

Article

Safety of Lightweight Embankment and Optimal Design of Roadside Guardrail Foundation Under Vehicle Collision

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Abstract

Foamed concrete has been used to construct lightweight embankments as a substitute for conventional fills, aiming to promote its engineering application in soft-soil regions. However, the dynamic response and safety mechanism of foamed concrete embankments during vehicle collision are not yet fully understood. In this paper, the safety performance of lightweight foamed concrete embankments under vehicle–guardrail collision and the optimal design of the guardrail foundation are investigated from the perspectives of lateral displacement and stress distribution. Through static uniaxial compression tests, the stress–strain curves, compressive strength, elastic modulus, and statistical variability of foamed concrete with six different mix proportions were obtained. On this basis, a coupled finite element model of the vehicle–guardrail–lightweight embankment system was established (the guardrail and its foundation were modeled using a linear elastic constitutive model, the embankment using a crushable foam model, and the vehicle using a 1.5 t passenger car model validated by full-scale crash tests). According to the passenger car impact conditions specified in current Chinese regulations (velocity 100 km/h, angle 20°), the peak lateral displacement and peak principal stress of the lightweight embankment were analyzed for four foundation base slab lengths (L_0 , $1.1 L_0$, $1.2 L_0$, $1.3 L_0$). The results show that increasing the base slab length effectively reduces lateral displacement and stress concentration. Increasing the length by 10–20% reduces the peak lateral displacement by up to 68%, and the peak principal stress remains far below the material strength. From the perspectives of structural stability and cost-effectiveness, a 10–20% increase in the base slab length is recommended. The ratio of the peak principal stress to the material strength can serve as a criterion for evaluating the safety margin and assessing the rationality of the foundation design. This study provides quantitative evidence for optimizing the guardrail foundation base slab length to enhance the collision safety of lightweight foamed concrete embankments, and the proposed design range offers a cost-effective reference for practical engineering applications in soft-soil regions.

Keywords: foam concrete; mechanical properties; lightweight embankment; finite element simulation; guardrail foundation



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1. Introduction

The dynamic response of lightweight embankments under vehicle collisions and the safety and stability of roadside guardrail foundations serve as core indicators for evaluating the rationality of lightweight embankment engineering and road protection facility design in soft-soil regions. However, this issue is governed by the coupled effects of multiple factors, including the physical and mechanical parameters of lightweight soil, embankment filling technology, guardrail foundation forms, collision speed and angle, and vehicle type. Moreover, these influencing factors exhibit pronounced nonlinearity and uncertainty under impact loading. Wang et al. [1] systematically analyzed the structural damage and maintenance economy of vehicles under low-speed collisions based on C-IASI test data, clarifying the engineering characteristics of high frequency and high maintenance costs associated with low-speed collisions. Zhan et al. [2] established a two-stage LSTM-BN model to realize accurate real-time prediction of vehicle collision risks, revealing the governing mechanism of the nonlinear coupling of human-vehicle-road multi-dimensional factors on collision risk. Kim et al. [3] conducted collision analysis on reinforced concrete guardrails using a node-independent model, uncovering the cooperative mechanical behavior between bridge decks and guardrails. Chen et al. [4] evaluated the crashworthiness of guardrails on long-span cable-stayed bridges via multi-angle collision simulations, identifying the controlling effect of impact angle on guardrail failure modes and vehicle trajectories. Zhang et al. [5] developed a vehicle–guardrail collision model using finite element method (FEM), clarifying the influences of vehicle type, speed, and angle on guardrail deformation and energy absorption. Gu [6] investigated the performance of corrugated beam guardrails in lightweight foam soil sections and verified the ultimate crash capacity and foundation stability of guardrails using the energy method. Ma et al. [7] performed collision simulations on novel assembled composite guardrails with explicit FEM, revealing the influence of guardrail connection details and foundation forms on crash performance. Habtemariam et al. [8] implemented high-speed vehicle–guardrail collision simulations using the discrete element method, providing a lightweight numerical approach for complex impact scenarios. Zheng et al. [9] studied the heavy vehicle crash resistance of FRP–concrete composite guardrails, highlighting the key roles of composite structures and rigid foundations in enhancing protective efficiency. Wei et al. [10] proposed a novel high-strength steel lightweight guardrail and conducted its structural and safety performance design, offering an optimized scheme for guardrails adapted to lightweight subgrades. Pan et al. [11] revealed the failure mechanism of urban road guardrails under vehicle impact using the finite element method, and proposed guardrail optimization schemes from the perspectives of columns, bases, and connection details. Yu et al. [12] compared the crashworthiness of rotary guardrails and corrugated beam guardrails, confirming that rotary guardrails exhibit superior performance in vehicle guiding, energy absorption, and deformation control. Wu et al. [13] optimized the structure of a new type of corrugated beam guardrail through orthogonal tests, and clarified the influences of guardrail plate thickness, column thickness, and block thickness on crashworthiness. Gong [14] systematically investigated the effects of slope parameters of concrete barriers on vehicle impact protection, and put forward the optimal combination of slope parameters. Pan et al. [15] summarized the dynamic response characteristics of frame structures and bridge piers under vehicle collision, and revealed the differences in failure modes between reinforced concrete and concrete-filled steel tubular structures under impact loading. Liu et al. [16] established a guardrail collision risk assessment model based on catastrophe theory, realizing quantitative safety grade evaluation under multi-factor coupling. Wen et al. [17] conducted sensitivity analysis of guardrail crashworthiness parameters considering anchorage effects, indicating that anchor plate and column thicknesses are key factors affecting protective performance. Ma et al. [18]

analyzed the dynamic response of anti-collision guardrails in the cable zone of cable-stayed bridges under vehicle impact, providing a basis for guardrail design in special bridge sections. Zhang et al. [19] carried out full-scale impact tests and numerical simulations on recycled foamed concrete wall-type guardrails, verifying the crashworthiness and reliability of the new lightweight guardrail. Yang et al. [20] established a 3D simulation model via explicit FEM, and systematically evaluated the crash performance of the movable median guardrail from the aspects of energy absorption, vehicle acceleration, collision trajectory and guardrail dynamic response. Cao et al. [21] conducted high-fidelity finite element simulations to investigate the requirements and failure modes of concrete barriers under MASH TL-4 and TL-5 conditions. An inelastic pushover analysis method was proposed to evaluate the bearing capacity of these concrete barriers. Based on the damage modes observed in pushover analysis, a modified yield line method (MYLM) was developed to estimate the load-carrying capacity of concrete barriers. Xu et al. [22] analyzed the failure modes, influencing factors and impact force responses of conventional and strengthened RC structures under vehicle collision.

Shi et al. [23] reported that incorporating ceramsite lightweight aggregates increased the peak stress by 151% and energy absorption density by 211%, enabling rapid attenuation of pressure waves. A recent review by Boddepalli et al. [24] highlighted that the low self-weight, good energy absorption, and deformation capacity of foamed concrete make it particularly suitable for seismic-resistant and impact-prone applications. Economically, the lightweight nature reduces foundation treatment costs. Cai et al. [25] demonstrated that a bridge-head-free cone slope retaining wall using foamed concrete effectively saves construction costs while reducing differential settlement with increased replacement thickness. Environmentally, foamed concrete can incorporate industrial by-products to lower its carbon footprint. Zhang et al. [26] showed that replacing 70% of cement with ground circulating fluidized bed fly ash (CFBFA) reduced global warming potential by 52.3% and total cumulative energy consumption by 43.2%. These combined advantages make foamed concrete an ideal lightweight fill for embankments in soft-soil regions. Chen et al. [27] systematically investigated the dynamic compressive behavior of foamed concrete over a wide strain-rate range (500 s^{-1} to 1300 s^{-1}) and temperatures (25°C to 600°C) using a high-temperature viscoelastic SHPB technique, establishing a reliable stress–strain constitutive model for impact applications. Regarding guardrail foundation design, Jia and Li [28] optimized the separated concrete guardrail foundation for expressway reconstruction projects, demonstrating that foundation stability directly affects safety performance and that soil compaction positively correlates with guardrail stability. Li et al. [29] developed a practical finite element model for a guardrail post embedded in soil, where the post–soil interaction was represented by nonlinear uncoupled springs, and validated the approach using explicit FEM. Similarly, Sassi and Ghrib [30] created a numerical model of a rigid impactor striking a roadside post, comparing a continuum soil model (Drucker–Prager) with a simplified subgrade method using parallel springs and dampers, and found the simplified method efficient and accurate for simulating soil–post interaction under impact.

Although extensive research has been conducted on the dynamic response of vehicle–guardrail collision systems, most existing studies are based on conventional soil subgrades or rigid pavements. Foamed concrete, as a lightweight embankment material, exhibits fundamentally different mechanical behaviors under impact loading due to its low density, high porosity, and high compressibility. Nevertheless, critical research gaps remain: (1) Existing studies on foamed concrete are almost exclusively focused on static loading conditions. Its dynamic constitutive relationship, failure criteria, and energy absorption mechanism under high-strain-rate vehicle impact are still unclear. (2) Current optimization of guardrail foundations is primarily targeted at conventional soil or rock subgrades, with a

lack of systematic investigation into the contact stress distribution, deformation compatibility, and overall stability of the L-shaped foundation resting on a compressible lightweight embankment. (3) Safety evaluation indices (e.g., lateral displacement limit, stress diffusion efficiency, local crushing tolerance) for lightweight embankments under vehicle collision have not yet been established, leaving engineering design without clear guidelines.

To address the above gaps, this paper pursues the following three objectives: Objective 1: To experimentally characterize the static mechanical properties (compressive strength, elastic modulus, stress–strain relationship) of foamed concrete with different mix proportions through uniaxial compression tests, providing basic material data for subsequent numerical simulations. Objective 2: To develop a coupled finite element model of the vehicle–guardrail–lightweight embankment system, and to analyze the lateral displacement and stress distribution of foamed concrete embankments with varying strengths under a standard collision scenario, thereby revealing their dynamic response characteristics. Objective 3: To propose and validate an optimal design of the guardrail foundation (specifically, the base plate length) that effectively reduces deformation and stress concentration in the lightweight embankment, and to provide a cost-effectiveness recommendation.

