

Effect of Backfill Stiffness on Minimising Settlement in Rail Bridge Approaches

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ABSTRACT: Non-uniform settlement at the interface between rigid bridge structures and adjacent embankments is a persistent problem in rail bridge approaches, degrading ride comfort, increasing maintenance costs, and, in severe cases, threatening operational safety. While backfill compressibility is widely recognised as a key contributor to this problem, quantitative guidance on how the elastic modulus of backfill materials governs the magnitude of differential settlement and displacement remains limited. This study addresses this gap using three-dimensional finite element (FE) analysis in Midas GTS NX to systematically investigate the influence of backfill elastic modulus, ranging from 25 MPa to 28,000 MPa, on the settlement and displacement behaviour of a jacked-frame-bridge rail approach. The soil was represented using a modified Mohr–Coulomb constitutive model calibrated with parameters derived from a geotechnical investigation report for a jacked frame bridge project in Shandong, China, while the backfill, subgrade, track and bridge structures were modelled as elastic materials. Static construction-stage analyses were performed to obtain the maximum vertical and horizontal displacements, together with the differential settlement and differential horizontal displacement across four monitoring sections spanning the bridge–embankment interface. The results show that increasing the backfill elastic modulus substantially reduces both differential settlement and maximum displacement, with the greatest improvement occurring within the 0–10,000 MPa range; beyond approximately 15,000 MPa, further increases yield only marginal benefit. The maximum vertical settlement decreased by 10%, the maximum ground heave by approximately 81%, and the differential horizontal displacement across the transition zone approached zero at high modulus values. These findings provide engineers with a quantitative basis for selecting backfill materials that balance mechanical performance against cost, and for identifying the elastic modulus threshold beyond which further material upgrades bring diminishing structural benefit.

KEYWORDS: Rail Bridge Approaches, Backfill, Elastic Modulus, Non-uniform Settlement, and Finite Element Method

1. INTRODUCTION

As the number of urban transportation vehicles has surged dramatically, upgrading transportation networks to meet growing traffic demands has become a continuous process. This is particularly true in urban areas, where the intersection of traffic routes is common and the construction of new roads passing under existing railways is increasingly prevalent. Typically, the design of these newly constructed underpass roads involves a jacking frame bridge structure at the intersection with the railway. The new bridge structure becomes part of the original embankment, transforming it from a single embankment into a combined embankment and bridge structure. Upon the bridge's completion, a rail bridge approach is created between the two structures to mitigate non-uniform settlement caused by their structural differences.

These rail bridge approaches are crucial in road and bridge engineering. However, the differences in the rigidity between road and bridge structures mean that the subgrade near the bridge is prone to uneven road surfaces, bumpiness at the bridge approach, and non-uniform settlement. Hyslip et al. (2009) and Tutumluer et al. (2012) indicated these factors not only affect driving comfort and safety but also increase maintenance costs and may cause structural damage. In severe cases, such issues can lead to train derailments.

These issues have impelled many scholars to conduct extensive research on bridge approaches, particularly on the causes of non-uniform settlement at bridge approaches and the most effective mitigation measures. For example, Hopkins and Deen (1969) identified several reasons for non-uniform settlement in these sections, including the properties of the subgrade and foundation soil materials, the height of the embankment, the type of abutment, the

compaction of the embankment fill, soil erosion in the rail bridge approaches between the abutment and embankment fill, and the construction sequence. Briaud et al. (1997) ranked the factors affecting the severity of the transition section in decreasing order of impact, namely, the compressibility of the backfill soil, non-uniform settlement of the foundation soil beneath the backfill, construction practices, overload, inadequate drainage, and the quality of the backfill soil. Long et al. (1998) identified additional causes of uneven settlement in rail bridge approaches in Illinois, including the failure of approach slabs, improper slope control during construction, and localised deformation of the foundation soil. White et al. (2007) found that unsealed expansion joints, erosion of granular backfill and improper construction significantly affect the performance of rail bridge approaches, noting that the volume change of the backfill soil ranges from 5% to 18%. Yasrobi et al. (2016) emphasised that improper construction is a primary cause of approach slab settlement and advocated for monitoring the compaction of backfill soil, as well as using pads to reduce lateral loads and displacements caused by temperature variations. These findings underscore the importance of implementing appropriate construction techniques and materials management when aiming to mitigate settlement issues. Liu (2020) conducted a comprehensive literature review on bridge bump phenomena, systematically classifying the influencing factors into internal and external categories. The internal factors included the embankments and foundations, drainage systems, approach slabs, abutments and expansion joints, and external factors included climatic conditions, traffic volume, construction processes, design standards and supervision. Although scholars have differing views on the relative importance of these influencing factors in the performance of bridge approaches, the performance and selection of

backfill materials are widely considered key determinants of non-uniform settlement at bridge approaches.

Recently, a great deal of research and analysis has been conducted on the selection and performance of backfill materials in bridge approaches. For example, Wu and Helwany (1990) and Luna (2004) observed that insufficient compaction of backfill materials can lead to significant compression. Hoppe (1999) recommended increasing the compaction of backfill materials to 95% of the standard value as well as controlling the fine particle content to between 4% and 20%. Monley and Wu (1993) employed tensile reinforcement materials to alleviate settlement, while Abu-Hejleh et al. (2001) and Helwany et al. (2003) used synthetic materials to substantially reduce settlement; however, Marquart (2004) noted that while geogrids are effective, they cannot eliminate settlement issues. Abu-Hejleh et al. (2006) upgraded geosynthetic reinforcement systems to further mitigate settlement problems. Additionally, Hartlen (1985) recommended using lightweight fill materials to reduce settlement, and Helwany and Koutnik (2007) found that expanded polystyrene (EPS) effectively reduces settlement, although at a higher financial cost. Mekawry (2004) improved drainage capabilities using recycled tyre fragments, and Malai et al. (2022) demonstrated that lightweight EPS effectively reduces the rate of settlement. Cao (2019) reported that high-strength foam concrete, when used as a backfill material, enhances both strength and durability, producing only minor cracks without causing structural damage. The studies noted here primarily focus on selecting appropriate backfill for bridge approaches and the technical controls applied during the construction process. However, there has been limited research on the relationship between the performance of backfill materials and non-uniform settlement in bridge approaches.

