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Production Research and Development

Bridge Approach Bumping Disease and the Application of New Prestressed Approach Slabs

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Abstract: With the increase in the service life of domestic infrastructure, the bridge approach bump formation has become increasingly common. This paper discusses the causes of bridge approach bump formation, which is primarily attributed to the differential settlement between rigid abutment foundations and flexible embankment foundations. This paper also provides a review of factors contributing to the formation of bumps, such as the cracking of approach slabs and soil erosion behind abutments. A prestressed UHPC (ultrahigh performance concrete) approach slab is proposed, and its structural performance is evaluated through finite element analysis, verifying the load-bearing capacity of this new type of approach slab. The novel prestressed approach slab exhibits excellent crack resistance, effectively reducing soil erosion behind abutments and mitigating uneven settlement of foundations near bridge abutments, thereby alleviating the problem of bridge approach bump formation. This study on prestressed approach slabs provides a theoretical basis for slab design and offers a valuable reference for mitigating the formation of bridge approach bumps.

Keywords: bridge approach bump; foundation settlement; approach slab; UHPC; prestressed approach slab; grillage model

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1 Introduction

With the increase in the service life of domestic infrastructure, bridge approach bump (BAB) formation has become an increasingly prevalent phenomenon. To date, the hazards related to BABs have evolved from a mere issue of riding comfort to a complex crisis encompassing safety, economic, and social impacts [1]. In terms of safety, bumps can lead to a loss of vehicle control, resulting in traffic accidents and even secondary collision risks. From the economic perspective, BAB causes damage to bridge and roadbed structures, increasing highway maintenance costs while accelerating vehicle wear. With respect to social impact, BABs can trigger traffic congestion and reduce the efficiency of regional road networks. Additionally, the high-frequency vibrations induced by bumps may cause progressive damage to both the superstructure (e.g., displacement of beam supports) and the substructure (e.g., loosening of pier foundations) of bridges, threatening their long-term structural safety.

The BAB phenomenon is a typical long-standing issue in bridge engineering, fundamentally arising from abnormal structural dynamic responses when vehicles pass through the transition zone between a bridge and roadbed because of differential settlement or degradation of expansion joint functionality [2,3]. This problem is particularly prominent in coastal areas. On the one hand, the complex geological conditions in these regions, ranging from soft silt soils to hard rock formations with abrupt transitions, make it difficult to coordinate settlement differences between the bridge approach and roadbed. On the other hand, frequent extreme weather events such as typhoons and heavy rainfall accelerate foundation erosion and material deterioration, further exacerbating structural deformation risk. Moreover, coastal areas are economically vibrant with dense traffic flow and a high proportion of heavy-duty vehicles. Long-term, high-frequency dynamic loads accelerate abrasion and the damage of expansion joints, creating a vicious cycle of "settlement-damage-worsening settlement."

Currently, technical bottlenecks exist in the prevention and mitigation of BABs across the entire spectrum of design, construction, and maintenance. Overall, during the design phase, traditional specifications lack precision in predicting coupled multifactor settlement. The design approach for approach slab lengths and longitudinal gradients often overlooks vehicle dynamic response characteristics, resulting in insufficient structural adaptability. During the construction phase, the compaction rate of backfill soil behind abutments often fails to meet standards, and drainage system construction defects are common, which are primary contributors to foundation softening. In terms of maintenance management, existing monitoring methods rely on manual inspections and localized detection, making early warning of differential settlement difficult [4].

Traditional prevention measures for BABs focus mostly on construction process optimization or localized reinforcement, and systematic research on the mechanisms of multifactor coupling are lacking. Conventional maintenance methods often depend on post-occurrence repairs, and proactive intervention mechanisms are lacking, which leads to recurring issues and persistently high maintenance costs.

Therefore, an in-depth analysis of the underlying mechanisms and evolution patterns of BABs from an interdisciplinary perspective is urgently needed. The research should cover areas such as the modeling of geology–structure–traffic interactions, the development of new settlement control technologies, and the construction of intelligent monitoring and early warning systems to achieve a transition from passive treatment to active prevention. This research has direct engineering value for enhancing the durability and safety of bridges in coastal areas, and it also provides theoretical support for the lifecycle management of transportation infrastructure in complex environments.

2 Analysis of the Mechanism and Factors Associated with Bridge Approach Bump Formation

2.1 Analysis of the Mechanism of Bridge Approach Bump Formation

To address issues related to the transition of vehicles from a rigid bridge deck to a flexible road surface, an approach slab arranged as shown in Figure 1 is a common measure to mitigate bumping. The approach slab is typically supported on one end by the abutment and on the other end by a sleeper beam.

For a highway bridge with an approach slab length of L and a design speed of V, the simplified alignment corresponding to differential settlement at the bridge approach—resulting in a longitudinal slope transition at the approach slab—is shown in Figure 2 below:

