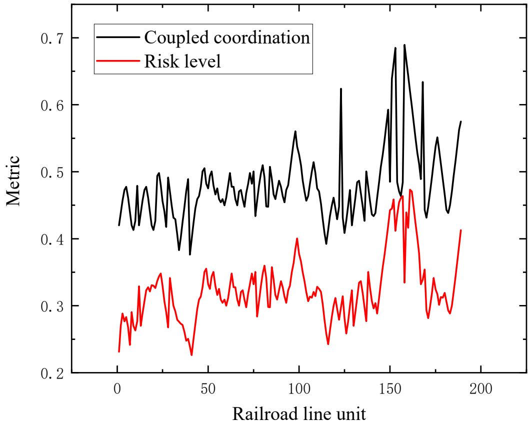


Fig. 4. Comparison results of railroad line flood coordination and hazard level

5 Conclusions

(1) Significant influence of design capacity and natural environment: The design capacity of railroad bridges and culverts, especially the 100-year design flood level, has an important influence on the normal operation of railroads. Meanwhile, NDVI, as a key indicator in the natural environment system, shows that the vegetation cover has a significant influence on the operation condition of the railroad line, which is especially prominent in the diffuse flow area.

(2) Regional differences in coupling coordination degree: Lanzhou-Xinjiang Railway within the Gansu section show moderately high coupling coordination degree in the Hexi Corridor region, especially in Jinchang City and Zhangye City, which need to be monitored and prevented with focus in order to reduce the risk of disasters caused by diffuse flooding and to ensure the normal operation and maintenance of the railroad.

(3) Effectiveness of the flood risk assessment model: through the analysis of the relationship between the coupling coordination degree and the risk level, the diffuse flood risk is the highest in the No.168. railroad line section, and the risk level of other line sections decreases in order. The result is consistent with the risk level classification in the literature, which further indicates that the flood risk assessment method based on

the coupled coordination model can accurately quantify the risk of different railroad segments, and provides a practical scientific basis for the management of and response to railroad floods.

Acknowledgment

This work is supported by National Natural Science Foundation of China (72261024), and Gansu Provincial Science and Technology Program Funding (23ZDFA002,24YFGA041), and Gansu Province Key Talent Program (2023RCXM27), and Gansu Provincial Department of Education Industrial Support Program for Higher Education Institutions Project (2022CYZC-32), and Gansu Provincial Transportation Department Science and Technology Project (2022-27).

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