Because this study relies on finite element (FE) analysis to characterise soil–structure interaction, it is useful to situate the adopted approach within recent advances in FE modelling of geotechnical problems. Jamsawang et al. (2021) combined field monitoring with three-dimensional FE back-analysis to diagnose the failure of a composite soil–cement retaining wall, demonstrating that FE modelling calibrated against field data can reliably identify the root cause of unexpected ground movement. Likitlersuang et al. (2018) used FE modelling to simulate railway embankments constructed on soft soil, highlighting the sensitivity of predicted settlement to the constitutive model and stiffness parameters adopted, which reinforces the importance of the parameter-selection approach followed in this study. Govindasamy et al. (2020) combined FE analysis with a contraction-ratio method to assess tunnel-induced ground movement in the Kenny Hill Formation, underscoring the value of realistic ground modelling for predicting deformation around underground and near-surface structures. Ongpaporn et al. (2022) further illustrated how 3D numerical modelling, informed by detailed site investigation, can be used to evaluate the stability and deformation behaviour of geotechnical structures under varying ground and loading conditions. Collectively, these studies confirm that FE analysis, when supported by an appropriate constitutive model and well-calibrated parameters, provides a reliable basis for investigating the soil–structure interaction problem examined in this study.

To fill this gap in knowledge, this study primarily investigates the impact of the elastic modulus of backfill materials on non-uniform settlement in the bridge approach section. In the study, a model of a highway underpass beneath a railway was created using the finite element software Midas GTS NX. The study then analyses the impact of backfill materials with different elastic moduli on the non-uniform settlement of the bridge approach section. Additionally, the study examines the impact of backfill materials with different elastic moduli on the maximum displacement generated during the construction process in the bridge approach section. The study aims to provide a reference for the selection of backfill materials in the transition sections of railway abutments, specifically exploring how different elastic moduli affect non-uniform settlement and displacement. The results are intended to guide engineers and

researchers in optimising the stability and performance of these critical railway abutment transition sections.

2. FINITE ELEMENT ANALYSIS

With the advancement of modern computational tools, the finite element method (FEM) has been widely applied in geotechnical engineering. Numerical simulation methods significantly reduce the time needed to solve complex problems encountered in real-world civil engineering projects. Moreover, the ability to adjust parameters repeatedly allows for an instant reduction in the cost of traditional experiments. This enables efficient and cost-effective comparative analysis of structures under varying conditions, providing reliable predictions—particularly for projects where on-site experiments are difficult, and budgets are constrained.

2.1 Model size

Before building the model, the dimensions of the model must be determined. Constructing an underpass beneath an existing railway subgrade is different from conducting construction on a normal ground surface because the existing railway subgrade has already largely undergone consolidation settlement since its completion. Therefore, during the underpass construction process, foundation pit excavation becomes the primary factor that triggers new settlements. Thus, the impact range of the foundation pit excavation can serve as a reference for determining the model dimensions. Studies by Huang et al. (2013), Xi et al. (2023), and Cao et al. (2024) indicate that the influence range of foundation pits is generally two to four times the excavation depth. Furthermore, Cao et al. (2024) noted that the influence depth is twice the excavation depth of the foundation pit. In this study, the model's excavation depth is 5 metres, and the analysis domain is defined by extending outward from the edges of the foundation pit by a distance equal to five times that depth. The study area was defined as five times the excavation depth to ensure that the boundary conditions were far away from the excavation zone, thereby guaranteeing the accuracy of the analysis results. In this model, the lengths of both the X-axis and Y-axis are 70 metres, and the Z-axis measures 25 metres. For detailed model specifications, please refer to Figure 1. With regard to the discretisation of the model, the mesh was generated in Midas GTS NX using the Hybrid Mesher for the 3D solid domain, which produces a mixed solid mesh generated from a background surface mesh of triangular and quadrilateral elements (Delaunay 2D mesh generator). A pattern mesh was used to guide element distribution, with an angle criterion of 15° and a length ratio criterion of 0.7, at mesh optimisation level 3. The complete model comprises 43,355 elements and 28,502 nodes, corresponding to 86,214 degrees of freedom and 82,449 equations. Each analysis was completed with a total CPU time of approximately 153.0 seconds and a wall-clock time of approximately 157.4 seconds, confirming that the model size was computationally efficient for the parametric study of 13 backfill modulus values. A graded mesh, with finer elements concentrated near the excavation boundary and progressively coarser elements towards the model boundaries, was adopted to balance computational accuracy with efficiency; a mesh sensitivity check was carried out to confirm that further refinement did not materially change the predicted settlement and displacement results, ensuring that the reported trends are not an artefact of mesh discretisation.

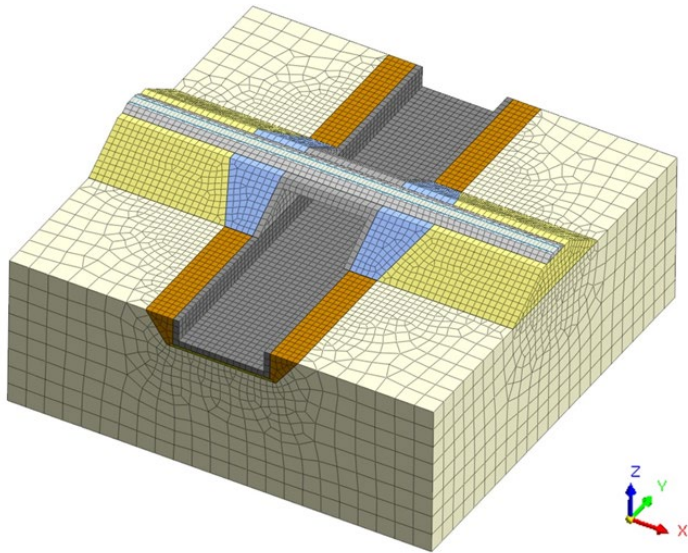


Figure 1 The numerical model of the completed jacking construction

2.2 Constitutive relationship

This study employed the modified Mohr–Coulomb (MMC) model in Midas GTS NX software as the constitutive model for the soil. This choice is crucial for simulating the behaviour of the soil under different loading conditions because the accuracy of the constitutive model directly affects the reliability of deformation predictions and stress distribution calculations.