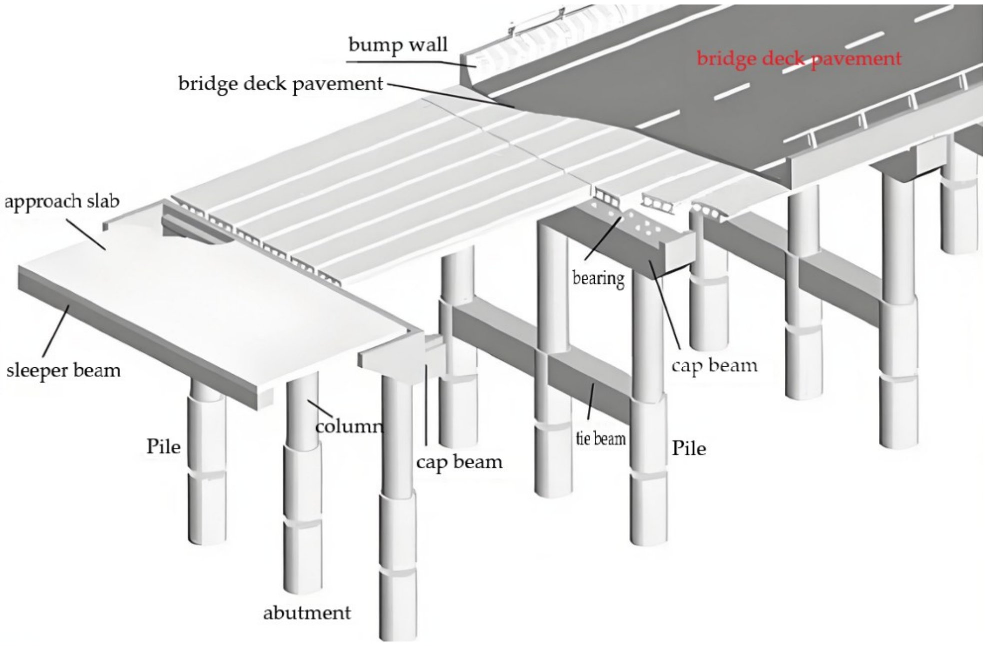


Figure 1 Schematic diagram of approach slab arrangement

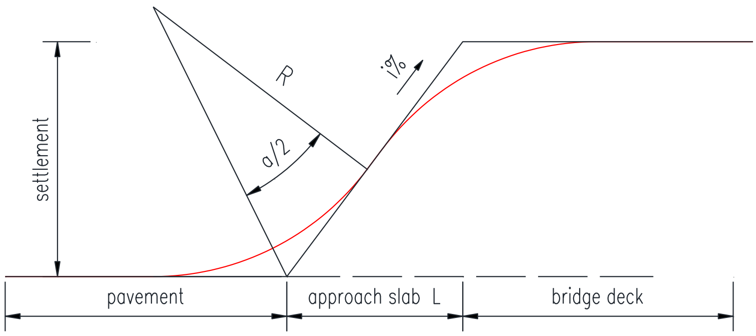


Figure 2 Simplified longitudinal alignment of the approach slab

When a vehicle passes from the bridge deck over the approach slab, this road section can be considered a vertical curve. The vehicle experiences a centrifugal force on the vertical curve, whose value is given by the following equation:

$$F = \frac{MV^2}{R} \tag{1}$$

where

F — Centrifugal force acting on the vehicle (N).

M — Mass of the vehicle (kg).

V — Velocity of the vehicle (m/s).

R — Radius of the convex vertical curve (m).

The condition under which the centrifugal force F reaches $0.1M$ is defined as the critical bumping state ($\mu = 0.1$), while the condition under which F reaches $0.2M$ is defined as the limit bumping state ($\mu = 0.2$) [4]. By definition, the critical bumping state generally corresponds to a relatively comfortable ride, whereas the limit bumping state represents the upper limit of tolerance. Exceeding this limit renders the bridge approach unsuitable for prolonged vehicle operation. From Equation (1), the radius R can be expressed as follows:

$$R = \frac{MV^2}{F} = \frac{MV^2}{\mu \cdot Mg} = \frac{V^2}{\mu \cdot g} \tag{2}$$

where μ is the ratio of centrifugal force F to vehicle weight (Mg), which is an important index for determining driving comfort.

According to Figure 2, the radius R of the convex vertical curve can be expressed as follows:

$$R = \frac{0.5L}{tan(\frac{\alpha}{2})} \approx \frac{L}{\alpha} \tag{3}$$

The longitudinal slope gradient i of the bridge approach slab can be expressed as follows:

$$i = \frac{L}{R} = \alpha \tag{4}$$

According to Equations (2) to (4), when the vehicle speed is constant, the radius of the vertical curve for the critical bumping state (μ = 0.1), the radius for the limit bumping state (μ = 0.2), and the longitudinal slope value i can be determined on the basis of the value of μ. Considering different vehicle speeds and taking an 8-meter-long approach slab as an example, the corresponding vertical curve radius and longitudinal slope for the critical bumping state (μ=0.1) can be calculated using the formulas (Table 1).

Table 1 Vertical curve radius and longitudinal slope for the critical bumping state

Vehicle speed V (km/h)	**Approach slab length L /m**	**Vertical curve radius R /m**	**Longitudinal slope i /%**
60	8	283.56	2.82
80	8	503.80	1.59
100	8	787.48	1.02

From the above analysis, it is evident that the essential cause of BABs lies in the differential settlement that occurs at the two ends of the approach slab. The greater the differential settlement between the rigid bridge abutment foundation and the flexible road foundation is, the steeper the longitudinal slope at the bridge approach, and the more pronounced the BAB phenomenon becomes.

2.2 Factors Associated with Bridge Approach Bump Formation

Through a multifaceted analysis of the factors contributing to BABs, the potential causes and their interrelationships were determined, which are summarized as follows:

(1) Differential settlement between the bridge abutment and backfill soil is the essential cause of bump formation.
(2) Nonuniform settlement of natural foundations due to self-weight and external loads.
(3) Differential settlement caused by improper construction practices or unreasonable construction sequences. While these factors cannot be completely eliminated, measures can be taken to minimize their impact.
(4) Influence of fill material selection, environmental changes, and treatment measures on differential settlement.
(5) Inadequate drainage leading to foundation settlement and soil erosion. This issue can arise from design or structural defects, even when good construction quality is ensured. It primarily manifests as gaps at the connection between the bridge culvert and embankment, which gradually widen under the combined effects of water erosion and traffic loads [5].
(6) Structural factors: Approach slab designs may fail to account for the impact of foundation bearing capacity and settlement, leading to displacement and cracking under dynamic loading. Alternatively, cracking may occur because of

unreasonable stress distribution resulting from the aforementioned settlement issues, which can generate a vicious cycle in which water infiltration exacerbates foundation settlement beneath the slab. Another common scenario is excessive settlement outside the sleeper beam at the rear end of the approach slab, causing the vehicle bumping point to shift forward. Settlement-induced water infiltration results in a vicious cycle, altering the intended stress distribution on the slab, accelerating backfill settlement, and worsening the bumping effect.

The first four factors can be mitigated through construction management and quality control, but they clearly interact with the latter two factors. The approach slab structure relies on the support of the underlying foundation, with vehicle loads transmitted through the slab to the foundation soil. This represents a typical long-term compatibility issue between the structure and the foundation.

2.3 Traditional Bridge Approach Bump Solutions

In bridge design, in addition to foundation treatment, the installation of an approach slab is the primary structural measure used to address bumping caused by differential settlement at bridge approaches. The approach slab, located between the abutment and backfill, is a key structure for preventing BABs, as shown in Figure 3. It facilitates the transition of vehicles from the rigid bridge to the flexible roadbed, distributes vehicle loads to reduce pressure on the foundation soil, and minimizes compressive deformation. Additionally, it promotes drainage, preventing rainwater from infiltrating into the foundation, thereby reducing soil erosion and compression deformation.

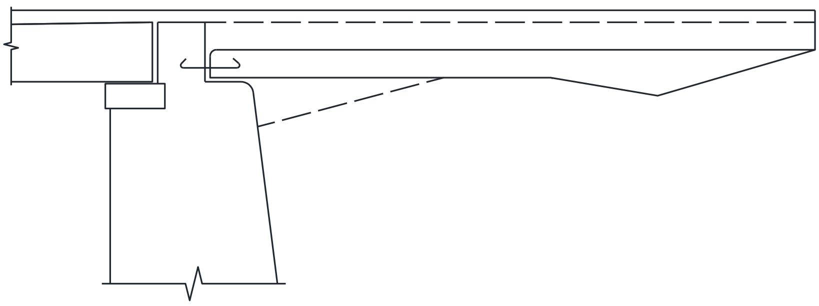


Figure 3 Typical bridge approach slab

The design aims to achieve a smooth transition using the approach slab. However, one end of the slab is supported by the relatively rigid abutment, whereas the other end rests on a sleeper beam bearing on the foundation. Without preventive measures, surface water can infiltrate through cracks at both ends of the slab, gradually eroding the backfill soil behind the abutment. This leads to backfill deformation or loss, ultimately causing subgrade settlement. Under long-term traffic loads, BAB becomes inevitable, significantly affecting vehicle speed and ride comfort.

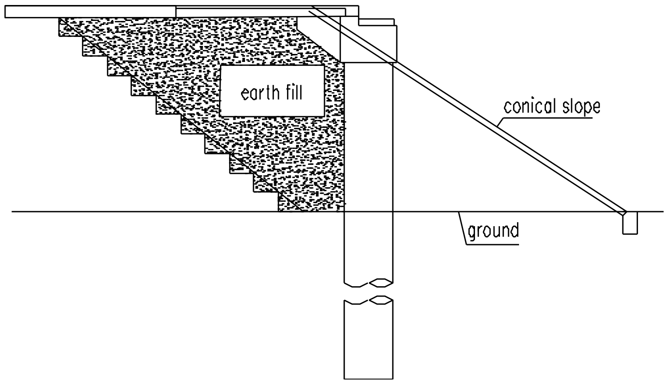
To address this issue, various solutions have been proposed by researchers, including the following:

(1) Gradual treatment of the foundation in the abutment transition zone (Figure 4a).

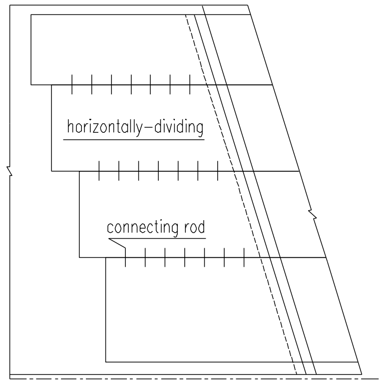
(2) Transverse segmentation and splicing of the approach slab (Figure 4b) to reduce differential settlement.

(3) Semiembedded foundation for the approach slab to mitigate settlement (Figure 4c).

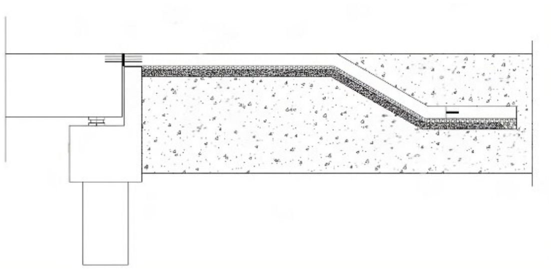
(4) Utilization of pile foundations or partition walls to maintain soil integrity, followed by the integration of the approach slab with the abutment using horizontal or vertical reinforcement (Figures 4d and 4e). This rigid connection enables the slab's deformation to mitigate foundation settlement.



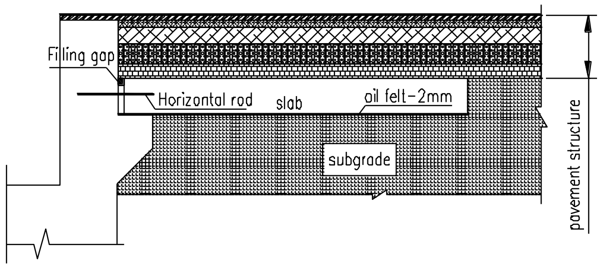
a) Gradual treatment of approach slab foundation in abutment transition zone



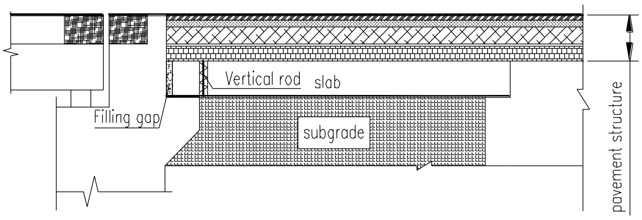
b) Transverse segmentation of approach slab



c) Variable-gradient approach slab



d) Longitudinal connection of approach slab



e) Vertical connection of approach slab

Figure 4 Common measures used to prevent differential settlement of approach slabs

While the aforementioned solutions mitigate BAB formation to some extent, they fail to resolve the issue completely. On the one hand, these solutions are proposed on the basis of full consideration of the soil bearing capacity. However, once the approach slab cracks, surface water can infiltrate through the cracks, erode the backfill soil, and ultimately lead to backfill deformation or loss, causing differential settlement of the foundation. On the other hand, for solutions that integrate the slab with the abutment, the rigid connection induces negative bending moments in the slab. Under long-term traffic loads, the slab may gradually crack, eventually resulting in backfill deformation or loss and differential foundation settlement.

Therefore, design approaches for addressing BAB formation should follow these principles:

(1) Protect the structural integrity (crack resistance) of the approach slab.
(2) Utilize the approach slab’s structure to prevent soil erosion and ensure that no rigid displacement occurs.
(3) Implement measures to ensure that the backfill soil itself does not undergo excessive natural settlement (addressed through construction measures).

3 Newly Prestressed UHPC Lattice-Type Approach Slab

On the basis of the above analysis, a new type of prestressed approach slab designed as a bidirectional orthogonal ribbed beam grid slab made with UHPC-100 material is proposed in this paper. Prestress is applied within the longitudinal ribs of the new slab. By installing longitudinal prestressing tendons, structural performance can be effectively enhanced, reducing deflection of the approach slabs and preventing crack formation, thereby avoiding water infiltration that could lead to foundation settlement and structural sinking. More importantly, the UHPC (ultrahigh performance concrete) slab combined with prestress is lightweight and reduces the load on the underlying foundation. Prestressing allows the slab to be used with a predetermined camber, leveraging the tensile resistance of UHPC to adapt to foundation deformations. Finally, the prestressed slab can extend cantilever style, achieving a true transition from rigid and semirigid to flexible pavement. Since the cantilever portion is related to vehicle loads, this study focuses on the mechanical performance of the slab between the abutment and the sleeper beam.

3.1 Design Parameters of the New Prestressed UHPC Approach Slab

The prestressed lattice-type UHPC approach slab has a longitudinal length of 8 m and a transverse width of 12 m, accommodating two bidirectional lanes and two nonmotorized vehicle lanes on either side. The general layout of the slab is shown in Figures 5 and 6. The material used is UHPC-100 concrete (the material parameters are listed in Table 2), reinforced with steel bars and longitudinal prestressing tendons.

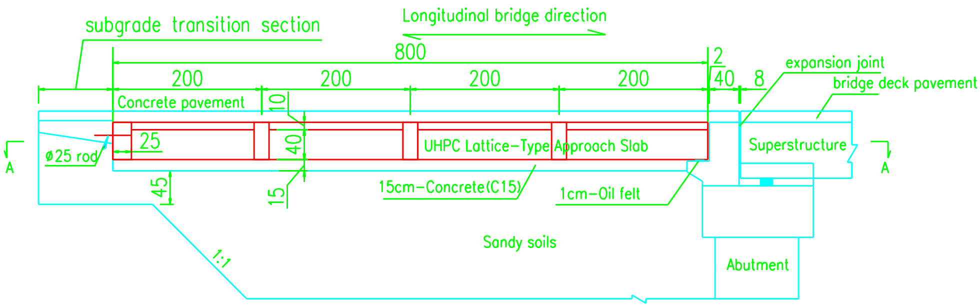


Figure 5 Elevation layout of the approach slab (unit: cm)

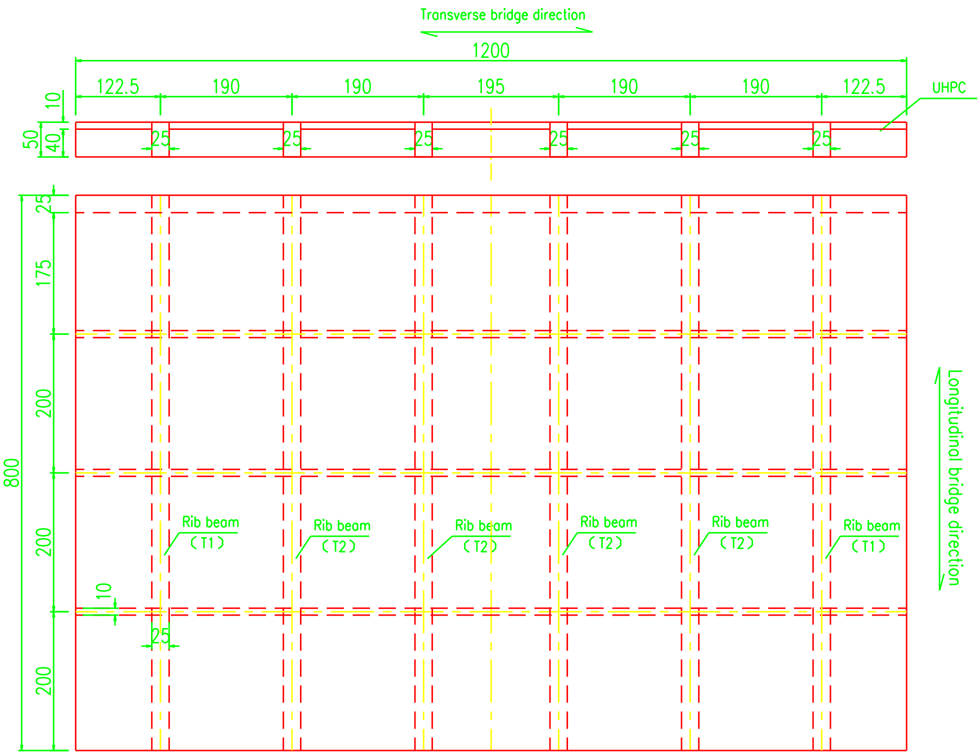


Figure 6 Structural section and plan view of the approach slab (unit: cm)

Table 2 Mechanical performance parameters of UHPC [6,7]

Grade	Compressive strength /MPa	Tensile strength /MPa	Elastic modulus /GPa	Poisson's ratio
UHPC-100	100	15	40	0.2
UHPC-150	150	20	45	0.25

The longitudinal ribs along the bridge direction have a width of 25 cm and a height of 50 cm (Figure 7). Among them, the T1-type ribs are for nonmotorized vehicle (pedestrian) lanes, and the T2-type ribs are for motor vehicle lanes; the prestressing tendon configurations for the two rib types are YM15-3 and YM15-9, respectively.

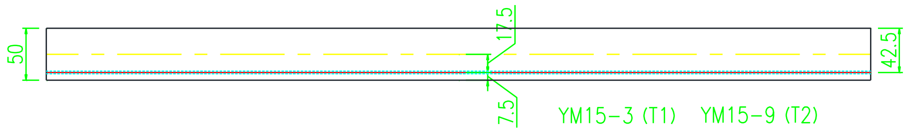


Figure 7 Prestressing tendon layout (posttensioning method) (unit: cm)

3.2 Finite Element Model and Boundary Conditions

Given the large width of the slab and its ribbed plate structure, a model is built using the grillage method, with bridge deck shell elements established (Figure 8).

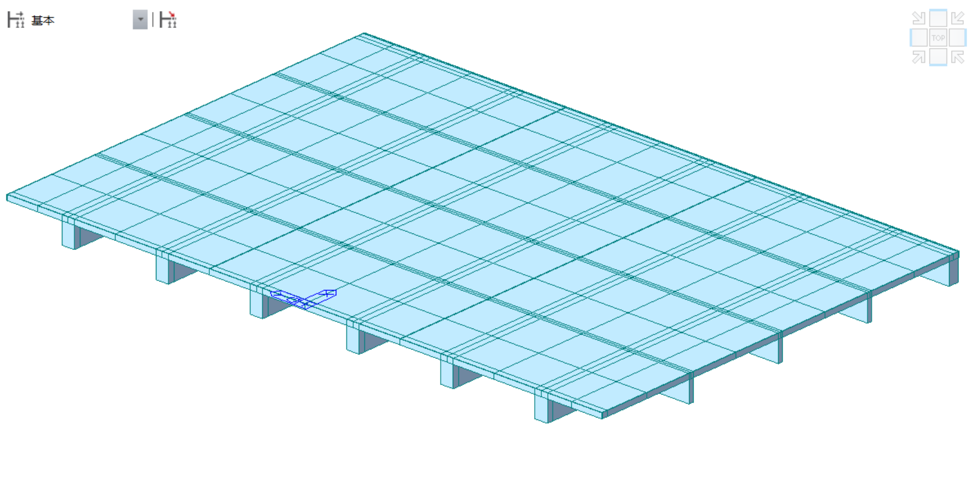


Figure 8 Approach slab model in Midas Civil software

3.2.1 Boundary Conditions

A simply supported boundary condition is set on the abutment side. On the roadbed side, a sleeper beam is modeled using compression-only vertical soil springs with a stiffness of 100,000 kN/m. The longitudinal and transverse ribs are also connected using compression-only soil springs, with vertical stiffnesses of 5,000 kN/m and 2,000 kN/m, respectively. The method for calculating the vertical stiffness at the nodes of the longitudinal and transverse ribs is as follows.

For artificially compacted hard clay, the subgrade reaction coefficient K_h is 2.0E+04 kN/m^3 [8]. With a node spacing of approximately 1 m in the model, a longitudinal rib width of 0.25 m, and a transverse rib width of 0.1 m, the vertical stiffnesses for the longitudinal and transverse rib nodes are calculated as follows:

Longitudinal rib node vertical stiffness: k_{z_x} =0.25×1×20,000 = 5,000 kN/m.

Transverse rib node vertical stiffness: k_{z_y}=0.1×1×20,000 = 2,000 kN/m.

3.2.2 Load Conditions

① Structural self-weight + secondary dead load (secondary paving load: 3.6 kN/m², applied as a uniformly distributed load on the bridge deck shell elements, as shown in Figure 9).

② Prestressing load: T1 tendons (YM15-3) for the side longitudinal ribs and T2 tendons (YM15-9) for the middle longitudinal ribs, with an effective stress of 1,000 MPa after accounting for prestress losses.

③ Moving load: Lane surface loading (standard vehicle and crowd loads).

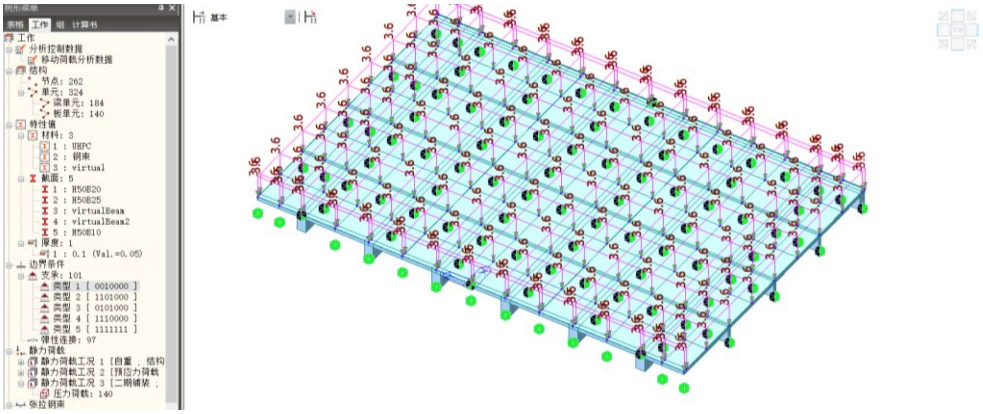


Figure 9 Loading position of the secondary paving

4 Analysis of Calculation Results

4.1 Deformation Analysis

Under the combined action of self-weight and secondary dead loads, the maximum vertical displacement of the structure is approximately -1.9 mm, which occurs at the mid-span (see Figure 10). Under prestress alone, the structure exhibits an upward camber, with a maximum displacement of approximately 7.6 mm at the mid-span (see Figure 11). Under standard load combinations, the maximum displacement of the structure is approximately 5.9 mm (see Figure 12). Owing to the high stiffness at the support locations, the vertical displacement is nearly zero.

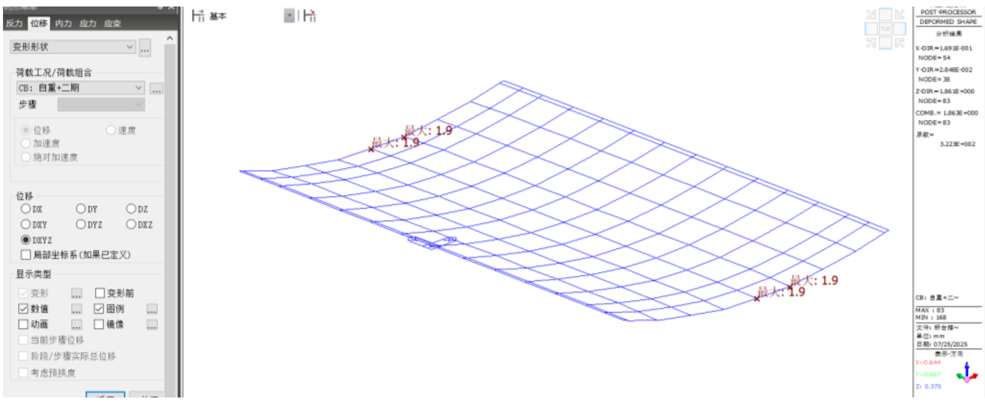


Figure 10 Structural displacement under self-weight + secondary dead loads (unit: mm)

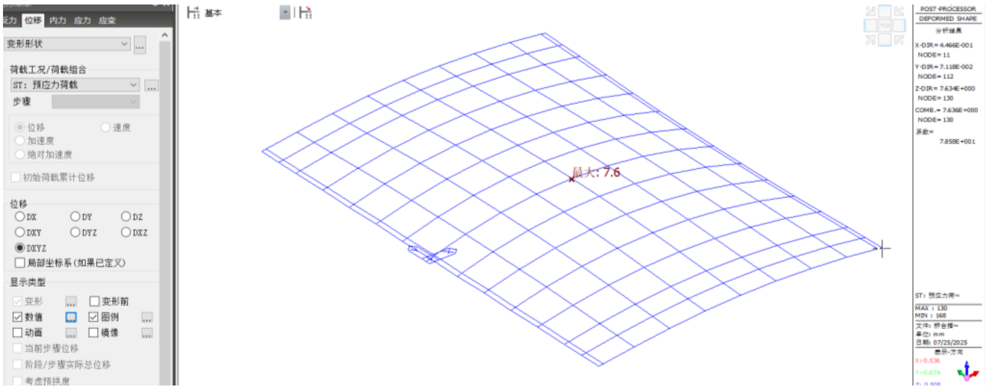


Figure 11 Structural displacement under prestress loading (unit: mm)

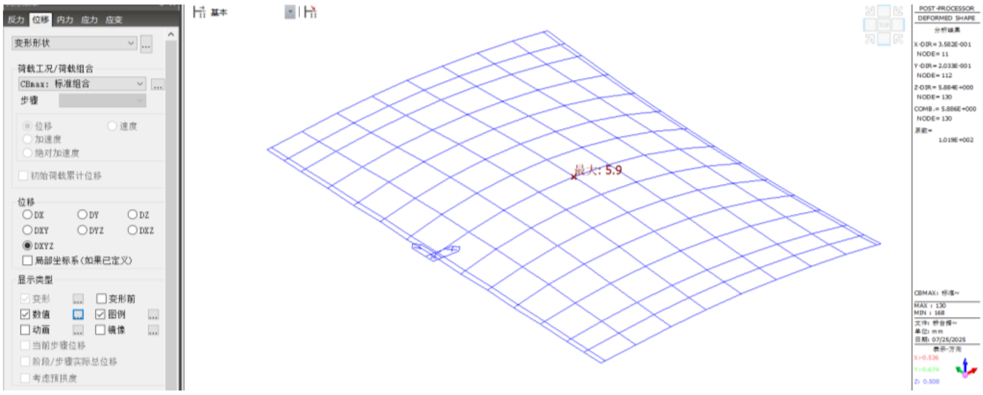


Figure 12 Structural displacement under standard load combination (CBmax) (unit: mm)

4.2 *Stress Analysis of Beam Elements (Top Surface)*

Under self-weight and secondary dead loads, the top surface is in compression, with a maximum stress of approximately 1.7 MPa near the 1/4 span of the longitudinal ribs (see Figure 13). Under prestress, the top surface experiences tension, with a maximum stress of approximately 5.1 MPa at the sleeper beam support on the roadbed side (see Figure 14). Under standard load combinations, the stress range on the top surface of the main beam is between -7.4 MPa and 8.8 MPa (see Figure 15). Most areas of the top surface of the longitudinal ribs are under compressive stress, but tension occurs near the support locations (see Figure 16).

The maximum tensile stress on the top surface is 8.8 MPa, and the maximum compressive stress is -7.4 MPa. The majority areas of the longitudinal rib remain under compression. All stresses on the top surface are within the tensile and compressive strength limits of UHPC-100.

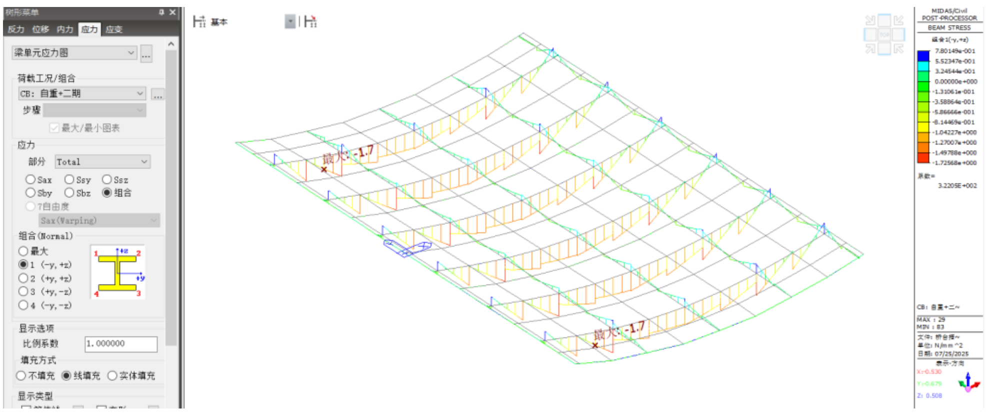


Figure 13 Top surface stress of beam elements under self-weight + secondary dead loads (unit: MPa)

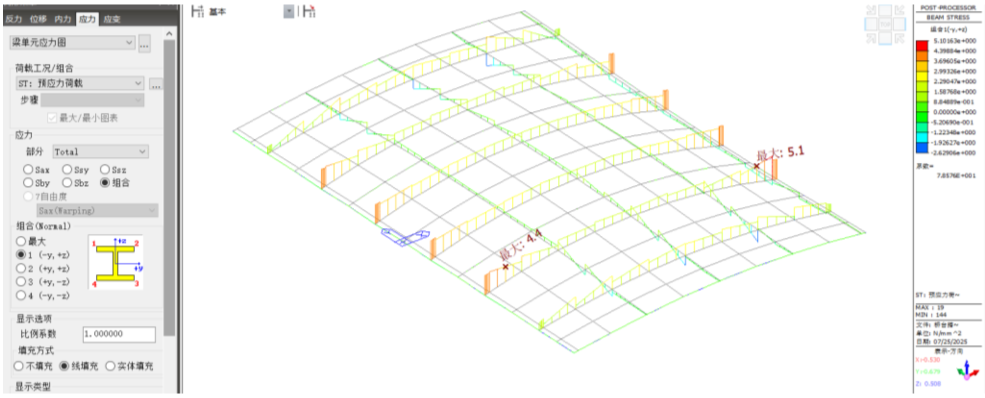


Figure 14 Top surface stress of beam elements under prestress loading (unit: MPa)

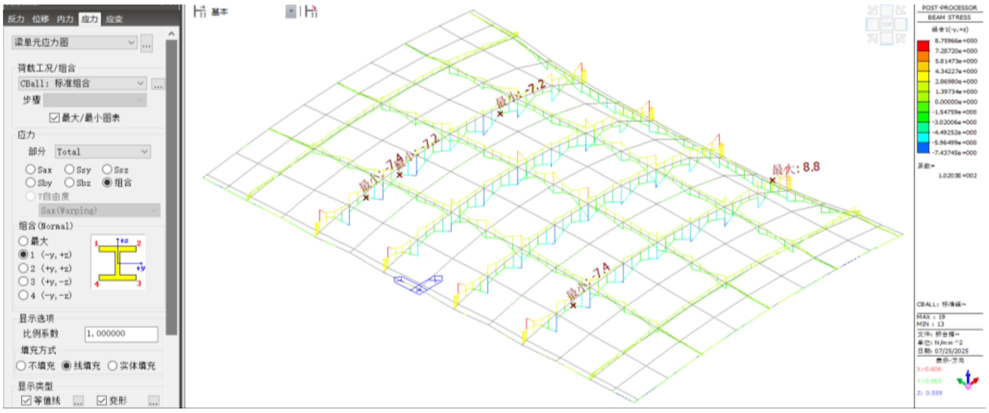


Figure 15 Envelope diagram of the top surface stress of beam elements under standard load combination (unit: MPa)

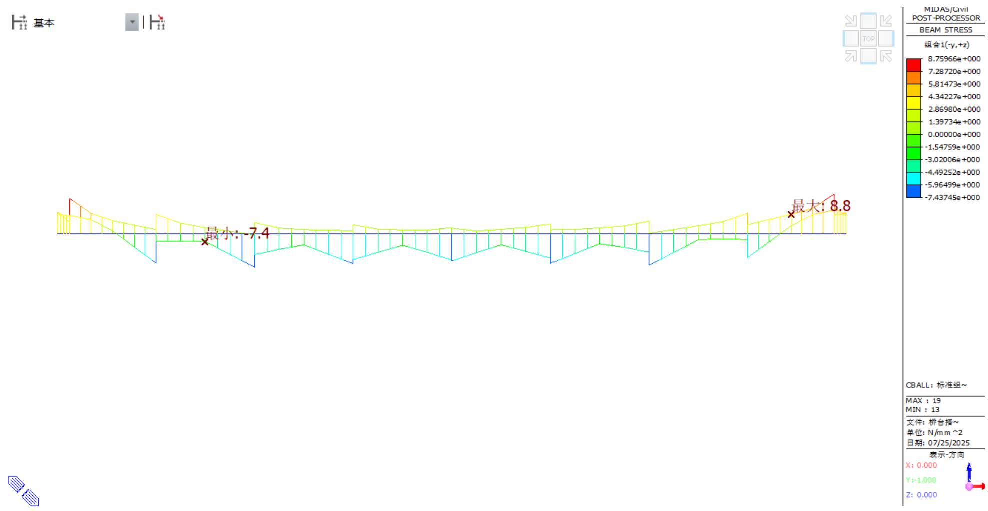


Figure 16 Envelope diagram of the top surface stress of longitudinal ribs under standard load combination (unit: MPa)

4.3 *Stress Analysis of Beam Elements (Bottom Surface)*

Under self-weight and secondary dead loads, the bottom surface is in tension, with a maximum stress of approximately 3.5 MPa near the mid-span (see Figure 17). Under prestress, the bottom surface is under compression, with a maximum stress of approximately -19.1 MPa near the supports and approximately -17 MPa in other areas.

Under standard load combinations, the stress on the bottom surface is between 10.0 MPa and -20.0 MPa. Tensile stresses occur only on the transverse ribs, with most areas experiencing tensile stresses below 5.0 MPa. Localized areas near the intersections of the supports and longitudinal ribs have tensile stresses reaching 10.0 MPa (see Figure 18), which is negligible. The bottom surface of the longitudinal ribs is entirely under compression, with stresses ranging from -3.0 MPa to -20.0 MPa (see Figure 19). The maximum tensile and compressive stresses do not exceed the design strength of UHPC-100 concrete. The stress in the transverse ribs is relatively low, and the maximum stress does not exceed 5.0 MPa. The maximum tensile stress near the supports is 10 MPa, but this is a stress singularity caused by elastic boundaries and can be disregarded in practice.

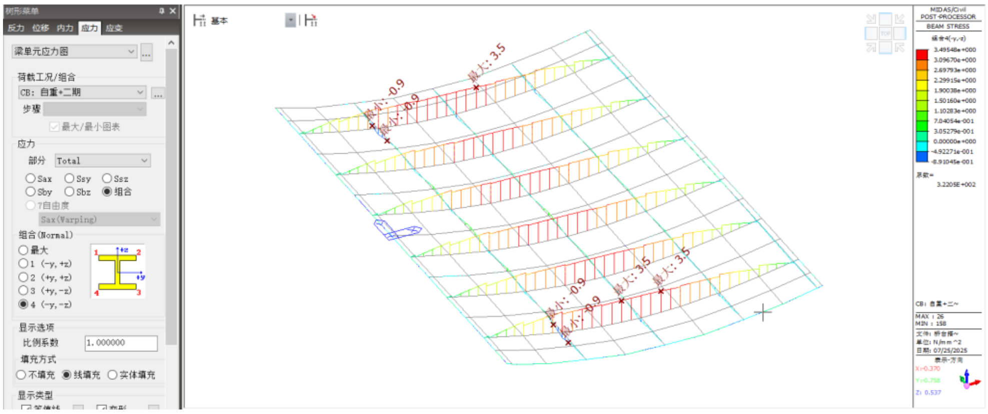


Figure 17 Bottom surface stress of beam elements under self-weight + secondary dead loads (unit: MPa)

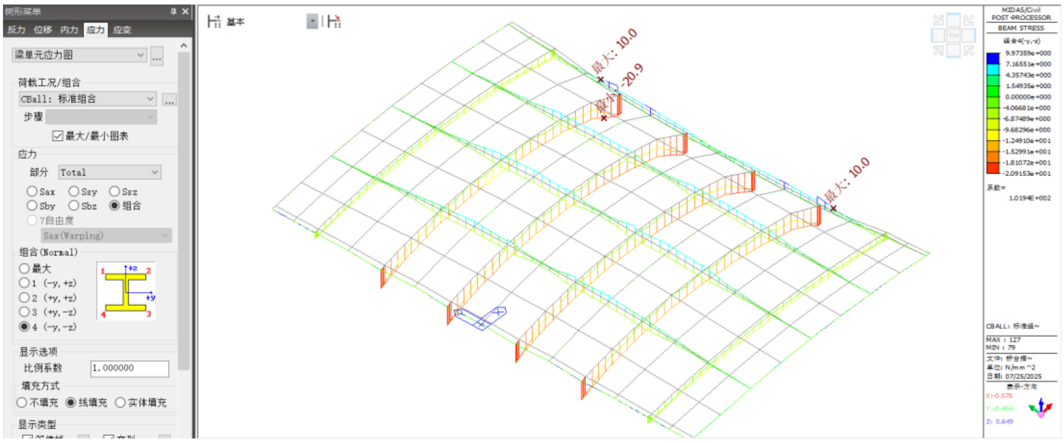


Figure 18 Envelope diagram of the bottom surface stress of beam elements under standard load combination (unit: MPa)

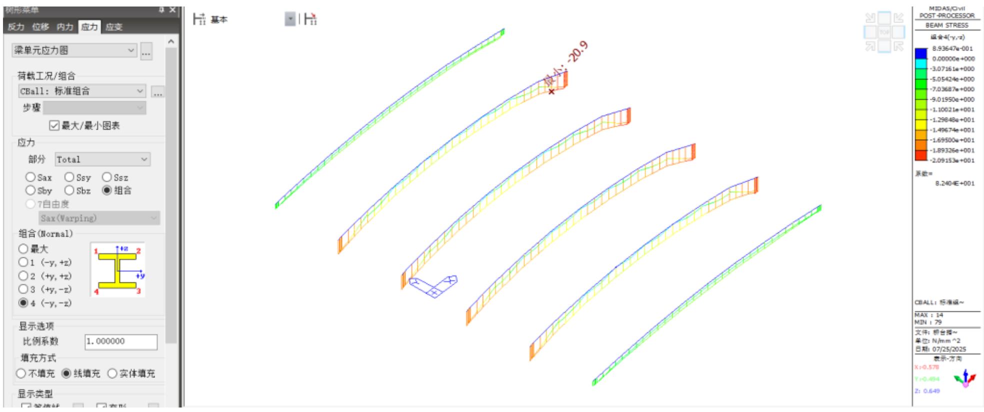


Figure 19 Envelope diagram of the bottom surface stress of longitudinal ribs under standard load combination (unit: MPa)

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4.4 Stress Analysis of Shell Elements

It can be seen from Figure 20 that the maximum tensile stress in the shell elements is 5.8 MPa, which occurs only in localized areas. The overall maximum equivalent stress in the shell elements is less than 3.8 MPa.

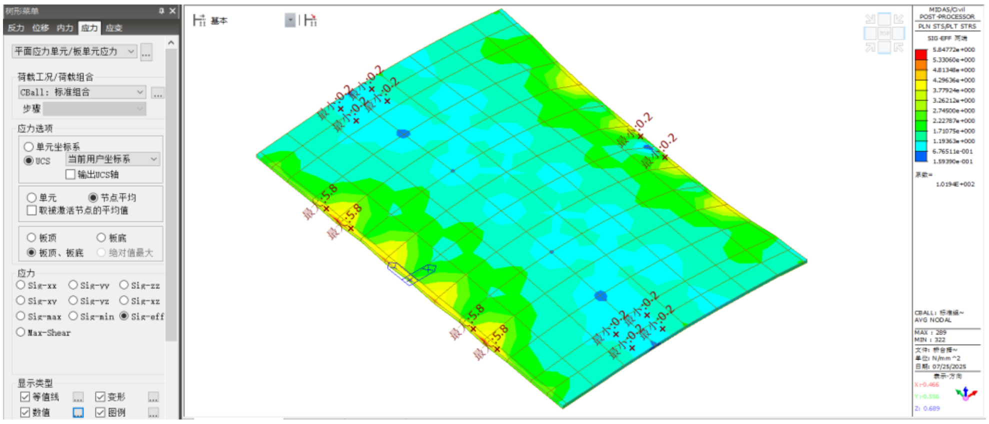

Figure 20 Envelope diagram of shell element stress under standard load combination (unit: MPa)

5 Conclusions

In this article, the hazards of BABs are systematically reviewed, their causes are analyzed, and associated factors are identified. On the basis of a qualitative analysis, a new prestressed UHPC approach slab with a lattice structure is designed, and its mechanical performance is verified through finite element analysis. The main conclusions of this article are as follows:

(1) The root cause of BAB formation is differential settlement at the two ends of the approach slab. Factors contributing to this differential settlement include inhomogeneity between the bridge abutment and backfill soil, improper construction practices, inadequate drainage at the bridge approach, and soil erosion beneath the slab due to long-term loading and slab damage.

(2) Traditional measures to prevent bridge approach bumps, such as gradual foundation treatment, variable-gradient slabs, transverse segmentation of the slab, longitudinal and transverse connections between the slab and abutment, and waterproofing and drainage measures, can only partially mitigate differential settlement. Once the approach slab cracks, water can infiltrate the backfill soil through the cracks, making BAB formation inevitable in the long term.

(3) The use of prestressed ribbed slabs, made of high-tensile-strength UHPC, reduces the self-weight of the approach slab while enhancing its performance, preventing excessive displacement and stress. Even when localized tensile stresses occur, the UHPC slab remains crack-free, preventing soil erosion beneath the slab and effectively resolving the BAB phenomenon.

Conflict of interest: All the authors disclosed no relevant relationships.

Data availability statement: The data that support the findings of this study are available from the corresponding author, Zhang, upon reasonable request.

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