Full-scale vehicle collision tests, while providing the most direct validation, are prohibitively expensive, time-consuming, and involve safety risks. Numerical simulation using the finite element method offers a practical alternative that allows systematic parametric studies under controlled conditions. In this study, a validated passenger car model is employed, and the material models for foamed concrete are calibrated against experimental static test data. The finite element approach enables us to investigate the influence of various foundation lengths (four cases) on embankment response, which would be impractical through physical testing. It is acknowledged that numerical modeling involves simplifications (e.g., linear elastic assumption for the guardrail, omission of embankment slopes), and these limitations are discussed in the relevant sections. Nevertheless, for comparative design optimization, the method provides reliable insights.

This work provides three novel contributions beyond existing literature. First, while previous studies on foamed concrete have focused on static properties, this study systematically characterizes its static mechanical parameters (strength, modulus, statistical variability) and directly uses them as inputs for impact simulation. Second, unlike existing vehicle–guardrail collision models that assume conventional subgrades, this study develops a coupled model explicitly representing the lightweight embankment with a crushable foam material and the L-shaped foundation with contact interaction. Third, this study proposes a quantitative optimization of the guardrail foundation base slab length (10–20% increase) based on both lateral displacement and peak stress criteria, providing a cost-effective design reference specifically for lightweight embankments in soft-soil regions.

2. Study on Static Mechanical Properties of Foamed Concrete

2.1. Raw Materials of Foamed Concrete Specimens

Foamed concrete specimens are primarily composed of cement, a foaming agent, and water. According to the relevant specifications for raw materials [31], Grade 42.5R ordinary Portland cement (Conch brand, Nanjing Jiangning Zhonglian Cement Plant) was used in this study, with a density of 3110 kg/m³ and a specific surface area of 256 m²/kg. A composite protein foaming solution (Henan Huatai Engineering Co., Ltd., Anyang, China) was employed, and foaming was conducted using an air compression foaming machine. Regarding the water requirements [32], tap water was adopted in this test, as it is among the generally preferred water sources for concrete.

2.2. Mix Proportion Design

With reference to the classification of road filling performance indicators specified in Specification T177, the minimum strength grade for urban expressways, highways, first-class highways and arterial roads is 0.8 MPa, and the minimum wet density is taken as 5 kN/m³. The water–binder ratio of foamed concrete is generally selected in the range of 0.55–0.65.

The mix proportion design of the foamed concrete specimens is shown in Table 1.

Table 1. Mix proportion design of foam concrete specimens.

Specimen Groups	Cement (kg/m ³)	Water (kg/m ³)	Bubble Cluster (L/m ³)
A	350	215	672
B	325	200	695
C	400	230	641
D	365	219	663
E	375	225	653
F	324	227	668

2.3. Static Tests of Foamed Concrete

2.3.1. Test Program

Uniaxial compression tests were carried out using an electro-hydraulic servo universal material testing machine produced by Jiangsu Zhuoheng Measurement and Control Technology Co., Ltd. (Nanjing, China). A constant loading rate of 0.6 kN/s was uniformly applied to the prepared cubic foamed concrete specimens of 100 mm × 100 mm × 100 mm until fracture occurred. The entire failure process was recorded by a high-speed camera. For each mix proportion of foamed concrete, three specimens were tested under uniaxial compression to ensure the reliability of the test results.

2.3.2. Static Compressive Mechanical Properties of Foamed Concrete Specimens

Grouped experiment shows the static uniaxial compressive stress–strain curves of foamed concrete specimens with different mix proportions at the same loading rate. According to the overall trend of the curves, the stress–strain response of foamed concrete under static uniaxial compression can be systematically divided into four stages: elastoplastic transition, rapid stress drop, stable strength maintenance, and final densification enhancement.

In the elastoplastic transition stage, i.e., at the initial loading, the stress of the foamed concrete specimen increases linearly with strain, and the elastic limit is reached at a strain of approximately 0.03. Beyond this point, the specimen enters the plastic stage until the peak stress is attained, and the slope of the curve in this stage is slightly lower than that in the elastic stage. Academically, this peak stress is generally regarded as the compressive strength of foamed concrete.

Subsequently enters the rapid stress drop stage. With compression, microcracks propagate and interconnect continuously, accompanied by progressive yielding and collapse of pore walls as well as pore densification. Compared with ordinary concrete, foamed concrete does not lose its bearing capacity rapidly when subjected to local damage. As strain increases, the stress gradually decreases to a stable value, and the ultimate strain of specimens with different mix proportions in this stage ranges from 0.1 to 0.3.

Then comes the stable strength maintenance stage. Owing to the collapse of pore walls and material densification in the previous stage, the stress fluctuates within a relatively stable range as strain continues to increase. This stage features a relatively long strain process. However, for specimens in Group C and Group D, uneven pore distribution

caused by insufficient manual mixing of cement paste and foaming solution results in a shorter strain duration in this stage.

The densification enhancement stage appears after a long period of stable strength. In this stage, a large number of internal pore walls of the foamed concrete specimen have undergone instability failure and been compacted, increasing the effective bearing area and redistributing the stress. With continuous loading, the stress rises sharply in an exponential manner and even exceeds the peak stress obtained in the elastoplastic transition stage.

In addition, foamed concrete exhibits an obvious structural behavior, leading to fluctuations in its stress–strain curves. When partial structures bear the load, the stress rises first; once these structures fail, the stress drops rapidly. Meanwhile, abundant independent and non-interconnected pores exist inside foamed concrete. Therefore, after the failure of one structural unit, the material will continue to fracture the next unit, causing another stress fluctuation of rise and fall. Notably, foamed concrete does not lose its bearing capacity at any strain level.

2.3.3. Static Compression Data of Foamed Concrete Specimens

It can be seen from the uniaxial compressive stress–strain curves that the strength of the prepared foamed concrete specimens ranges from 1.04 MPa to 1.38 MPa, which meets the requirements for engineering applications. According to the uniaxial compressive stress–strain curves, the static mechanical parameters of foamed concrete specimens in each group are listed in Table 2.

Table 2. Static Mechanical Parameters of Foam Concrete.

Test Groups	Specimen Number	Density (kg/m ³)	Compressive Strength (MPa)	Elastic Limit Strain	SD (MPa)	CV (%)	95% CI (MPa)
A	A01	432.3	1.08	0.029	0.036	3.5%	[0.95, 1.13]
	A02	431.2	1.03	0.028			
	A03	431.6	1.01	0.027			
	average	431.7	1.04	0.028			
B	B01	391.2	1.18	0.024	0.108	9.9%	[0.82, 1.36]
	B02	392.1	0.97	0.020			
	B03	392.7	1.12	0.019			
	average	392.0	1.09	0.021			
C	C01	487.8	1.21	0.038	0.095	8.5%	[0.88, 1.36]
	C02	487.1	1.13	0.049			
	C03	485.8	1.02	0.039			
	average	486.9	1.12	0.042			
D	D01	466.2	1.38	0.032	0.076	5.5%	[1.20, 1.58]
	D02	466.9	1.32	0.029			
	D03	466.4	1.47	0.038			
	average	466.5	1.39	0.033			
E	E01	491.3	1.22	0.024	0.036	3.1%	[1.09, 1.27]
	E02	492.3	1.17	0.022			
	E03	492.7	1.15	0.023			
	average	492.1	1.18	0.023			
F	F01	558.4	1.46	0.031	0.085	6.2%	[1.17, 1.59]
	F02	558.6	1.29	0.026			
	F03	559.7	1.39	0.027			
	average	558.9	1.38	0.028			

To assess the statistical reliability of the experimental data, we calculated the standard deviation (SD), coefficient of variation (CV), and 95% confidence interval (CI) for the compressive strength of each group. The coefficients of variation for all groups range from 3.1% to 9.9%, with the majority of groups exhibiting CV values below 7%. These relatively low CV values indicate that the specimen preparation and testing procedures were consistent, and that the mechanical property data are acceptable as input parameters for finite element modeling.

For each foamed concrete mix proportion, three specimens were selected for uniaxial compression tests to meet the minimum sample size requirement specified in the relevant standard [31]. Given that three specimens constitute a small sample with limited statistical reliability, the average values of each group are considered as preliminary reference data.

3. Materials and Methods

3.1. Establishment of Finite Element Model

The finite element model of the collision system between the vehicle and the roadside guardrail on the lightweight embankment in this paper consists of the guardrail and its foundation, the vehicle, the lightweight embankment, the subgrade and the foundation. The geometric model was constructed using 3D modeling software, and a finite element pre-processor was employed for mesh generation to improve simulation accuracy. Subsequently, comprehensive pre-processing—including assigning material parameters and setting reasonable initial and boundary conditions—was conducted for the explicit finite element analysis.

The geometric model was constructed using 3D modeling software, and a finite element pre-processor was employed for mesh generation to improve simulation accuracy. Subsequently, comprehensive pre-processing—including assigning material parameters and setting reasonable initial and boundary conditions—was conducted for the explicit finite element analysis.

In addition, key settings such as contact parameters, calculation control parameters and data output control were meticulously configured to ensure the accuracy of simulation results and comprehensively reflect the dynamic behaviors during the collision process.

3.1.1. Finite Element Model of Guardrail and Its Foundation

SA-grade F-type concrete guardrail was adopted in this study, which is composed of a variable cross-section structure above the pavement and an L-shaped foundation embedded in the soil. The focus of this study is on the response of the lightweight embankment and foundation, rather than on guardrail failure. Under the prescribed collision conditions, the maximum principal stress in the guardrail remains below 12 MPa, which is well under the strength limits of concrete, indicating that the guardrail behaves essentially elastically. Furthermore, the linear elastic model significantly improves computational efficiency for parametric studies. Therefore, the linear elastic constitutive model (*MAT_ELASTIC) was adopted for the guardrail material, and hexahedral solid elements defined by *SECTION_SOLID were applied for section properties. The detailed parameters are listed in Table 3.

Table 3. Material Parameter Settings of Concrete Guardrail and Its Foundation.

Road Structure	Density (kg/m ³)	Elastic Modulus (MPa)	Poisson's Ratio
guardrail and its foundation	2400	30,000	0.25

The establishment of this guardrail model does not take into account the configuration of vertical posts and reinforcing steel bars. The upper guardrail is coupled with the underlying foundation through contact conditions, which simplifies the model and improves computational efficiency. Figures 1 and 2 illustrate the mesh generation of each component of the guardrail.

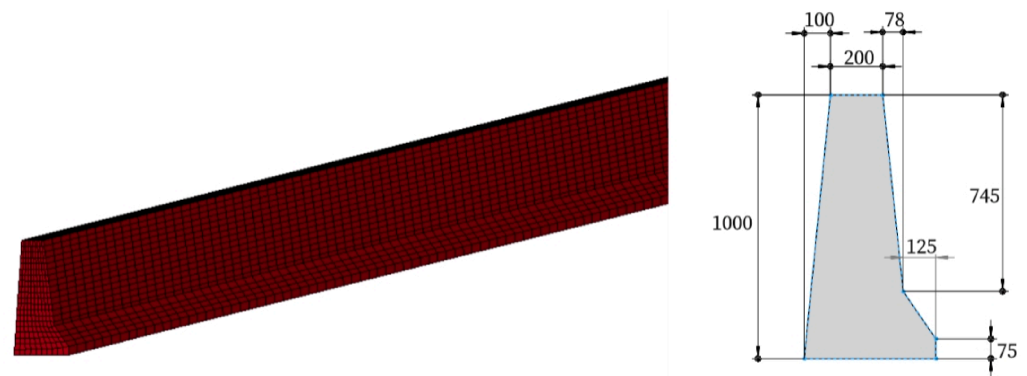


Figure 1. Upper Guardrail Model.

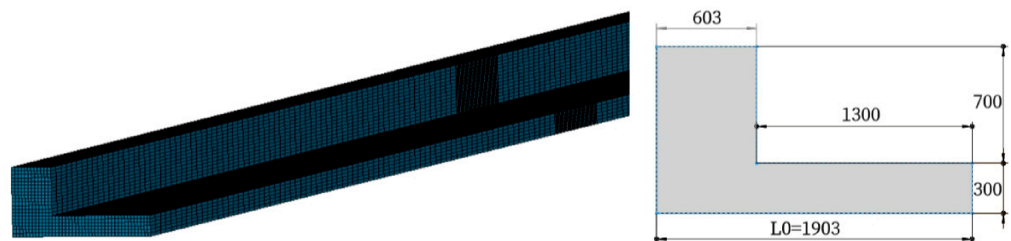


Figure 2. Underlying Foundation Model.

The mesh sizes of each component in the finite element model are as follows: the concrete wall and L-shaped foundation adopt hexahedral solid elements with a mesh size of 50 mm; the subgrade adopts hexahedral solid elements with a mesh size of 100 mm; the foamed concrete adopts hexahedral solid elements with a mesh size of 100 mm.

3.1.2. Finite Element Model of Lightweight Embankment

Foamed concrete was selected as the filling material for the lightweight embankment, and Model 63 crushable foam material model (*MAT_CRUSHABLE_FOAM), which is suitable for lateral collision simulation, was adopted. This model characterizes the mechanical behavior of the material via a stress–strain curve (*DEFINE_CURVE) and allows the setting of a tensile stress failure threshold. Six parameters need to be defined for the model, namely material density, elastic modulus, Poisson's ratio, characteristic stress–strain curve, tensile stress failure threshold, and material viscous damping coefficient. An additional failure material model (*MAT_ADD_EROSION) was employed to define the failure criterion of the foamed concrete specimen, with the principal failure strain as the failure index. Due to the uneven surface of the foamed concrete specimens, calculating the compressive strain using the crosshead displacement of the universal testing machine would introduce considerable errors. Therefore, it is inaccurate to determine the elastic modulus directly from the linear portion of the experimental stress–strain curve. According to the relevant national standard [33], there is a good linear relationship between the elastic modulus and the compressive strength, from which the elastic modulus can be derived based on the compressive strength value. Among the six tested groups (A–F), Groups A, E, and F were selected for subsequent finite element simulations. Group A represents the lowest strength level and serves as the baseline case. Group E represents an intermediate strength level.

Group F represents the highest strength level and also has the highest density, serving as an upper-bound scenario. The remaining groups were excluded for the following reasons: Group B has a compressive strength only 0.05 MPa higher than that of Group A, which does not constitute a distinct strength level; Group C exhibited uneven pore distribution and unreliable mechanical behavior due to insufficient manual mixing; Group D has a compressive strength nearly identical to that of Group F, but Group F has a higher density, representing a more extreme condition for the lightweight embankment. Therefore, Group F was selected instead of Group D. In this paper, material parameters were determined based on specimen data with compressive strengths of 1.04 MPa (Group A), 1.18 MPa (Group E), and 1.38 MPa (Group F), as listed in Table 4.

Table 4. Material Parameter Settings of Lightweight Embankment.

Simulation Group	Density (kg/m ³)	Elastic Modulus (MPa)	Tensile Failure Stress Threshold (MPa)	Poisson's Ratio	Viscous Damping Coefficient
MODEL-A	431.7	318	0.2	0.27	0.1
MODEL-E	492.1	354	0.2	0.25	0.1
MODEL-F	558.9	401	0.2	0.20	0.1

3.1.3. Finite Element Models of Foundation and Subgrade

The foundation soil is 6 m in height and 18 m in transverse width; the subgrade material is 1 m in height and 10.897 m in transverse width; the lightweight embankment is 6 m in height and 12 m in transverse width. The overall model has a longitudinal length of 60 m. To reduce modeling effort and computational complexity, non-essential components such as embankment slopes are omitted, as shown in Figure 3.

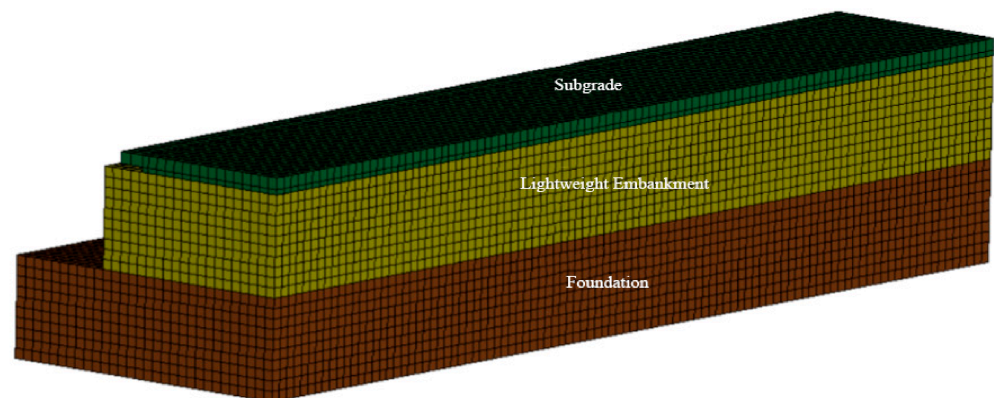


Figure 3. Model of foundation, subgrade and lightweight embankment.

A linear elastic stress–strain constitutive model (*MAT_ELASTIC) was selected for the subgrade material, and hexahedral solid elements defined by *SECTION_SOLID were adopted for the section properties. The corresponding material parameters are listed in Table 5.

Table 5. Parameter settings of subgrade materials.

Road Structure	Density (kg/m ³)	Elastic Modulus (MPa)	Poisson's Ratio
subgrade	2460	10,000	0.2

The geological cap model in LS-DYNA (<https://lsdyna.ansys.com>) was adopted for the foundation soil. By simplification (setting the two plastic parameters to zero),

it was converted into a capped Drucker-Prager model. The simplified model relies on only two strength parameters to characterize the main mechanical properties of the soil during shearing, and these parameters can be converted interchangeably with the cohesion and friction angle in the Mohr-Coulomb criterion. To conform to engineering practice, representative foundation soil parameters were selected in this study, namely a cohesion of 2.5 kPa and a friction angle of 40° . The detailed parameter values are given in Table 6.

Table 6. Material Parameters of Foundation Soil.

Parameter	Foundation Soil
Density (kg/m^3)	1600
Initial Cap Pressure X_0 (kPa)	200
Shear Modulus G (MPa)	14.1.95
Bulk Modulus K (MPa)	32
α (kPa)	1.9
θ (rad)	0.214
β (MPa)	0
γ (MPa)	0
Plastic Parameter W	1
Plastic Parameter D (MPa^{-1})	0.00725
Cap Curvature Parameter R	4
Fracture Strength T (kPa)	0

3.1.4. Finite Element Model of the Vehicle

This study adopts a complete vehicle model successfully developed and validated by the U.S. National Crash Analysis Center (NCAC) as the research basis. Given that the focus of this paper is on the safety performance of guardrails and the deformation and stress distribution of roadside lightweight embankments under collision conditions, the detailed internal deformation of the vehicle model is not the primary concern of this research. Therefore, on the premise of ensuring computational accuracy, the solid model is reasonably simplified: steering wheels, seats, and other electronic components are not included, while equivalent mass points are added at corresponding positions. The engine is replaced with a simplified rectangular rigid element. Acceleration sensors are arranged in the simplified model at the seat and the center of mass, and are rigidly connected to the vehicle structure using rigid elements to improve the accuracy of the vehicle model in collision analysis. In terms of structural construction, the front-end components are connected by spot welds, and other parts are connected by shared nodes and rigid elements. Meanwhile, mesh refinement is performed on potential collision regions. The simplified passenger car model is shown in Figure 4.

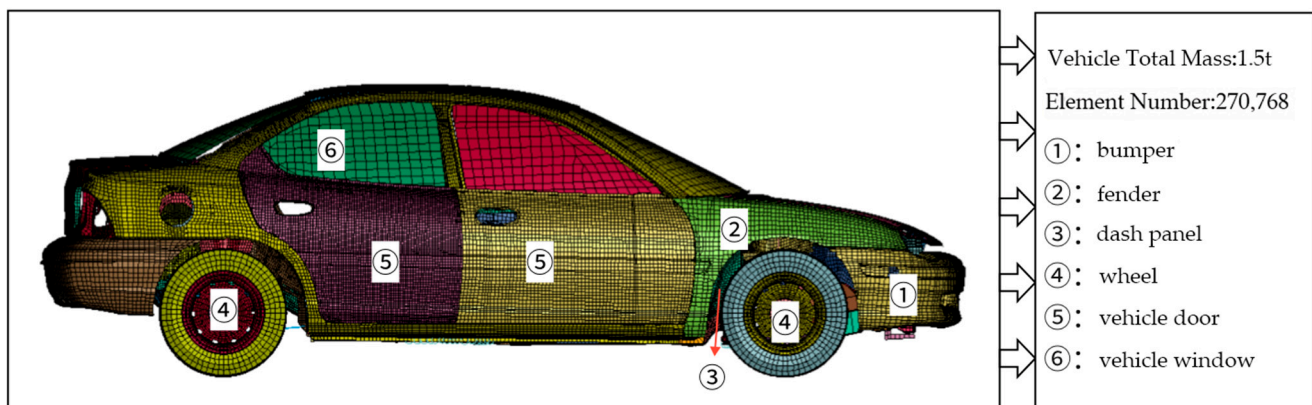


Figure 4. Simplified car model.

The body materials in the vehicle model mainly include linear elastic, elastoplastic, and rigid materials, and the elements are defined as the Belytschko–Tsay shell elements, which feature high computational efficiency and accurate results. Most components in the model adopt the piecewise linear plasticity material model (*MAT_PIECEWISE_LINEAR_PLASTICITY), including the bumper, doors, driver seat, etc. The engine, suspension beams, and braking system use rigid solid materials (*MAT_RIGID), while the tires are defined as linear elastic materials (*MAT_ELASTIC). The passenger car model adopted in this paper weighs 1.5 tons, and its finite element model consists of 270,768 elements. The parameters of the simplified vehicle model are listed in Table 7. The validity of this vehicle model has been verified by the NCAP front crash test, meeting the requirements for guardrail collision simulation.

Table 7. Parameters of the simplified car model.

Category	Parameter
Vehicle Length	4290 mm
Vehicle Width	1700 mm
Vehicle Height	1365 mm
Track	2648 mm
Front Track	1550 mm
Rear Track	1570 mm
CG Height	518 mm
Total Mass	1.5 t

The selected constitutive models capture the main nonlinear mechanisms relevant to the dynamic response of the lightweight embankment. The foamed concrete embankment is modeled using a crushable foam model (*MAT_CRUSHABLE_FOAM), which explicitly represents pore collapse, energy dissipation, and nonlinear stress–strain behavior under compression. The foundation soil is modeled using a capped Drucker–Prager model, which simulates shear failure and volumetric compaction. The energy-absorbing components of the vehicle (bumper, doors, suspension) are modeled using elastoplastic materials. However, certain phenomena are simplified: the concrete guardrail is linear elastic; the strain-rate effects of the foamed concrete are only implicitly represented through the static stress–strain curve, without explicit rate dependence. This is indeed a limitation, but for comparative optimization studies, the relative trends are still considered reliable. Several simplifications in this study may affect the accuracy of the computational results, but analysis shows that these simplifications are either well justified or lead to conservative estimates. First, the guardrail adopts a linear elastic constitutive model. Since its maximum principal stress remains below 12 MPa during the collision, far lower than the concrete strength, the nonlinear energy absorption is minimal, and the load transmitted to the embankment is slightly overestimated, resulting in conservative outcomes. Second, neglecting the lateral confinement of the embankment slopes may overestimate the lateral displacement to some extent, making the evaluation of the foundation length effect in the optimization analysis conservative, but does not affect the comparative conclusions. Third, the vehicle model removes non-structural components such as seats and electronic devices, replacing them with equivalent mass points, while retaining the experimentally validated NCAC vehicle dynamic characteristics. Therefore, the peak impact force and load transfer process remain reliable. Finally, representative values for the foundation soil parameters (cohesion 2.5 kPa, friction angle 40°) are adopted. Although site-specific variations may exist, this study primarily focuses on the relative comparison and optimization of the base slab length, and the conclusions are not sensitive to the absolute values of the soil parameters.

3.2. Setting of Coupling Parameters for the Vehicle–Lightweight Embankment Roadside Guardrail Collision System

3.2.1. Collision Conditions

The relevant standard [34], hereinafter referred to as Specification B05, specifies the relevant conditions for vehicle–guardrail collision tests in China as shown in Table 8 below.

Table 8. Parameter Settings for Collision Conditions.

Vehicle Type	Velocity (km/h)	Angle (°)	Vehicle Mass (t)
passenger car	100	20	1.5
coach	80	20	10, 14, 18
heavy truck	60	20	

In this study, the collision conditions for passenger cars were adopted as the simulation parameters in accordance with the specification. In addition, the location of the impact point also exerts a notable influence on the collision results. The impact point refers to the actual contact point where the vehicle collides with the guardrail. To more accurately reproduce real collision scenarios, the specific provisions on the impact point in Specification B05 were strictly followed in this paper. For collision tests between the vehicle and the standard guardrail segment, the impact point was set at one-third of the length from the starting point of the standard guardrail segment.

3.2.2. Boundary Conditions

Triaxial displacement constraints were applied at the bottom of the finite element model, and normal displacement constraints were imposed on both axial sides. All finite element structures except the lightweight embankment were constrained with normal displacement on their left and right sides. For the lightweight embankment, no constraints were applied on the side equipped with the guardrail, so as to investigate the deformation and stress distribution of the lightweight embankment under collision loads, while normal displacement constraints were applied on the opposite side to control the influence of other variables. In conventional model boundary treatment, triaxial displacement constraints are generally adopted on both axial sides when the model boundaries are sufficiently far away from the research zone. Nevertheless, normal displacement constraints were still used in this study. Such a treatment tends to yield more conservative estimations in the analysis of soil deformation.

3.2.3. Contact Settings

Various contact definitions were adopted among different components in the coupled vehicle–guardrail collision model. Single Surface contact describes the interaction between nodes and the target surface. Since the software can automatically detect penetration across all external surfaces of the model, single surface contact performs excellently in collision and impact problems. Node-to-Surface contact, owing to its asymmetric characteristic, allows the calculation to focus on the impacting nodes. However, when using nodes-to-surface contact, the node sets or part IDs of the contact surface and target surface must be explicitly specified to ensure computational accuracy. Surface-to-Surface contact allows flexible selection of contact and target surfaces based on predefined node sets and part numbers, providing greater flexibility and accuracy for complex collision scenarios where the contact objects cover a large known area. The contact types and corresponding parameter settings in the collision simulation of this study are summarized in Table 9.

Table 9. Contact Parameter Settings.

Contact Object	Contact Type	Friction Coefficient
Between vehicle components	CONTACT_AUTOMATIC_SINGLE_SURFACE	0.2
Between guardrail components	CONTACT_AUTOMATIC_SINGLE_SURFACE	0.4
Between vehicle and guardrail	CONTACT_AUTOMATIC_SURFACE_TO_SURFACE	0.15
Between vehicle and ground	LOAD_BODY_Z, RIGIDWALL_PLANAR	0.15
Between guardrail and lightweight embankment	CONTACT_AUTOMATIC_SURFACE_TO_SURFACE	0.6
Between subgrade and lightweight embankment	CONTACT_AUTOMATIC_SURFACE_TO_SURFACE	0.6
Between lightweight embankment and foundation	CONTACT_AUTOMATIC_SURFACE_TO_SURFACE	0.6

3.2.4. Output Settings

The minimum time step size is generally set to 1.12×10^{-6} s with its scale factor adjusted to 0.6. In addition, to suppress potential hourglassing in the simulation, the keyword CONTROL_HOURLASS is adopted, in which the hourglass energy coefficient QH is set to 0.1. Within the scope of this study, several key data items need to be focused on during the post-processing stage, including the dynamic variation in the total system energy, the trend of collision load, the maximum displacement of the lightweight embankment, the acceleration at the vehicle center of mass, and the lateral deformation of the guardrail. These data are indispensable for the in-depth analysis and comprehensive evaluation of the simulation results. Conventional stress nephograms and similar results can be viewed via the post-processing software. However, specific data such as energy evolution and time history of collision force require dedicated keywords to define their output. For this purpose, the keywords used for various types of output control during the simulation are listed in detail in Table 10.

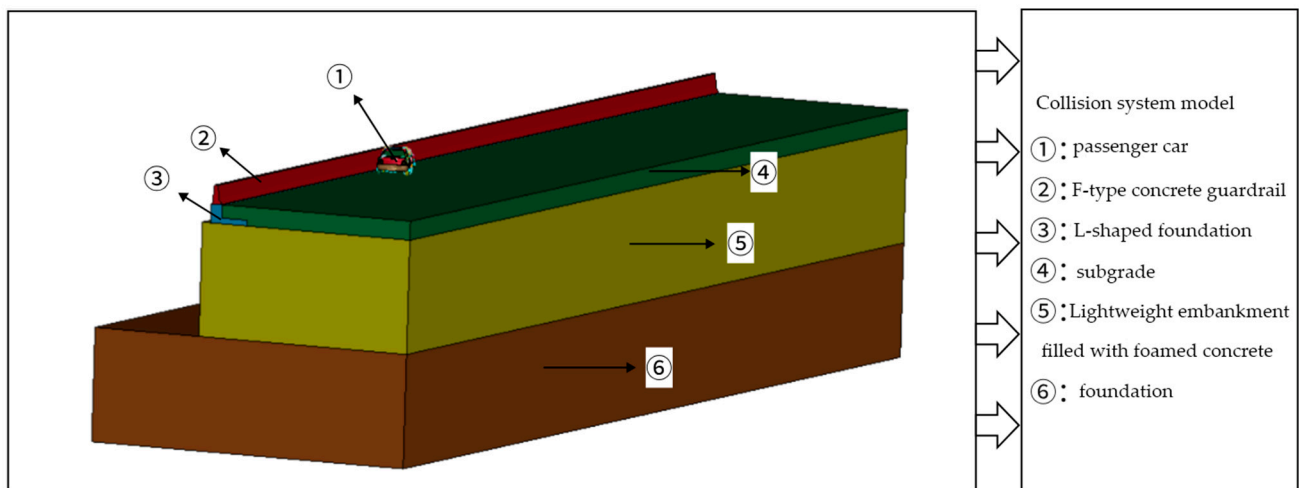
Table 10. Output control.

Data Type	Keyword Name
Collision load	DATABASE_RCFORC
Variations in energy, acceleration and others for each structure	DATABASE_MATSUM
System total energy, kinetic energy, internal energy, hourglass energy, etc.	DATABASE_GLATAT

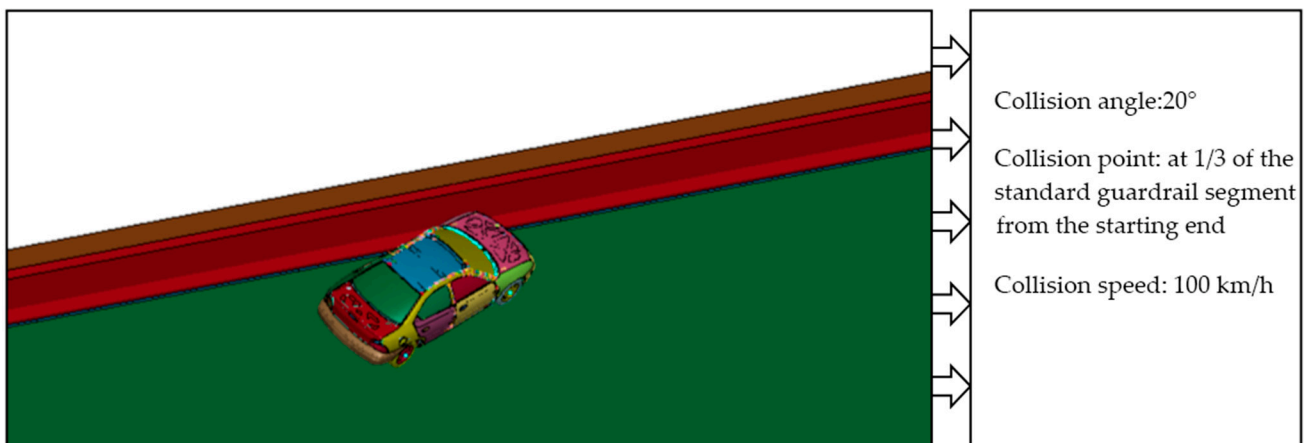
The finite element model of the vehicle—lightweight embankment roadside guardrail collision system is shown in Figure 5.

3.3. Safety Evaluation Indexes of Lightweight Embankment

The collision between vehicles and roadside guardrails on lightweight embankments generates enormous instantaneous impact loads, which may cause damage, deformation or displacement of lightweight materials. The vibration and deformation induced by such impact can further endanger the safety of the surrounding environment and infrastructure. However, systematic research on such collision effects is still insufficient at present, and their potential damage is often underestimated in engineering practice, which may lead to an increased risk of long-term structural failure. Therefore, this paper focuses on the two core aspects of embankment stress distribution and lateral displacement, with emphasis on the safety performance of foamed concrete as embankment material under vehicle impact on roadside guardrails, so as to provide a theoretical basis for the design and safety maintenance of road engineering.



(a) Overall schematic diagram



(b) Local schematic diagram

Figure 5. Finite element model of collision system between vehicle and roadside guardrail of lightweight embankment.

3.4. Simulation Scheme

In accordance with the relevant provisions in *Specification T 177*, when foamed concrete is used as subgrade filler for expressways, its compressive strength shall meet the following requirements: no less than 0.6 MPa within 0.8 m below the pavement bottom surface; no less than 0.5 MPa at a depth of 0.8–1.5 m below the pavement bottom surface; and no less than 0.4 MPa below 1.5 m beneath the pavement bottom surface. Accordingly, based on the static mechanical parameters of foamed concrete obtained from uniaxial compression tests, lightweight embankments were constructed with foamed concrete of 1.0 MPa, 1.2 MPa and 1.4 MPa compressive strength respectively in this chapter. Collision simulations with guardrails were carried out using the 1.5 t passenger car model that had passed the NCAP front crash test as described previously. The simulation scheme is presented in Table 11.

Table 11. Collision simulation scheme.

Working Condition Number	Strength of Lightweight Embankment (MPa)	Vehicle Model	Collision Velocity (km/h)	Collision Angle (°)
1	1.0	1.5 t passenger car	100	20
2	1.2			
3	1.4			

3.5. Model Reliability Verification Based on System Energy Conversion

Throughout the collision process, the total energy remains constant, which serves as the foundation for ensuring the accuracy of simulation results. The initial kinetic energy of the vehicle is mainly converted into internal material energy, sliding energy and residual kinetic energy of the vehicle after collision, accompanied by a small amount of hourglass energy. It should be noted that the hourglass energy must be controlled within 10% of the total energy. The system energy variation curve reveals the energy conversion and absorption mechanisms during the collision. The energy variation curves in the passenger car collision simulation are shown in Figure 6.

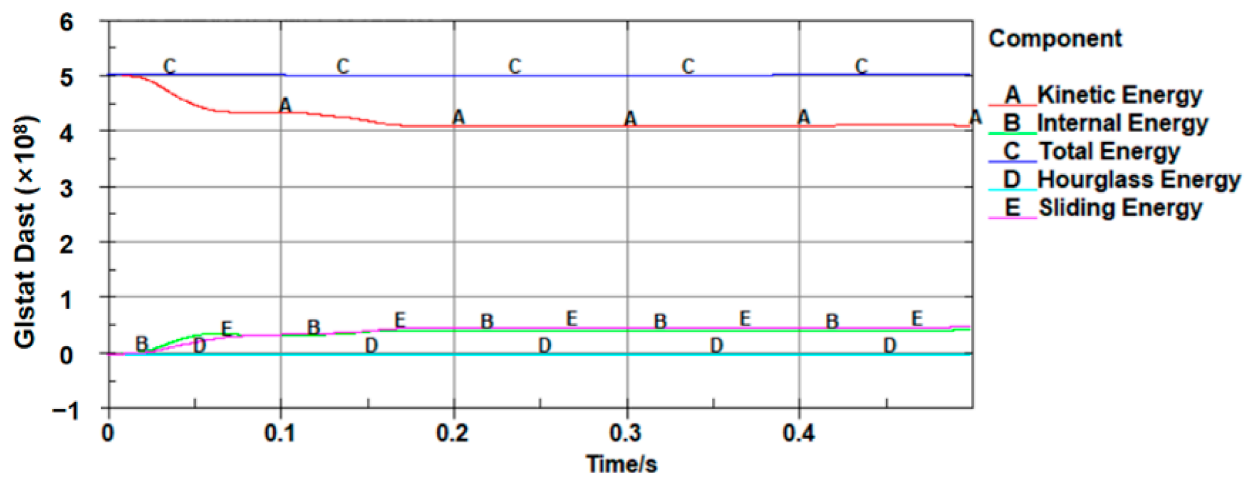


Figure 6. System energy variation curve under Working Condition 1.

As shown in Figure 6, for the highway embankment filled with 1.0 MPa foamed concrete (Case 1), the total energy of the vehicle impact system fluctuates slightly within 503.60–506.77 kJ over time, with a variation rate not exceeding 0.63%. The kinetic energy decreases from the initial 505.65 kJ to 411.96 kJ, a reduction of 93.69 kJ. The internal energy of the system increases from a minimum of 0 to a maximum of 43.80 kJ. The maximum hourglass energy is 0.57 kJ, accounting for less than 5% of the total energy, indicating valid calculation results.

For the highway embankment filled with 1.2 MPa foamed concrete (Case 2), as illustrated in Figure 7, with the progression of collision, the total energy of the vehicle impact system varies slightly within 503.66–507.52 kJ, with a variation rate below 0.77%. The kinetic energy drops from 505.61 kJ to 411.83 kJ, a decrease of 93.78 kJ. The system internal energy rises from an initial value of 0 to 44.00 kJ. The maximum hourglass energy is 0.59 kJ, less than 5% of the total energy, verifying the reliability of the simulation results.

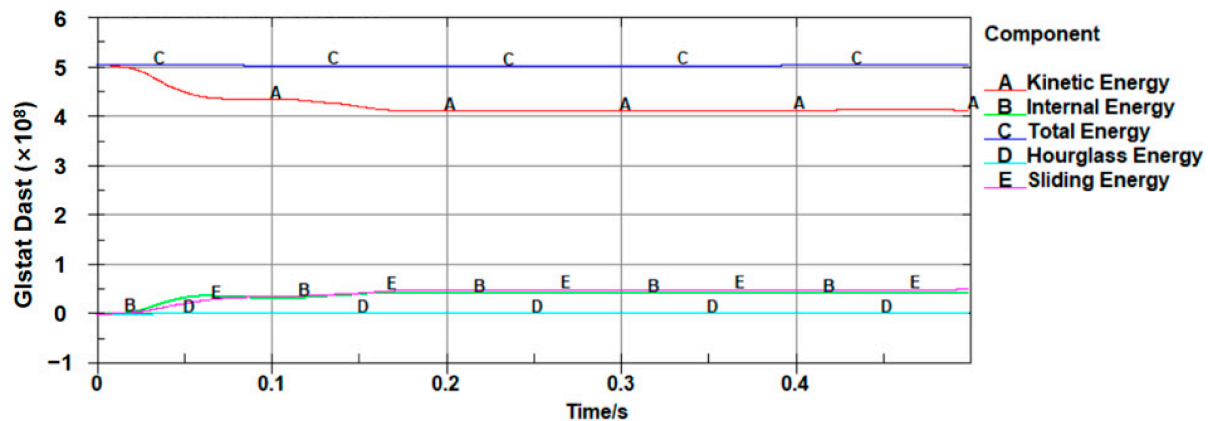


Figure 7. System energy variation curve under Working Condition 2.

Figure 8 presents the energy variation curve of the collision system for the 1.4 MPa lightweight embankment (Case 3). As the collision proceeds, the total energy of the vehicle impact system fluctuates slightly within 503.62–508.00 kJ, with a variation rate not exceeding 0.86%. The kinetic energy decreases from 505.60 kJ to 411.86 kJ, a reduction of 93.74 kJ, and the system internal energy increases by 44.50 kJ. The maximum hourglass energy is 0.53 kJ, which is less than 5% of the total energy, confirming that this simulation is reliable.

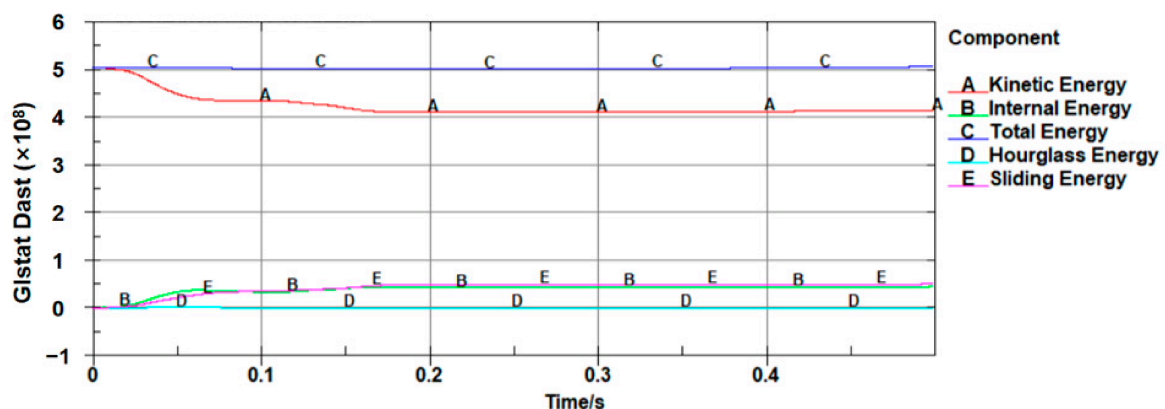


Figure 8. System energy variation curve under Working Condition 3.

3.6. Analysis of Collision Simulation Results for Lightweight Embankments with Different Strengths

Post-processing of the calculation results using LS-PREPOST (<https://lsdyna.ansys.com/ls-prepost-2/>) shows that under the three different working conditions, the stress distribution and lateral displacement nephograms of the lightweight embankment exhibit similar variation patterns when the passenger car collides with the roadside guardrail. Therefore, this study takes Case 1 as an example to discuss in detail the characteristics of stress distribution and displacement nephograms of the lightweight embankment.

Figure 9 shows the stress nephogram of the lightweight embankment during the collision between the passenger car and the roadside concrete guardrail. It can be seen from the figure that when the collision occurs, the impact force is effectively transferred from the underlying foundation of the guardrail to the lightweight embankment. The load transfer process not only alters the stress distribution of the lightweight embankment but also exerts a significant influence on its stability. The maximum principal stress within the lightweight embankment occurs at the same cross-sectional location in all cases, i.e., the vertical section directly beneath the vehicle impact point, specifically at the contact zone

between the edge of the L-shaped foundation base slab and the lightweight embankment. This location is the primary load-transfer path for the collision load downward from the guardrail foundation, and the right-angled corner at the edge of the base slab induces local stress concentration. Such stress concentration not only aggravates the deformation and damage of the lightweight embankment but may also threaten the overall stability of the embankment. In addition, it is found that the stress on the roadside lightweight embankment gradually decreases from top to bottom, with a relatively small overall variation amplitude. This indicates that the lightweight embankment possesses a certain capacity of self-adjustment and stabilization during the collision, enabling it to resist external loads to a certain extent.

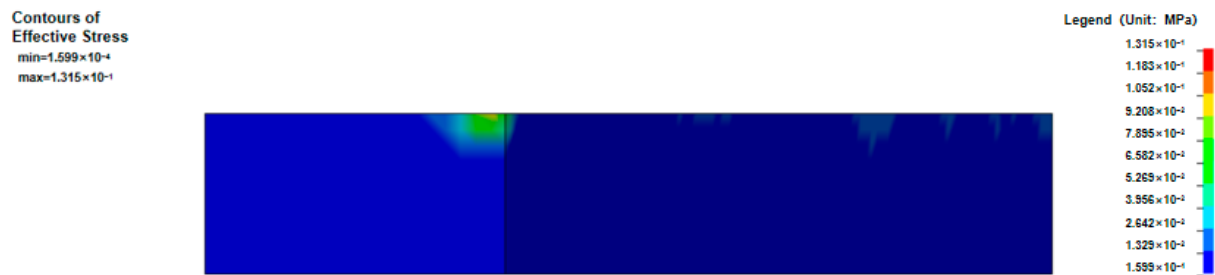


Figure 9. Stress nephogram of lightweight embankment under collision.

During the impact of the passenger car against the roadside guardrail, the lateral displacement nephogram of the lightweight embankment is shown in Figure 10. When the vehicle strikes the guardrail at a certain speed, the lateral component of the impact force first acts on the roadside guardrail. However, the guardrail does not exist in isolation but is rigidly connected to the underlying foundation beneath it. Consequently, the impact force is rapidly transferred from the guardrail to its underlying foundation and further diffused into the lightweight soil below the foundation slab. This load-transfer process subjects the lightweight soil to indirect impact force from the vehicle, resulting in corresponding deformation and displacement. Owing to its unique porous structure, lightweight soil exhibits a certain buffering effect. When the vehicle impact force is transmitted into the lightweight soil, the soil absorbs and dissipates part of the impact energy through its own deformation and displacement. Such a buffering effect helps alleviate the direct impact on the embankment, thereby reducing the degree of embankment damage. Although the lightweight soil possesses a certain buffering capacity, it still undergoes noticeable lateral displacement under the intense vehicle impact. In particular, the deformation of the lightweight embankment at the contact zone with the guardrail foundation slab is especially significant. This deformation not only alters the original geometry of the embankment but may also exert a substantial influence on its stability and safety.

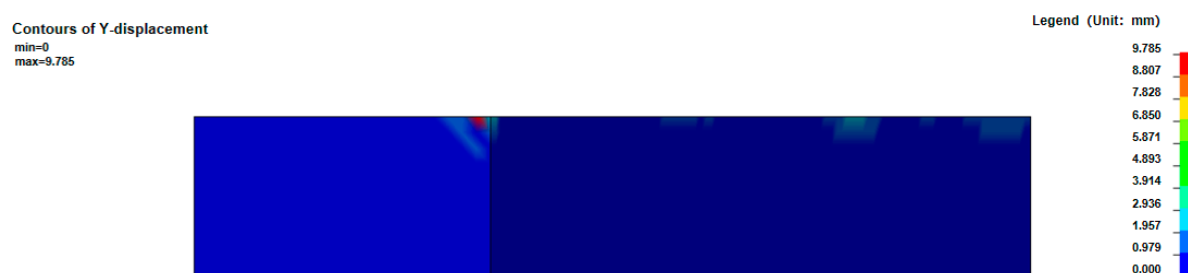


Figure 10. Transverse displacement nephogram of lightweight embankment under collision.

To more accurately quantify the lateral displacement of the lightweight embankment, the maximum lateral displacement data of the embankment under different working

conditions were obtained by simulating the vehicle impact process, as listed in Table 12. A comparative analysis of these data shows that when the embankment is filled with 1.0 MPa foamed concrete, its deformation is the most significant under the same vehicle impact force.

Table 12. Maximum transverse displacement of lightweight embankment under various working conditions.

Working Condition No.	Maximum Transverse Displacement (mm)
1	9.78
2	3.17
3	8.38

The results in Table 12 show an unexpected non-monotonic trend: the lateral displacement of the 1.2 MPa embankment is significantly smaller than that of the 1.0 MPa and 1.4 MPa embankments. The foamed concrete in Group E (1.2 MPa) has a lower elastic limit strain than Groups A and F, and its elastic modulus lies between those of Groups A and F. Moreover, the Poisson's ratio of Group E is between those of Group A and Group F. It is hypothesized that the combination of intermediate stiffness and moderate Poisson's ratio in Group E promotes the formation of a limited local crushing zone directly beneath the foundation base slab. This local crushing dissipates a portion of the impact energy through pore collapse, thereby reducing the energy available to cause global lateral displacement. In contrast, the softer Group A material undergoes more global deformation with insufficient local energy dissipation, while the stiffer Group F material transfers the load more directly to the embankment with less local crushing; both result in larger lateral displacements. Furthermore, although the total internal energy increments are similar across the three cases, the distribution of energy within different regions of the embankment differs. In the 1.2 MPa case, more energy is dissipated locally in the crushing zone rather than being converted into global deformation energy. Taken together, these factors may explain the anomalous displacement observed in the 1.2 MPa case.

3.7. Optimal Design of Guardrail Foundation

Collision loads are transferred downward through the load-transfer system: “concrete guardrail—underlying foundation—lightweight embankment”. During this process, the L-shaped underlying foundation tends to rotate around its right-angle edge under impact load, leading to high stress concentration at the contact zone between the foundation slab and the lightweight embankment. Therefore, this study improves the resistance of the lightweight embankment to vehicle impact loads by increasing the base slab length (L_0) of the guardrail foundation. On the premise of meeting safety and stability requirements, reasonable optimal design is adopted to reduce construction and maintenance costs and enhance the overall economic benefits of the project. The specific optimization scheme is shown in Table 13.

Table 13. Optimal Scheme Design of Concrete Foundation Slab.

Group No.	Strength Index of Lightweight Embankment	Length of Foundation Slab	Vehicle Model	Collision Velocity	Collision Angle
Case0 Case1 Case2 Case3	1.0 MPa	L_0 (1 + 10%) L_0 (1 + 20%) L_0 (1 + 30%) L_0	1.5 t passenger car	100 km/h	20°

Note: Case0 represents the original condition, and Case1–3 are the optimized schemes, in which the foundation base slab length L_0 is 1903 mm.

4. Results

Figure 11 shows the stress distribution of the lightweight embankment with different base slab lengths when the passenger car impacts the roadside guardrail under the same collision conditions. Increasing the base slab length effectively reduces stress concentration and lateral deformation of the lightweight embankment primarily by altering the load path and stress diffusion pattern of the collision load as it transfers downward from the guardrail. When the vehicle strikes the guardrail at a given angle, the L-shaped foundation tends to rotate slightly about its right-angled edge under the horizontal impact component. This rotation creates a localized compressive stress concentration zone between the slab edge and the top surface of the embankment. Under the original slab length ($1.0 L_0$), almost the entire load is transmitted to the embankment through the narrow strip at the slab edge, resulting in a high peak stress and significant local compression deformation. When the slab length is increased, two favorable changes occur in load transfer. First, the contact area increases: the interface between the underside of the slab and the embankment expands from a narrow strip to a wider band, significantly reducing the pressure per unit area. Second, the load diffusion angle increases: the vertical load introduced at the slab edge can spread deeper and wider into the embankment, analogous to the stress bulb effect beneath a rigid foundation on an elastic half-space. Consequently, the peak stress decreases and the stress gradient within the embankment becomes gentler. Meanwhile, the reduction in lateral displacement is mainly attributed to enhanced rotational restraint of the foundation. A longer slab provides a larger overturning resistance arm, which reduces the rotation angle of the foundation under the same horizontal impact force, thereby decreasing the lateral push on the embankment. In summary, increasing the slab length simultaneously improves two mechanisms: vertical stress diffusion and lateral rotational stability. Thus, without changing the material quantity (only length is increased, not thickness or reinforcement), the overall safety performance of the lightweight embankment under impact loading is effectively enhanced. In addition, by comparing Figure 11c,d, it is found that when the base slab length is increased by 30%, the internal stress distribution and stress magnitude of the lightweight embankment are basically consistent with those when the length is increased by 20%. This indicates that after the base slab length increases to a certain extent, the stress distribution of the lightweight embankment reaches a relatively stable state, and further increasing the base slab length will no longer exert a significant effect on the stress distribution of the lightweight embankment.

Figure 12 shows the peak lateral displacement of the lightweight embankment corresponding to different base slab lengths. For the original base slab length L_0 , the impact caused by the passenger car at a given speed results in significant lateral displacement of the embankment, with a peak value of 9.78 mm. However, when the base slab length is increased by 10% and tested under identical collision conditions, the peak lateral displacement of the lightweight embankment drops to 4.93 mm, representing a reduction of 49.6% compared with the original case. As the base slab length is further increased by 20%, the peak lateral displacement decreases to 3.12 mm under the same collision scenario, a reduction of 68.1%. When the length is increased by 30%, the peak lateral displacement slightly decreases to 2.84 mm, with an overall reduction of approximately 71.0%. With the gradual increase in base slab length, the peak lateral displacement of the lightweight embankment under the same collision conditions shows a decreasing trend, yet the rate of reduction gradually slows down. This phenomenon indicates that, after a certain length is reached, the effect of further increasing the base slab length on improving the stability of the lightweight embankment diminishes gradually. Properly extending the base slab length can effectively transfer the collision load acting on the guardrail downward into the

entire lightweight embankment. Such load transfer enables the whole structure to resist the load jointly, thus preventing instability failure caused by excessive local deformation.

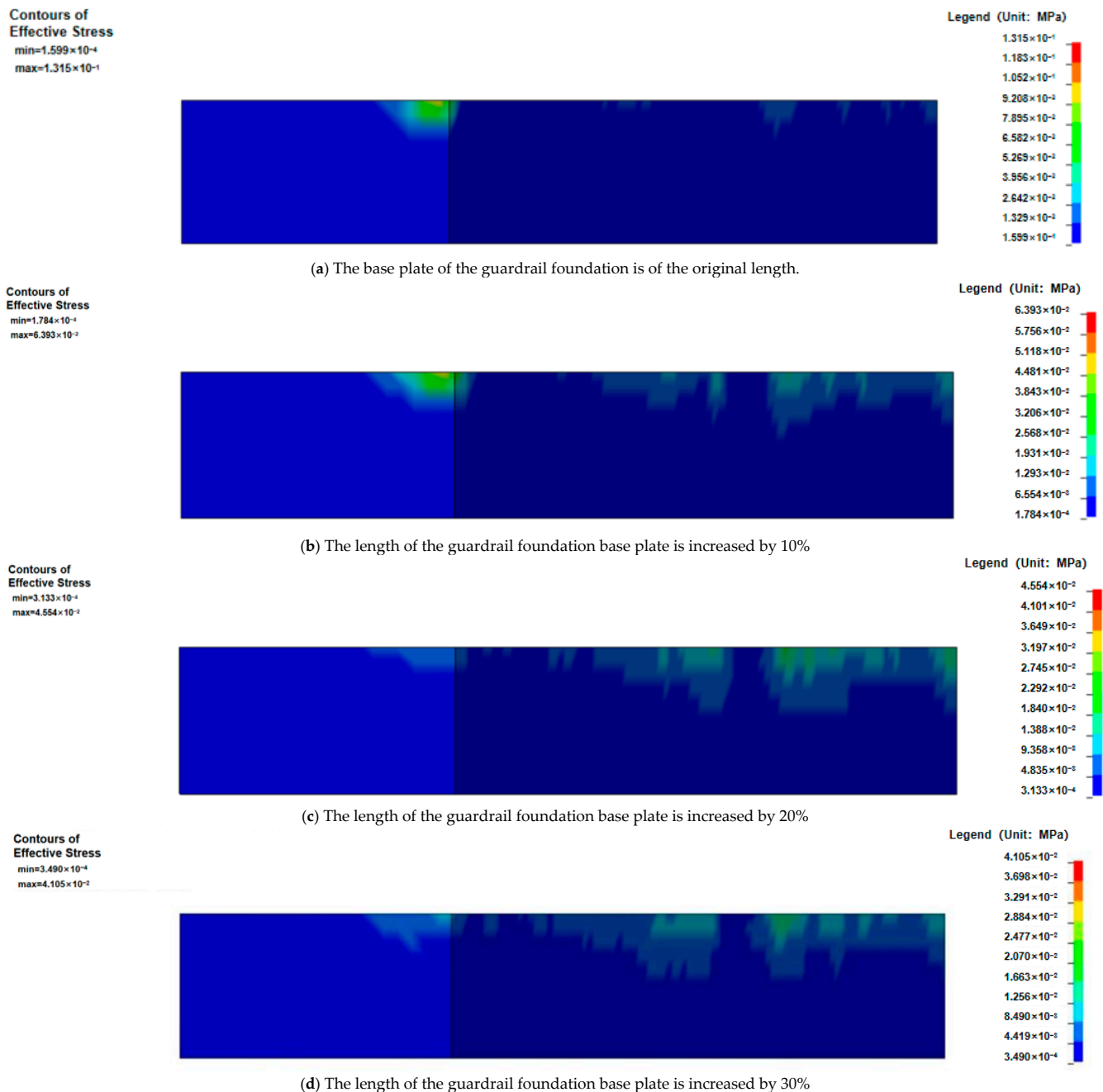


Figure 11. Stress Distribution Cloud Diagram of Lightweight Embankment Under Different Foundation Slab Lengths.

The calculated peak stress is far below the elastic limit strength of the material, indicating that during the collision, the designed foundation configuration can effectively distribute the impact stress, leaving sufficient engineering safety margin.

Comparing the trends of lateral displacement and stress distribution obtained in this study with those reported in the existing literature reveals good consistency. Regarding lightweight embankments, Gu [6] analyzed the ultimate impact resistance of corrugated beam guardrails on foamed lightweight soil sections using an energy method, and pointed out that foundation stability is a key factor affecting guardrail performance. This echoes our finding that increasing the base slab length significantly reduces embankment deformation.

In terms of foamed concrete materials, Shi et al. [23] reported that ceramsite-based foamed concrete exhibits high energy absorption under high strain rates (with a 151% increase in peak stress), indicating excellent impact resistance. In our study, the peak principal stress of the lightweight embankment under collision remained far below the material strength (only 13%), further confirming its safety margin.

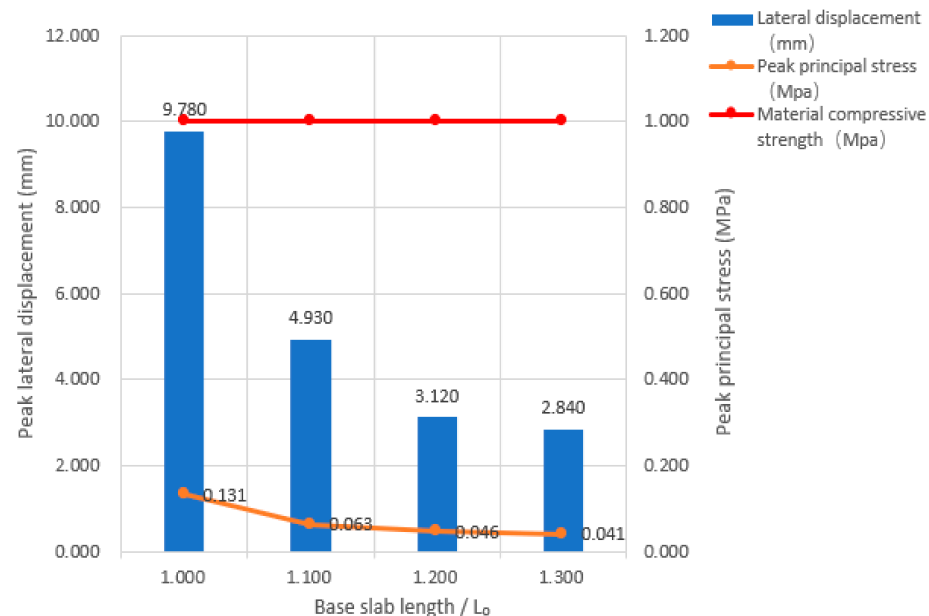


Figure 12. Peak lateral displacement and peak stress of lightweight soil embankment under impact.

With respect to guardrail foundation optimization, Sassi and Ghrib [30] found that soil-post interaction plays a dominant role in the dynamic response of guardrails. In the present study, increasing the length of the L-shaped foundation base slab enhanced the rotational resistance of the foundation. Both studies emphasize the importance of foundation-soil interaction. Furthermore, Zhang et al. [19] conducted full-scale impact tests on recycled foamed concrete wall-type guardrails and demonstrated the good crashworthiness of lightweight guardrails, which is consistent with our conclusion that no global failure occurs in the foamed concrete embankment under the investigated collision conditions.

It should be noted that the above comparisons are largely trend-based and qualitative, because there are few quantitative studies in the existing literature that specifically address the coupled system of a foamed concrete lightweight embankment and an L-shaped guardrail foundation under vehicle collision. The quantitative results of this study, such as the decreasing trend of displacement with increasing base slab length, can serve as a reference benchmark for future similar research.

5. Conclusions

The experimental results show that foamed concrete with a density of 431–559 kg/m³ has a compressive strength of 1.04–1.38 MPa and an elastic modulus of 318–401 MPa. Under the investigated collision conditions (1.5 t passenger car, 100 km/h, 20° impact angle), increasing the foundation base slab length from 1.0 L_0 to 1.2 L_0 reduces the peak lateral displacement of the lightweight embankment by 68% (from 9.78 mm to 3.12 mm) and the peak principal stress by 39% (from 0.131 MPa to 0.0455 MPa). The peak principal stress is only 13% of the material strength, indicating a sufficient safety margin.

Under the specific conditions investigated in this study (1.5 t passenger car, 100 km/h impact velocity, 20° impact angle, and foamed concrete compressive strengths ranging from 1.0 to 1.4 MPa), increasing the base slab length can effectively reduce lateral deformation

and stress concentration of the lightweight embankment. Within this scope, increasing the base slab length by 10–20% appears to be a reasonable optimization scheme that can improve the stability of the embankment–guardrail system while achieving favorable cost-effectiveness. It should be noted that this conclusion is limited to the investigated conditions; further validation under a wider range of vehicle types, impact angles, and material strengths is required before generalizing to other engineering applications.

This study lacks direct experimental validation. The proposed foundation optimization is based solely on numerical simulations without comparison against laboratory tests, field measurements, or full-scale crash test data. While indirect validation is provided by energy balance, mesh stability, material parameters derived from tests, and the use of a validated NCAC vehicle model, the absolute values of predicted displacements and stresses should be interpreted with caution. Therefore, the recommended 10–20% increase in base slab length should be considered as a preliminary design reference.

Future research may focus on the following aspects: (1) validating the numerical predictions through small-scale model tests or comparison with existing crash test data; (2) incorporating rate-dependent nonlinear material constitutive models to better capture the high-strain-rate behavior of foamed concrete; (3) extending the study to other vehicle types (e.g., trucks, buses), impact velocities (60–100 km/h), and impact angles (10–30°); (4) exploring multi-objective optimization of other foundation geometric parameters (e.g., slab thickness, L-shaped foundation shape); and (5) conducting a sensitivity analysis with finer length increments (e.g., 5%, 15%) to more precisely determine the optimal range. Further research along these directions will better facilitate practical applications in soft-soil regions. (6) In this study, only three specimens were prepared for the uniaxial compression tests. Although this meets the minimum requirement of the specification, the relatively small sample size limits the comprehensive characterization of statistical reliability. It is recommended that at least six specimens be prepared per group in future studies, and that more systematic statistical analyses (e.g., analysis of variance, regression analysis) be introduced to more accurately evaluate the statistical variability of material parameters and its influence on impact resistance.

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References

- Wang, C.; Yu, Q.Y. Research on vehicle maintenance economy based on C-IASI low-speed collision tests. *Insur. Theory Pract.* **2026**, 94–112. Available online: <https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CCJD&dbname=CCJDLAST2&filename=BXLS202601008> (accessed on 21 June 2026).
- Zhan, Y.X.; Zhang, G.L.; Wen, J.H. Real-time vehicle collision risk prediction model based on LSTM-BN. *J. Transp. Inf. Saf.* **2026**, 1–11. Available online: <https://link.cnki.net/urlid/42.1781.U.20260421.1430.018> (accessed on 21 June 2026).
- Kim, J.J.; Ahn, J.S. Vehicle Collision Analysis of the Reinforced Concrete Barriers Installed on Bridges Using Node-Independent Model. *Appl. Sci.* **2024**, *14*, 10518. [\[CrossRef\]](#)
- Chen, H.; Fang, H.; Zhu, Y.Y.; Jin, H.; Wei, X.C.; Dai, L. Evaluation of multi-angle vehicle collision protection capability for long-span cable-stayed bridge guardrails. *Highway* **2026**, *71*, 317–326.
- Zhang, H.N.; Qi, C.J.; Wang, W.B.; Zhao, H.T. Finite element analysis of vehicle-guardrail collision dynamics based on ABAQUS. *Fail. Anal. Prev.* **2026**, *21*, 19–26, 79.
- Gu, W. Study on structural performance of corrugated guardrails in lightweight foam soil sections. *Shanxi Sci. Technol. Commun.* **2023**, 62–67. Available online: <https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFQ&dbname=CJFDLAST2024&filename= SXJT202306017> (accessed on 21 June 2026).
- Ma, E.G.; Fu, C.X.; Li, S.Y.; Liu, J.T.; Wang, Z.H.; Li, Z.J. Simulation performance analysis of new assembled composite guardrails under vehicle collision. *Urban Roads Bridges Flood Control* **2026**, 101–105. [\[CrossRef\]](#)
- Habtemariam, A.K.; Brunnabend, L.; Fischer, K.; Stolz, A. Discrete element method simulation of high-speed vehicle collisions with road barrier systems. *Comput. Part. Mech.* **2024**, *12*, 709–720. [\[CrossRef\]](#)
- Zheng, Z.; Yang, B.; Yuan, P.; Geng, B. Impact resistance of FRP-concrete composite guardrails against heavy vehicle collisions. *J. Chongqing Univ.* **2024**, *47*, 51–63.
- Wei, H.; Wei, Y.; Dai, Z.; He, T.; Wu, C.; Peng, D.; Zhang, F. Structural design and safety performance of a novel high-strength steel lightweight guardrail. *PLoS ONE* **2025**, *20*, e0317353. [\[CrossRef\]](#) [\[PubMed\]](#)
- Pan, Y.S. Failure Analysis and Optimization Design of Road Guardrail Under Vehicle Impact Load. Master's Thesis, Tianjin University, Tianjin, China, 2023.
- Yu, H.; Li, Q. Simulation analysis of vehicle impact on rotating anti-collision guardrail. *Technol. Highw. Transp.* **2021**, *37*, 128–132+139.
- Wu, D.H.; Chen, Z.Q.; Zeng, J.C.; Li, G.H. Research on structural simulation optimization of a new highway corrugated beam guardrail. *J. Guizhou Univ. (Nat. Sci.)* **2024**, *41*, 91–98.
- Gong, S. Influence of slope parameters of concrete guardrail on vehicle impact protection. *J. China Foreign Highw.* **2024**, *44*, 243–251.
- Pan, Z.H.; Zou, X.W.; Zhang, Y.Y. Exploration on dynamic response of frame structure under vehicle impact. *Dev. Guide Build. Mater.* **2025**, *23*, 115–117.
- Liu, Y.C.; Zhang, S.B.; Luo, J.; Yuan, H.; Zhang, C.L.; Zhao, C.Y.; Wang, R. Risk assessment of vehicle-expressway guardrail collision based on catastrophe theory. *J. Xihua Univ. (Nat. Sci. Ed.)* **2025**, 1–8. [\[CrossRef\]](#)
- Wen, M.; Xu, B.; Xiong, Z.H.; Ao, L.Q.; Chen, B.K.; Zhang, W. Sensitivity analysis of parameters considering anchoring factors for anti-collision performance of guardrails. *China J. Highw. Transp.* **2026**, *39*, 291–301.
- Ma, X.L.; Zang, X.Y. Dynamic response analysis of anti-collision guardrail in cable-stayed bridge cable area under vehicle impact. *Munic. Eng. Technol.* **2022**, *40*, 78–84.
- Zhang, X.C.; Fang, H.; Zhang, Z.; Jiang, W.; Zhu, L.; Zhang, Q.L.; Gao, H. Vehicle crash test and simulation of new recycled foamed concrete wall-type guardrail. *China J. Highw. Transp.* **2024**, *37*, 122–137.
- Yang, J.; Xu, G.; Cai, C.S.; Kareem, A. Crash performance evaluation of a new movable median guardrail on highways. *Eng. Struct.* **2019**, *182*, 459–472. [\[CrossRef\]](#)
- Cao, R.; Agrawal, A.K.; El-Tawil, S.; Wong, W. Numerical Studies on Concrete Barriers Subject to MASH Truck Impact. *J. Bridge Eng.* **2020**, *25*, 04020035. [\[CrossRef\]](#)
- Xu, X.; Zhang, H.; Du, X.; Liu, Q. Vehicle collision with RC structures: A state-of-the-art review. *Structures* **2022**, *44*, 1617–1635.
- Shi, X.; Gu, L.; Wang, Z.; Cheng, Z.; Yang, J.; Zhang, G.; Gao, F. Research on dynamic mechanical behaviors and energy absorption characteristics of ceramsite-based foamed concrete composite. *Compos. Struct.* **2026**, *383*, 120087. [\[CrossRef\]](#)
- Boddepalli, U.; Gandhi, I.S.R.; Panda, B. State-of-the-art review on foam concrete properties and new trends of application in infrastructure. In *Sustainable Materials in Civil Infrastructure*; Woodhead Publishing: Cambridge, UK, 2024; pp. 3–24.
- Cai, G.; Zeng, M.R.; Kuang, Y.Y.; Kong, X.Y. Application of foam concrete subgrade with bridge-head-free cone slope retaining wall. *Hunan Commun. Sci. Technol.* **2024**, *50*, 46–51.
- Zhang, H.; Liang, Q.; Shao, M.; Jiang, N.; Ma, W.; Ge, Z.; Šavija, B. Optimization of low-carbon lightweight foamed concrete using ground circulating fluidized bed fly ash. *J. Clean. Prod.* **2025**, *489*, 144697. [\[CrossRef\]](#)

27. Chen, L.; Li, P.; Shi, K.; Bai, X.; Zhang, Y.; Yu, Z.; Zhang, D.; Guo, W.; Feng, Z.; Song, Z. Investigation on the temperature-strain rate coupled mechanical behavior and constitutive modeling of foamed concrete using a high-temperature viscoelastic SHPB technique. *Case Stud. Constr. Mater.* **2025**, *23*, e05476.
28. Jia, X.Z.; Li, Y. Research on layout scheme of separated concrete guardrail foundation for expressway reconstruction and expansion engineering. *Highway* **2018**, *63*, 247–252.
29. Li, H.X.; Lei, Z.B.; Xie, Y.H. Finite element model of guardrail post in foundation. *J. Chang. Univ. Technol. (Nat. Sci. Ed.)* **2004**, 24–25. Available online: <https://mqikan.cqvip.com/Article/ArticleDetail?id=9919426> (accessed on 21 June 2026).
30. Sassi, A.; Ghrib, F. Development of finite element model for the analysis of a guardrail post subjected to dynamic lateral loading. *Int. J. Crashworthiness* **2014**, *19*, 457–468. [[CrossRef](#)]
31. CJJ/T 177-2012; Technical Specification for Foamed Mixture Lightweight Soil Filling Engineering. China Architecture & Building Press: Beijing, China, 2012.
32. JGJ 63-2006; Standard of Water for Concrete. China Architecture & Building Press: Beijing, China, 2006.
33. GB/T 11969-2020; Test Methods of Autoclaved Aerated Concrete. China Standards Press: Beijing, China, 2020.
34. JTG B05-01-2013; Specification for Safety Performance Evaluation of Highway Guardrails. China Communications Press: Beijing, China, 2013.

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