The traditional Mohr–Coulomb (M-C) model can well describe the shear strength and failure behaviour of the soil during single loading cycles, but it cannot accurately simulate the soil response under unloading or cyclic loading conditions. Schanz et al. (1999) introduced the concept of soil hardening, which suggests that soil strain development is controlled by both non-linear elasticity and

plasticity. To more realistically reflect this characteristic, this study used the modified M-C model, which is based on the principles of the hardening soil model and can reasonably describe the mechanical behaviour of soil during loading and unloading processes.

Compared with the traditional M-C model, the modified M-C model introduces non-linear elasticity and plastic hardening mechanisms, allowing for a more accurate description of the soil's mechanical response under large deformations and stress redistribution. Additionally, the model can account for the soil's dilatancy and strain-softening effects, making the computational results more consistent with actual engineering conditions.

This study used a purely elastic constitutive model to simulate other structures such as the track, tie beams and frame bridges. The foundation soil parameters were derived from the geotechnical investigation report of a jacked frame bridge in Shandong, China. The general physical and mechanical properties of the soil are listed in Table 1, the non-linear characteristics are presented in Table 2, and the parameters of other structural components are detailed in Table 3.

The soil parameters listed in Tables 1 and 2 were derived from site-specific oedometer and triaxial test data reported in the geotechnical investigation for the project, following the parameter-determination procedures established for the hardening-soil family of models by Surarak et al. (2012), Likitlersuang et al. (2013a) and Likitlersuang et al. (2013b), and, for coarser-grained fill materials, by Sukkarak et al. (2021). Specifically, the secant stiffness in shear-hardening loading (E_{0u}) and the tangential oedometer stiffness (E_{oc}^d) were obtained from oedometer and consolidated triaxial compression tests, the unloading/reloading stiffness (E_{ur}) was taken as approximately three times E_{0u} following common hardening-soil practice, and the power for stress-level dependency and failure ratio were calibrated against the measured stress–strain response. The elastic modulus values adopted for the soil in Table 1, and correspondingly the backfill modulus values examined in Table 5, are undrained moduli, and the vertical and horizontal displacements reported in Section 3 therefore represent the short-term (undrained) elastic settlement response of the transition section immediately following construction, rather than the long-term consolidated settlement.

Table 1 Soil layer general parameters (Dong et al., 2024)

	Soil depth	Unit weight	Friction angle	Cohesion	Deformation modulus	Bearing capacity	Poisson ratio	Thermal expansivity	Damping ratio
Silty clay	m	kN/m ³	°	kN/m ²	MPa	KPa			
	25	19	13.8	21.8	11	70	0.3	1×10 ⁻⁶	5%

Table 2 Soil layer non-linear parameters (Li et al., 2019; Liu et al., 2020; Xing, 2021; Midas-GTS, 2004)

	Secant elastic modulus in shear hardening ($E_{g,p}$)	Tangential stiffness primary oedometer test loading (E_{oedref})	Elastic modulus at unloading (E_{ur})	Ultimate dilatancy angle	Reference pressure (P_{ref})	Power of stress level dependency	Porosity(n)	K_{0nc}	Failure ratio (R_f)
Silty clay	kN/m ²	kN/m ²	kN/m ²	°	kN/m ²				
	6300	6300	18,900	0	100	0.5	0.6	0.76	0.9

Table 3 Structural member parameters (Dong et al., 2024)

Structural member	Unit weight / (kN/m ³)	Modulus of elasticity / (MPa)	Poisson ratio	Thermal expansivity	Damping ratio
Rail	78.5	2.1×10 ⁵	0.3	1.25×10 ⁻⁵	5%
Railway ballast	21	2.4×10 ²	0.36	1.25×10 ⁻⁵	5%
Subgrade	18	30	0.2	1.2×10 ⁻⁵	5%
Jacking frame bridge	25	3.4×10 ⁴	0.2	1.2×10 ⁻⁵	5%

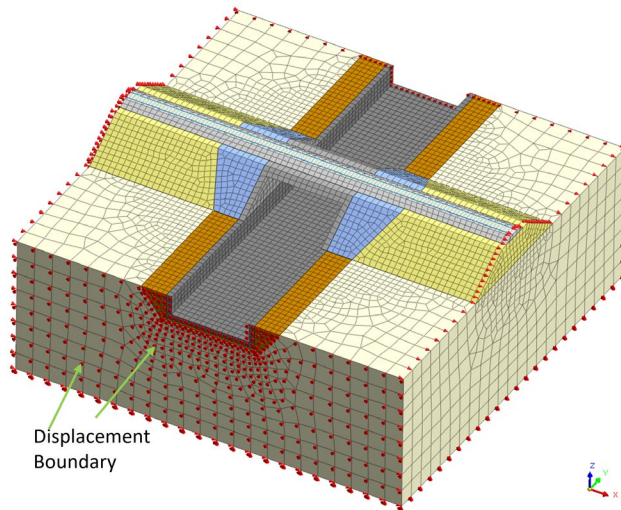


Figure 2 Boundary conditions

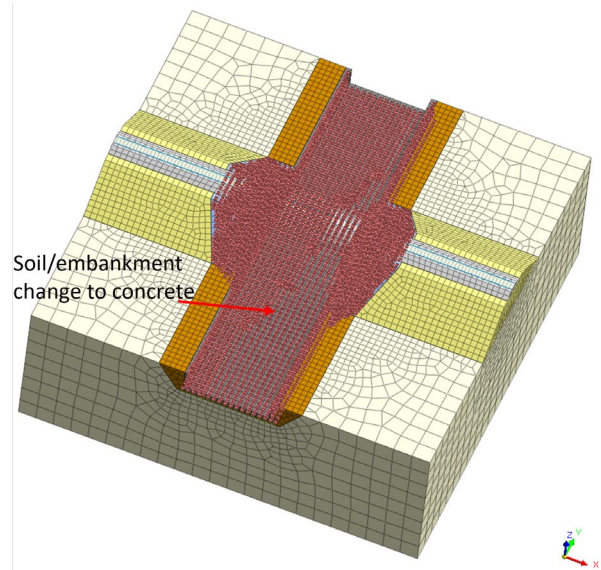


Figure 3 Change material property

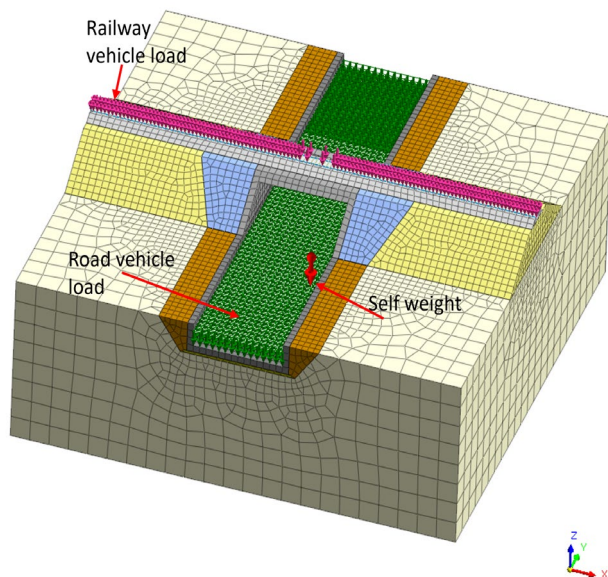


Figure 4 Load setting

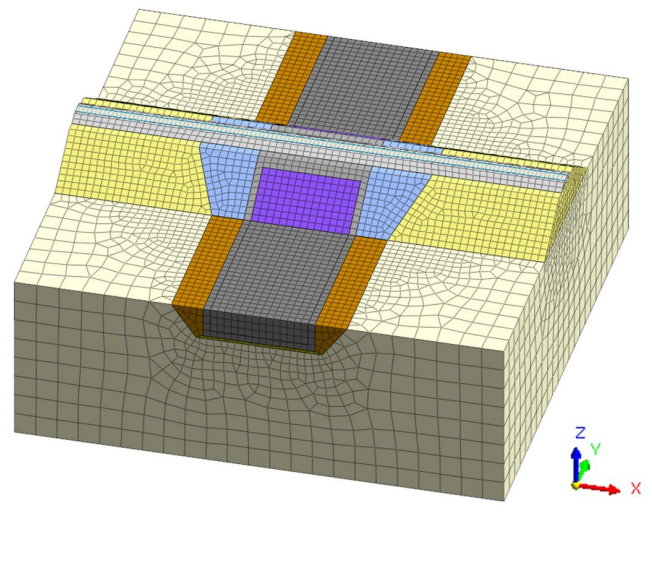


Figure 5 Pre-construction state

2.4 Load conditions

The load settings used in this study were primarily divided into two categories. The first category is the self-weight of all model components. Based on the material density, the self-weight load was applied to the corresponding components to accurately reflect the actual stress state. The second category consists of the loads from the railway and highway vehicles. For railway vehicle loads, the specifications outlined in the Code for Design of Railway Earth Structure (China Railway First Survey and Design Institute Group Co. Ltd, 2016) relating to mixed passenger and freight loads were followed. For the load on newly constructed roads, this study used the load types specified for trunk roads in the Code for Design of Urban Road Engineering (Ministry of Housing and Urban-Rural Development, 2016). The train load selected for the railway was for a mixed passenger and freight line, consisting of a uniformly distributed load of 85 kN/m and a concentrated load of 250 kN. The spacing between the concentrated loads is 1.6 metres, and the distance between the concentrated load and the uniformly distributed load is 0.8 metres. The highway load adopts a standard axle load of 100 kN

for a dual-wheel single axle configuration. In Figure 4, the red arrows represent the self-weight, the magenta indicates the railway load, and the green represents the highway load.

2.5 Construction phases

Given that the principal focus of this study is analysing the differential settlement, vertical displacement and horizontal displacement in rail bridge approaches, particularly in relation to the elastic modulus of backfill materials, it is unnecessary to comprehensively examine the entire construction process. Therefore, this study does not include analysis of the jacking process of the frame bridge or other procedures unrelated to the construction steps of the facility. Instead, the study concentrated on the static analysis of the rail bridge approaches before and after excavation, aiming to explore the impact of the elastic modulus of backfill materials on the transition section. By focusing on a single variable, the study sought to provide more precise academic insights in the relevant field. Figure 5 presents the pre-construction condition, while Figure 1 presented the post-construction condition. The detailed steps defining

the construction phases in the numerical simulation are presented in Table 4.

Table 4 summarises the four analysis stages, which follow the actual excavation and jacking sequence used on site: the initial in-situ stress state is first established under the existing subgrade and track loading (Stages 1–2); displacements are then reset to isolate

construction-induced movement (Stage 3); and the excavation soil within the footprint of the frame bridge is passivated (removed from the model) while the frame bridge and highway loading are simultaneously activated (Stage 4), thereby replicating the field jacking process in which the bridge structure is advanced into the excavated void as the surrounding soil is remove.

Table 4 Construction phases (Dong et al., 2024)

No	Phase	Phase content
1	Initial stress state of soil layer	Activate the soil; add the dead weight and boundary conditions; and clear the dead weight displacement of soil
2	Status of existing railway line	Activate existing subgrade, track and corresponding load
3	Displacement zeroing	Clear the displacement of structure and soil
4	Jacking in frame bridge	Passivate excavation soil, activate frame bridge, add highway vehicle load

2.6 Define the properties of the backfill materials

The elastic modulus is a key parameter for measuring a material's ability to resist elastic deformation under external forces. A higher elastic modulus indicates a greater resistance to deformation. In the bridge approach section, selecting an appropriate elastic modulus of backfill materials can help reduce uneven settlement caused by the differing structural systems between the subgrade and the bridge abutment.

The range of elastic modulus for the backfill materials examined in this paper is 25 MPa to 28,000 MPa. This range was selected by considering the elastic moduli of several commonly used backfill materials near bridge approaches, such as graded aggregate base, foam lightweight concrete and concrete.

According to relevant studies, the elastic modulus of graded crushed stone is typically in the range of 100 to 300 MPa under normal conditions. For well-compacted, high-quality graded crushed stone, the elastic modulus may reach 300–500 MPa. In cases of high moisture or insufficient compaction, the elastic modulus can fall below 100 MPa. Yu et al. (2020) reported that lightweight foamed concrete with lower densities (300–1200 kg/m³) typically exhibits a lower elastic modulus of approximately 0.1–3 GPa. For higher-density foamed concrete (approximately 1400–1600 kg/m³), the elastic modulus can be significantly higher, generally ranging from 4–6 GPa. In some cases, specially optimised high-density foamed concrete can reach an elastic modulus of up to 7 GPa or more, demonstrating how increased density and targeted formulations can

enhance the mechanical performance of foamed concrete. Han (2011) utilised nanoindentation and other advanced methods to evaluate the elastic modulus of foamed concrete and related composite materials. Through optimised formulations, the elastic modulus of the foamed concrete achieved values as high as 10 GPa or more, showcasing significant improvements in mechanical properties with specific material adjustments. The elastic modulus of concrete typically ranges from 25 GPa to 50 GPa. According to Eurocode 2 (European Committee for Standardization, 2004), normal-density concrete generally has an elastic modulus between 30 GPa and 40 GPa, while high-strength concrete can reach up to 50 GPa. ACI 318 (American Concrete Institute, 2019) provides a formula for calculating the elastic modulus based on concrete density and compressive strength, suggesting that for normal-weight concrete, the elastic modulus is approximately 25 GPa to 45 GPa. However, for backfill materials in bridge approach slabs, the concrete strength typically ranges from C15 to C25. Therefore, this study considers the upper limit of the elastic modulus of C25 concrete to be 28,000 MPa.

To better illustrate the relationship between elastic modulus and differential settlement, this study set the unit weight of the backfill material to 7 kN/m³. This value represents the lower unit weight typical of lightweight foamed concrete used as backfill material for bridge approach sections. Detailed properties of the backfill materials are provided in Table 5. Modulus of elasticity values examined (MPa): 25, 50, 100, 200, 400, 500, 1100, 2400, 3200, 5000, 10,000, 20,000, 28,000.

Table 5 Fill materials parameter

Structural member	Unit weight / (kN/m ³)	Modulus of elasticity / (MPa)	Poisson ratio	Thermal expansivity	Damping ratio
Fill materials in transition section	7	25, 50, 100, 200, 400, 500, 1100, 2400, 3200, 5000, 10000, 20000, 28000	0.1	1.25×10 ⁻⁵	5%

2.7 Define the sections

The differential settlement and differential horizontal displacement of the bridge approach section are determined by the settlement and horizontal displacement differences at several key sections. Section 1-1 and Section 4-4 represent the contact surfaces between the bridge approach and the embankment, while Section 2-2 and Section 3-3 represent the contact surfaces between the bridge

approach and the bridge. The settlement and horizontal displacement differences between Section 1-1 and Section 2-2 reflect the differential settlement and differential horizontal displacement of one side of the bridge approach section. Similarly, the settlement and horizontal displacement differences between Section 3-3 and Section 4-4 reflect the differential settlement and differential horizontal displacement of the bridge approach section on the other side. Details of the sections are presented in Figure 6.

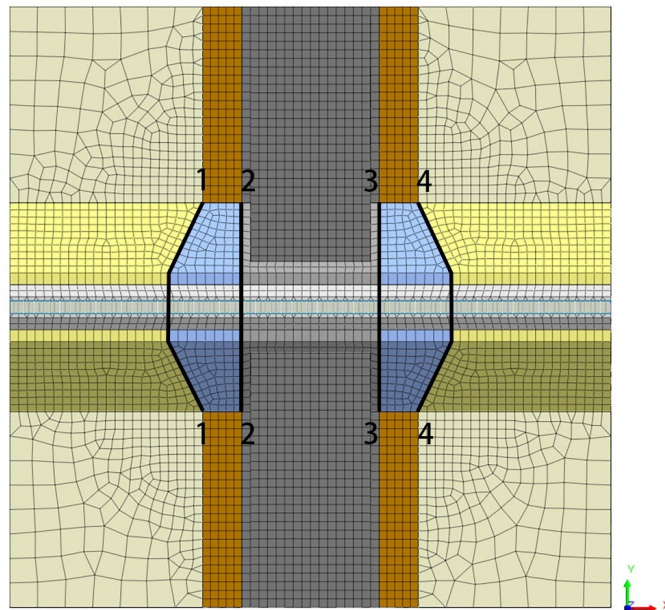


Figure 6 Uneven settlement and horizontal displacement at Sections 1-1 to 4-4

3. RESULTS ANALYSIS AND DISCUSSION

3.1 Results Analysis

After conducting a series of numerical simulation analyses, the results of the study clearly demonstrate that as the elastic modulus of the backfill material increases, both the maximum vertical and horizontal

displacements in the rail bridge approaches decrease accordingly. Furthermore, the differential settlement between the bridge and the embankment also reduces as the elastic modulus of the backfill material increases. This indicates that increasing the elastic modulus of the backfill material plays a positive role in mitigating displacement and differential settlement in the transition section.

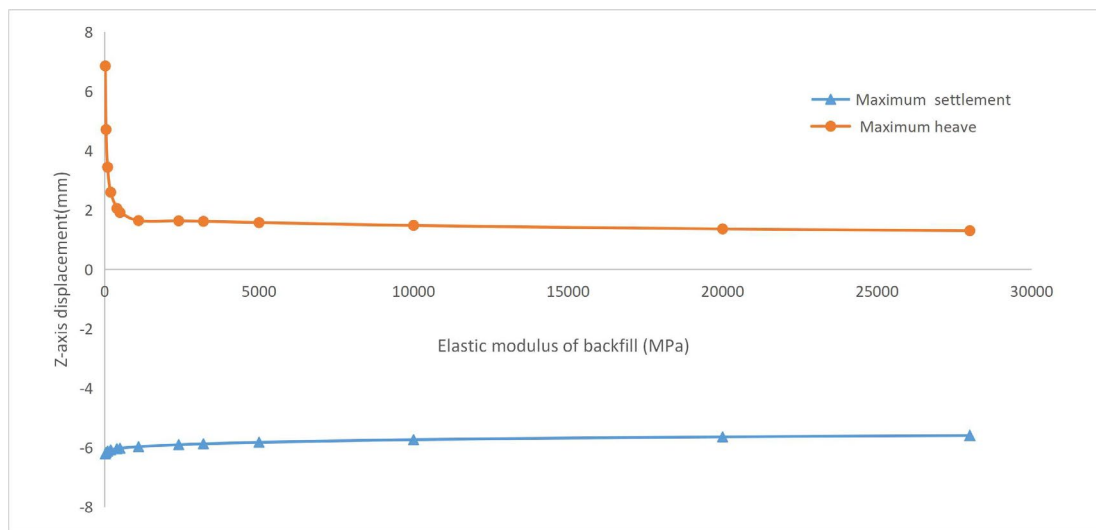


Figure 7 Maximum heave and settlement along the Z-axis under different elastic modulus values

Figures 7 to 8 clearly demonstrate that as the elastic modulus of the backfill material increases, the maximum displacements in all three directions decrease to varying extents. The elastic modulus of the backfill material has the most significant impact on vertical displacement. As the elastic modulus increases from 25 MPa to 28,000 MPa, the maximum settlement decreases from -6.21 mm to -5.59 mm, a reduction of 10%. Meanwhile, the maximum ground heave decreases from 6.85 mm to 1.31 mm, a reduction of approximately 81%. The considerable reduction in maximum ground heave with increasing elastic modulus greatly enhances safety during construction. In comparison, the influence of the backfill material's elastic modulus on horizontal displacements is relatively minor, with varying responses observed in the two horizontal directions. Along

the X-axis (in the direction of train travel), when the elastic modulus is 25 MPa, the maximum horizontal displacement is 2.05 mm. As the elastic modulus increases to 28,000 MPa, the displacement decreases only slightly to 2.00 mm, showing negligible change. In contrast, along the Y-axis (perpendicular to the direction of train travel), the displacement reduction is more noticeable—from 1.13 mm to 0.752 mm—representing a reduction of approximately one-third. Overall, the elastic modulus has a smaller impact on horizontal displacements than on vertical displacements, with a more pronounced effect along the Y-axis than the X-axis. Notably, when the elastic modulus of the backfill exceeds 5000 MPa, the maximum displacement along all three axes stabilises. A particularly negligible effect occurs when the elastic modulus surpasses 15,000 MPa.

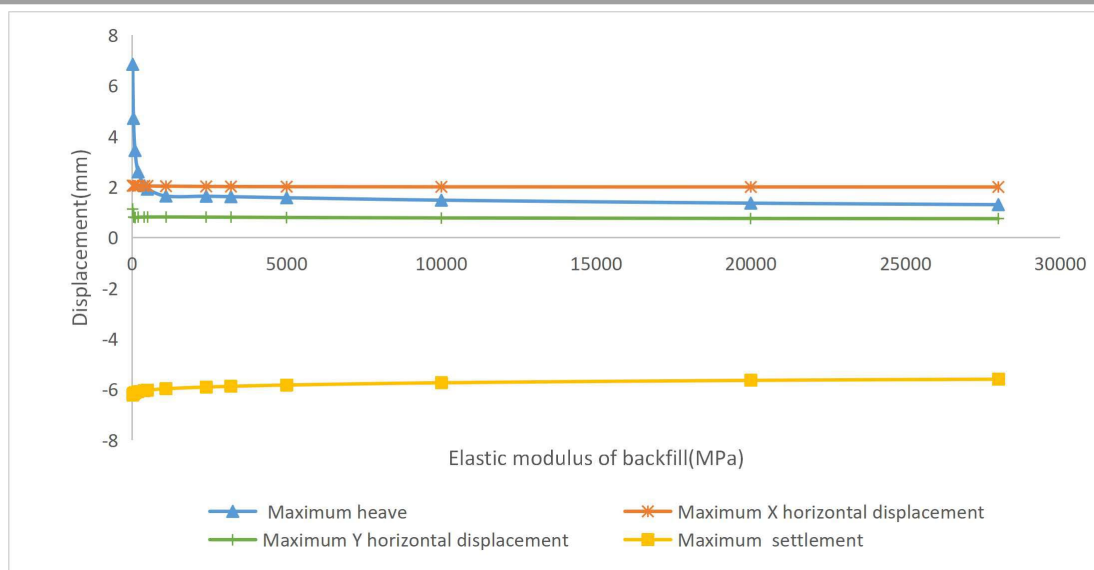


Figure 8 Effect of backfill stiffness on multidirectional maximum displacements

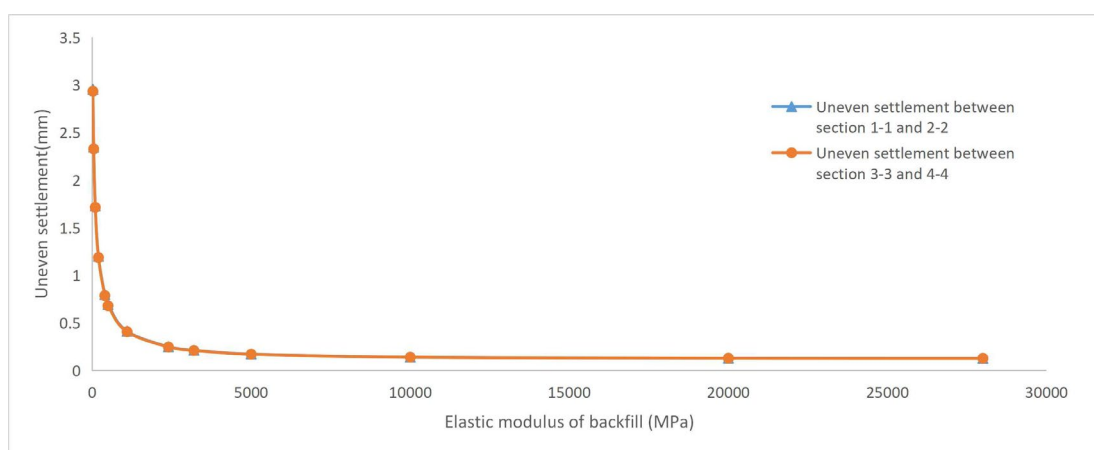


Figure 9 Uneven settlement between Sections 1-1 and 2-2, and Sections 3-3 and 4-4 under different elastic modulus values

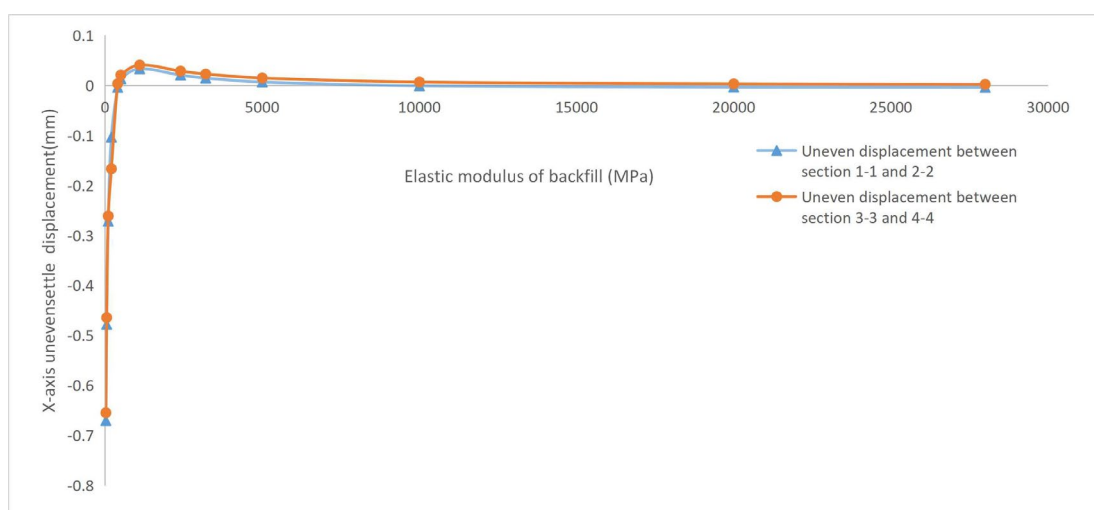


Figure 10 Uneven displacement along the X-axis between Sections 1-1 and 2-2, and Sections 3-3 and 4-4 under different elastic modulus values

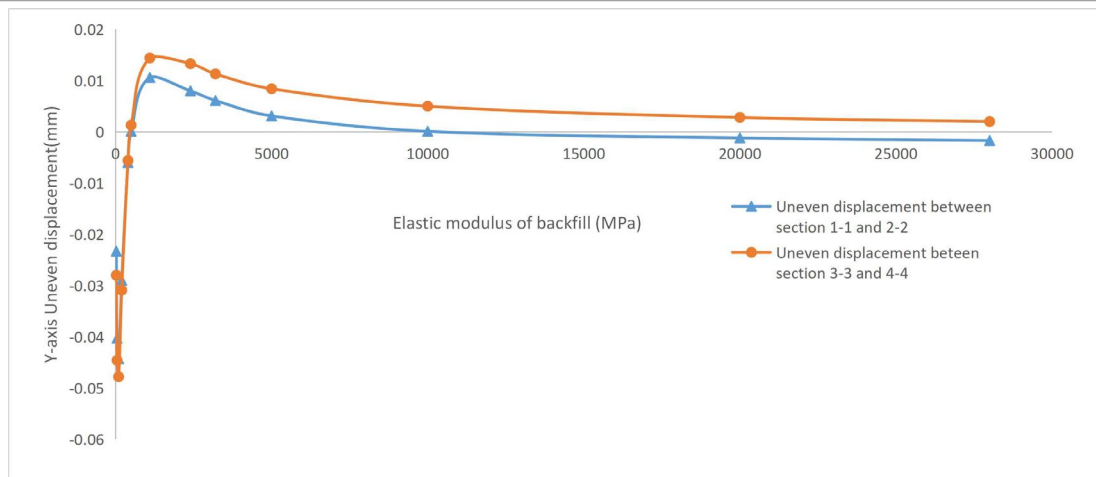


Figure 11 Uneven displacement along the Y-axis between Sections 1-1 and 2-2, and Sections 3-3 and 4-4 under different elastic modulus values

Figure 9 illustrates the relationship between the elastic modulus of backfill materials and differential settlement. The results indicate that as the elastic modulus increases, the differential settlement between the left and right sides decreases significantly. When the modulus ranges from 25 MPa to 1000 MPa, the differential settlement remains approximately 3 mm. However, once the modulus exceeds 5000 MPa, the rate of decrease slows, and the curve gradually levels off. At approximately 15,000 MPa or higher, the settlement stabilises close to zero, demonstrating that a high elastic modulus effectively minimises the settlement difference between the bridge and embankment. Furthermore, the settlement curves on both sides nearly overlap, suggesting similar settlement behaviour under varying modulus values. Overall, increasing the elastic modulus reduces differential settlement most effectively at lower modulus levels, with a stabilising effect observed at higher values.

Figure 10 presents the relationship between the elastic modulus and differential displacement along the X-axis. As the modulus increases, the displacement differential between the left and right sides diminishes and approaches zero. In the 25 MPa to 1000 MPa range, a notable displacement difference is observed: approximately -0.7 mm between Section 1-1 and Section 2-2, and $+0.7$ mm between Section 3-3 and Section 4-4. As the modulus increases, these differences rapidly decline. At approximately 5000 MPa, the displacement values of these sections converge and stabilise near zero. Although the initial displacement directions of Sections 1-1/2-2 and Sections 3-3/4-4 are opposite, they become more aligned with increasing modulus, and the disparity nearly vanishes. This indicates that a higher elastic modulus significantly reduces differential displacement along the X-axis, particularly at lower values.

Figure 11 illustrates the relationship between the elastic modulus and differential displacement along the Y-axis. With increasing modulus, the differential displacement gradually stabilises, and the variation on both sides tends towards zero. Within the 25 MPa to 5000 MPa range, displacement shows substantial variation: Section 1-1 and Section 2-2 exhibit a sharp rise followed by a decline, whereas Section 3-3 and Section 4-4 show a sharp decline followed by a gradual increase. As the modulus continues to rise, the displacement differences diminish. At approximately 20,000 MPa and higher, the curves converge and remain stable near zero. These findings highlight that a high elastic modulus contributes to a more uniform distribution of displacement along both axes.

In summary, Figures 9, 10 and 11 collectively demonstrate that increasing the elastic modulus of backfill materials significantly reduces differential settlement and displacement, particularly at lower modulus levels. As the modulus becomes very high, these improvements tend to plateau. Such uniformity in settlement and displacement is critical to maintaining the structural integrity and long-term durability of the bridge-embankment system.

3.2 Discussion

The trends reported above are expressed in terms of the absolute elastic modulus of the backfill; however, settlement behaviour at a soil–structure interface is arguably governed less by the absolute stiffness of the backfill than by its stiffness relative to the adjoining structural and subgrade elements. In this model, the jacking frame bridge has an elastic modulus of 3.4×10^4 MPa and the existing subgrade an elastic modulus of only 30 MPa (Table 3), so across the examined backfill range of 25 to 28,000 MPa, the backfill-to-subgrade stiffness ratio increases from roughly unity to nearly three orders of magnitude, while the backfill-to-bridge stiffness ratio remains below 1 throughout (a maximum of about 0.82 at 28,000 MPa). This helps explain why the differential settlement and displacement curves in Figures 9–11 flatten once the backfill modulus exceeds approximately 15,000–20,000 MPa: once the backfill is stiff enough to approach the same order of magnitude as the bridge structure, further increases in absolute stiffness contribute comparatively little additional restraint, because the backfill is no longer the most compliant element in the load path. Conversely, at the lower end of the tested range (25–1000 MPa), the backfill remains far more compliant than both the subgrade and the bridge, so it continues to accommodate most of the differential deformation, consistent with the sharper reduction in differential settlement observed in that range. This relative-stiffness perspective is therefore complementary to, rather than contradictory with, the absolute elastic modulus values reported in this study, and suggests that the transferability of the specific modulus thresholds identified here (e.g., 15,000 MPa) to other projects depends on the stiffness of the adjoining bridge and subgrade structures at each site.

4. CONCLUSION

This study used three-dimensional finite element analysis to quantify how the elastic modulus of backfill materials, over the range of 25 MPa to 28,000 MPa, governs differential settlement and maximum displacement in rail bridge approaches. The principal and, to the authors' knowledge, previously unquantified finding is that this relationship is strongly non-linear and threshold-governed rather than proportional: differential settlement and displacement decrease sharply as the backfill modulus increases up to approximately 10,000–15,000 MPa, beyond which further stiffening produces only marginal additional benefit, a pattern consistent with the backfill approaching the relative stiffness of the adjoining subgrade and bridge structure (Section 3.2). Within the tested range, the maximum vertical settlement decreased by 10% and the maximum ground heave by approximately 81%, while the differential horizontal displacement across the transition zone approached zero at high modulus values. Practically, these results indicate that engineers do not need to specify

the highest-modulus backfill material available to control differential settlement in rail bridge approaches; instead, selecting a backfill with an elastic modulus at or above the identified threshold range achieves most of the achievable reduction in differential settlement and displacement, after which further increases in modulus mainly add cost rather than performance. This provides a quantitative basis for balancing structural performance against material and construction cost when selecting backfill for jacked-frame-bridge transition sections. The findings should, however, be interpreted within the limitations of the study: the analysis is static and does not capture the effects of dynamic/cyclic train loading, long-term consolidation, or groundwater; the identified modulus threshold reflects the specific soil, geometry and structural stiffness values adopted in this model and, as discussed in Section 3.2, may shift for projects with different subgrade or bridge stiffness; and the backfill was modelled as an isotropic elastic material rather than with a full elasto-plastic constitutive model. