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Optimization and Engineering Application of Mountain Highway Alignment Schemes Based on Topographic and Geological Constraints

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Abstract

This study establishes a multi-source constraint factor system for mountain highway alignment selection based on "topography–geology–engineering" considerations. Elevation, slope, terrain relief, valley incision density, hazard susceptibility, distance to fault fracture zones, and engineering design indicators are uniformly transformed into spatial constraint intensities. Furthermore, a geological hazard risk penalty mechanism is introduced, and an alignment optimization method integrating "risk assessment–constraint transformation–path search–scheme verification" is developed. The A* algorithm is employed for path searching. The proposed method is applied and validated in a county road reconstruction project in Tibet. The results show that, compared with the traditional river-following scheme, the recommended scheme reduces the route length by approximately 8.0%, decreases the length traversing high-risk areas by about 83.3%, lowers the average constraint intensity by approximately 33.9%, and achieves the optimal comprehensive evaluation value. The study demonstrates that the proposed method can transform geological hazard risk from a qualitative avoidance condition into a quantitative optimization constraint, thereby enabling proactive disaster avoidance and comprehensive optimization of mountain highway alignment schemes. The results can provide technical support for route selection decision-making in complex mountainous areas.

Keywords

Mountain Highway; Alignment Optimization; Topographic and Geological Constraints; Geological Hazard Risk; Multi-Source Constraint Factors

1. Introduction

Affected by complex terrain, deeply incised river valleys, steep slopes with large elevation differences, fault structures, adverse geological bodies, and other factors, highway alignment layout in mountainous areas commonly faces problems such as large engineering scale, high construction difficulty, and prominent disaster risks [1].

Improper route selection may readily lead to high embankments and deep cuttings, an excessive proportion of bridges and tunnels, slope instability, and increased maintenance costs in the later operation stage, and may even induce geological hazards such as landslides, collapses, and debris flows [2]. In recent years, extensive studies have been conducted by scholars both in China and abroad on highway route selection in mountainous areas. Research on topographic constraints has mainly focused on the influence of indicators such as elevation, slope gradient, slope aspect, terrain relief, and valley incision degree on route corridor selection, horizontal and vertical alignment design, and bridge–tunnel arrangement [3]. In engineering practice, scheme comparison is often carried out based on typical alignment patterns, such as river-following routes, ridge-crossing routes, and hillside routes [4]. Related studies commonly employ GIS, DEM, and spatial cost models to transform topographic factors into resistance surfaces for least-cost path searching and alignment suitability analysis [5]. Overall, evaluation methods for topographic factors are relatively mature; however, their coupling with geological risks and engineering constraints remains insufficient. With regard to geological hazard risk assessment, domestic studies have mostly adopted methods such as the analytic hierarchy process, information value method, fuzzy comprehensive evaluation, weights-of-evidence method, and machine learning techniques to conduct susceptibility zoning for hazards including landslides, collapses, and debris flows, thereby supporting geological route selection and slope treatment for highways [6]. International studies, by contrast, place greater emphasis on remote sensing interpretation, multi-source spatial data fusion, and the application of models such as random forests, support vector machines, and logistic regression in hazard susceptibility mapping [7]. These achievements provide important support for identifying geological risks along mountain highways. Nevertheless, most studies still regard disaster risk as a basis for verification or mitigation after the route has been determined, and such risk has not yet been sufficiently incorporated into the route-generation stage. In terms of alignment optimization and scheme comparison, scholars at home and abroad have applied GIS, genetic algorithms, ant colony algorithms, particle swarm optimization, and multi-objective optimization methods to route selection for highways, railways, and pipelines, establishing comprehensive cost functions to search for optimal or near-optimal paths [8]. Meanwhile, multi-criteria decision-making methods, including the analytic hierarchy process, entropy weight method, TOPSIS, and fuzzy comprehensive evaluation, have also been widely used for comparing alternative alignment schemes [9]. However, existing studies are mostly characterized by a mode of "generating schemes first and evaluating their merits afterward." Topographic, geological, and engineering constraints lack a unified representation and dynamic feedback mechanism, making it difficult to fully meet the requirements of proactive disaster avoidance and refined design for highways in complex mountainous areas.

Based on the above considerations, this study focuses on the optimization of highway alignment schemes in mountainous areas. A multi-source constraint factor system for route selection is constructed under the framework of “topography–geology–engineering,” in which topographic controls, geological hazard risks, and engineering design requirements are incorporated into a unified evaluation framework. Furthermore, an alignment optimization method under geological hazard risk constraints is proposed. This study can promote the transformation of mountain highway route selection from “experience-based avoidance and post-event treatment” toward “risk-constrained and proactive optimization,” providing technical support for alignment scheme comparison, disaster risk avoidance, and engineering investment control in mountainous highway projects.

2. Construction of a “Topography–Geology–Engineering” Multi-Source Constraint Factor System

The alignment scheme of a mountain highway is jointly controlled by topographic conditions, geological safety, and engineering feasibility. To overcome the limitations of traditional route selection, such as “emphasizing topography while neglecting geology” or “determining the alignment first and conducting treatment afterward,” this study constructs a “topography–geology–engineering” multi-source constraint factor system following the principles of “quantifiable factors, spatially expressible information, and engineering interpretability.” Topographic constraints mainly reflect the influence of natural landforms on route extension, longitudinal gradient control, and bridge–tunnel arrangement. Geological constraints are used to characterize the controlling effects of adverse geological conditions, such as landslides, collapses, debris flows, and fault fracture zones, on route safety. Engineering constraints reflect requirements related to horizontal and vertical alignment, bridge and tunnel scale, connection with control points, and construction feasibility. The specific factors are listed in Table 1.

Table 1. Multi-source constraint factor system based on “topography–geology–engineering”

Criterion layer	Indicator layer	Indicator implication	Attribute
Topographic constraint	Elevation	Reflects ridge-crossing and elevation-difference control	Cost type
	Slope gradient	Reflects ground steepness and excavation difficulty	Cost type
	Terrain relief	Characterizes local elevation variation	Cost type
	Valley incision density	Reflects impacts on culverts, bridges, and drainage	Cost type
Geological constraint	Landslide susceptibility	Characterizes the probability of landslide development	Cost type
	Collapse susceptibility	Characterizes the risk of dangerous rock and rockfall	Cost type
	Debris-flow hazard	Characterizes the threat of gully hazards	Cost type
	Distance to fault fracture zone	Reflects the influence of tectonic fragmentation	Cost type

Engineering constraint	Horizontal alignment adaptability	Reflects constraints such as radius and deflection angle	Cost type
	Longitudinal gradient adaptability	Reflects the coordination between gradient and slope length	Cost type
	Bridge and tunnel engineering scale	Reflects engineering investment and construction difficulty	Cost type
	Compliance with control points	Reflects the requirement for node connection	Benefit type

Because the factors have different dimensions, standardization is required. For cost-type indicators for which larger values are more unfavorable, such as slope gradient, terrain relief, and hazard susceptibility, dimensionless processing is performed using Eq. (1):

$$x_i' = \frac{x_i - x_{i,\min}}{x_{i,\max} - x_{i,\min}} \tag{1}$$

where x_i is the original indicator value; $x_{i,\min}$ and $x_{i,\max}$ are the minimum and maximum values of the indicator, respectively; and x_i' is the standardized constraint value. A value closer to 1 indicates that route passage through the corresponding area is more unfavorable. For benefit-type indicators related to favorable factors, such as proximity to towns, interchange locations, or existing road networks, Eq. (2) is adopted:

$$x_i' = \frac{x_{i,\max} - x_i}{x_{i,\max} - x_{i,\min}} \tag{2}$$

For restricted areas that are prohibited or generally not allowed to be crossed, such as ecological redlines, core zones of active faults, and extremely high-risk hazard areas, a hard constraint factor is defined as follows:

$$H_j = \begin{cases} 1, & \textit{Allowed to pass} \\ 0, & \textit{Prohibited to pass} \end{cases} \tag{3}$$

After standardizing individual factors, the comprehensive constraint intensity is calculated using a weighted overlay method:

$$C = \sum_{k=1}^{3} W_k \sum_{i=1}^{n_k} w_{ki} x_{ki}' \tag{4}$$

where C denotes the comprehensive constraint intensity; W_k is the weight of the criterion layer for topography, geology, or engineering; w_{ki} is the weight of the i-th indicator in the k-th category; and x_{ki}' is the standardized value. Considering the significant influence of geological hazards on the safety of mountain highways, a risk penalty term is further introduced:

$$C^* = C + \lambda R_g \tag{5}$$

where C^* is the corrected comprehensive constraint cost; R_g is the geological hazard risk value; and λ is the risk penalty coefficient. As geological risk increases, the passage cost of the route also increases, thereby guiding the route to proactively avoid high-risk sections. For engineering application, the comprehensive constraint intensity is divided into five levels, as shown in Table 2.

Table 2. Classification of comprehensive constraint intensity and route-selection recommendations

Range of C^*	**Level**	**Engineering implication**	**Route-selection recommendation**
0–0.20	Low constraint	Gentle terrain and stable geology	Preferred for alignment layout
0.20–0.40	Relatively low constraint	Local general restrictions exist	Can be used as a main corridor
0.40–0.60	Moderate con-straint	Requires certain bridges, tunnels, or protection works	Pass with caution
0.60–0.80	Relatively high constraint	Large hazard risk or engineering scale	Avoid as far as possible
0.80–1.00	High constraint	High-risk or strongly restricted area	Avoid in principle

3. Route Optimization Method for Mountain Highways under Geological Hazard Risk Constraints

Geological hazard risk is further embedded into the route-generation process, and an alignment optimization method integrating “risk assessment–constraint transformation–path search–scheme verification” is established. This enables the route to proactively avoid high-risk sections during the formation stage. The technical workflow is shown in Fig. 1.

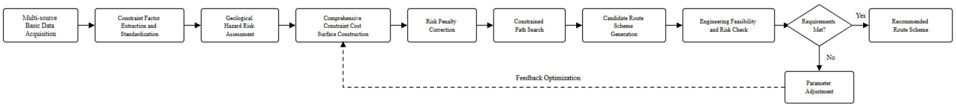

Fig 1. Route optimization workflow for mountain highways under geological hazard risk constraints

For hazards such as landslides, collapses, debris flows, and fault fracture zones, the comprehensive geological hazard risk value is expressed as:

$$C^* = C + \lambda R_g \tag{6}$$

where R_g is the comprehensive geological hazard risk value; R_j is the standardized risk value of the j-th type of hazard; α_j is its weight; and m is the number of hazard types. To highlight the constraining effect of high-risk areas on route searching, an exponential risk penalty function is introduced:

$$P_g = \exp(\beta R_g) - 1 \tag{7}$$

where P_g is the risk penalty value and β is the risk sensitivity coefficient. Combined with the comprehensive constraint intensity, the passage cost of a grid cell can be expressed as:

$$D_i = H_i\left(C_i + \lambda P_{g,i}\right) \tag{8}$$

where D_i is the passage cost of the *i*-th grid cell; C_i is the comprehensive constraint intensity; $P_{g,i}$ is the risk penalty value; λ is the risk penalty coefficient; and H_i is the hard constraint factor. For areas such as ecological redlines, core zones of active faults, and extremely high-risk hazard areas, H_i is assigned an extremely large value or set as impassable. The geological hazard risk levels and corresponding route control measures are shown in Table 3.

Table 3. Geological hazard risk levels and route control measures

Range of R_g	**Risk level**	**Route control measure**
0–0.20	Low risk	Preferred for passage
0.20–0.40	Relatively low risk	Passage is allowed
0.40–0.60	Moderate risk	Pass with caution
0.60–0.80	Relatively high risk	Avoid as far as possible
0.80～1.00	High-risk	Avoid in principle

Based on the comprehensive cost surface, route optimization can be transformed into a minimum cumulative-cost path problem from the starting point *S* to the terminal point *T*. Assuming that the route consists of a node set $L=\{n_1, n_2,\cdots, n_q\}$, the objective function is:

$$\min F(L) = \sum_{i=1}^{q} D_i l_i \tag{9}$$

where l_i is the passage length of the route within the *i*-th grid cell. The optimization process should satisfy constraints including avoidance of prohibited areas, maximum longitudinal gradient, and minimum horizontal curve radius:

$$L \cap \Omega_f = \varnothing, \quad i_{\max} \le i_{\text{allow}}, \quad R_{\min} \ge R_{\text{allow}} \tag{10}$$

where Ω_f denotes the prohibited crossing area, and i_{allow} and R_{allow} are the maximum allowable longitudinal gradient and minimum allowable radius specified by the design code, respectively. The A* algorithm can be adopted for path searching. To avoid excessive detours or unreasonable engineering scale in the minimum-cost path, candidate schemes should be comprehensively verified using the indicators listed in Table 4.

Table 4. Verification indicators for candidate alignment schemes

Indicator	**Calculation method**	**Attribute**
Route length	$L_s = \sum l_i$	Cost type
Average constraint intensity	$\bar{C} = \frac{1}{q}\sum C_i^*$	Cost type
Length crossing high-risk areas	$L_r = \sum l_i\left(R_g \ge 0.60\right)$	Cost type

Bridge–tunnel ratio	$\eta = \dfrac{L_b + L_t}{L_s}$	Cost type
Compliance with control points	Degree of node connection	Benefit type

The comprehensive evaluation value of a candidate route can be expressed as:

$$Q_s = \mu_1 L_s' + \mu_2 \overline{C}' + \mu_3 L_r' + \mu_4 \eta' - \mu_5 M' \tag{11}$$

where a smaller Q_s indicates a better scheme; M' is the standardized value of compliance with control points; and μ_1~μ_5 are the weights. Through the above method, geological hazard risk can be transformed from a qualitative avoidance requirement into a quantitative constraint in route optimization, thereby achieving proactive hazard avoidance and comprehensive optimization of mountain highway alignment schemes.

4. Engineering Application

To verify the engineering applicability of the proposed "geological hazard risk constraint–route optimization" model, a county road reconstruction project in Tibet was selected as the application case. The total length of the road section is approximately 30 km. The terrain along the route is dominated by deeply incised river valleys and steep mountainous areas, with local development of landslide deposits, collapse-prone dangerous rocks, and fault fracture zones. The traditional river-following alignment scheme suffers from problems such as high embankments and deep cuttings, as well as high hazard exposure. In this study, a 1:50,000 geological map, 30 m DEM, remote sensing interpretation results, and existing hazard point data were used. The comprehensive constraint intensity surface and risk penalty surface were calculated according to Eqs. (4)–(8), and then superimposed to form a passage cost surface for A* path searching.

Considering the constraints of starting and terminal points, connection with control points, and code-based longitudinal gradient requirements, three candidate schemes were generated: Scheme A, a low-elevation river-following alignment; Scheme B, a hillside bypass alignment; and Scheme C, a scheme involving local short tunnels. Comprehensive evaluation of each scheme was conducted according to Eq. (11), and the results are presented in Table 5. It can be seen that although Scheme A has the shortest route length, it crosses the longest sections of high-risk landslide and debris-flow areas and has the highest comprehensive constraint intensity. Scheme B performs better than Scheme A in terms of risk avoidance; however, due to the influence of terrain relief, its bridge and tunnel engineering scale remains relatively large. Scheme C adopts short tunnels in high-risk gully sections and avoids fault fracture zones, resulting in the shortest length crossing high-risk areas, the lowest average constraint intensity, and the optimal comprehensive evaluation value.

Table 5. Comprehensive comparison results of candidate alignment schemes

Scheme	Route length /km	Average constraint intensity	Length crossing high-risk areas/km	Bridge–tunnel ratio/%	Compliance with control points	Comprehensive evaluation value *Qs*
A	31.2	0.62	5.4	16	0.76	0.73
B	29.7	0.49	2.3	24	0.87	0.55
C	28.8	0.41	0.9	30	0.84	0.43

Compared with Scheme A, Scheme C shortens the route length by approximately 8.0%, reduces the length crossing high-risk areas by approximately 83.3%, and decreases the average constraint intensity by approximately 33.9%. Although the bridge–tunnel ratio of Scheme C is higher, it significantly reduces the length of hazard-exposed sections and the demand for subsequent protection works, thus demonstrating better comprehensive economy and safety. Further field investigation indicates that Scheme C adopts a small-radius bypass at the front edge of the landslide deposit and uses a short tunnel to cross the fault fracture zone, thereby avoiding large-scale high-slope excavation. Meanwhile, in gully sections, the route preferentially utilizes stable ridges for transition, reducing the impact of debris-flow scouring. These results indicate that the proposed method can shift geological hazard risk from an "object of post-event treatment" to a "constraint in scheme generation," enabling route optimization to shift from experience-dominated decision-making to risk-driven decision-making.

In summary, this engineering application demonstrates that the established "topography–geology–engineering" multi-source constraint system can effectively characterize the controlling factors of mountain highway alignment. The proposed optimization method can proactively avoid high-risk sections while satisfying design specifications and control-point requirements, showing good engineering operability and potential for wider application.

5. Conclusion

The alignment layout of mountain highways is jointly affected by complex terrain, adverse geology, and engineering control conditions. Traditional route-selection methods often regard geological hazard risk as a verification factor after the route has been determined, making it difficult to achieve proactive hazard avoidance. In this study, a "topography–geology–engineering" multi-source constraint factor system was constructed, in which topographic controls, geological hazard risks, and engineering design requirements were uniformly expressed as spatial constraint intensities. Furthermore, a risk penalty mechanism was introduced to establish a route optimization method integrating "risk assessment–constraint transformation–path search–scheme verification." The method was verified using a county road reconstruction project in Tibet. The main conclusions are as follows.

(1) The constructed multi-source constraint factor system can comprehensively characterize the controlling factors in mountain highway route selection. By incorporating elevation, slope gradient, terrain relief, valley incision density, hazard

susceptibility, distance to fault fracture zones, and engineering design indicators, the unified quantification of topographic, geological, and engineering factors is achieved, providing a basis for route corridor screening and scheme comparison.

(2) The proposed geological hazard risk constraint method embeds risks associated with landslides, collapses, debris flows, and fault fracture zones into the passage cost function. By combining the risk penalty term with hard constraint conditions, the route search can proactively avoid high-risk areas, realizing the transformation of geological risk from “qualitative avoidance” to “quantitative constraint.”

(3) The engineering application results show that the recommended Scheme C has a comprehensive evaluation value of 0.43, outperforming Scheme B with 0.55 and Scheme A with 0.73. Its average constraint intensity is 0.41, and the length crossing high-risk areas is 0.9 km, both lower than those of the other schemes, indicating that the method can effectively reduce hazard exposure along the route.

(4) Compared with the traditional river-following Scheme A, Scheme C shortens the route length from 31.2 km to 28.8 km, representing a reduction of approximately 8.0%; reduces the length crossing high-risk areas from 5.4 km to 0.9 km, corresponding to a decrease of approximately 83.3%; and decreases the average constraint intensity from 0.62 to 0.41, with a reduction of approximately 33.9%. Although the bridge–tunnel ratio increases to 30%, Scheme C reduces high-slope excavation and the need for subsequent geological hazard treatment, thereby providing superior overall safety and engineering rationality.

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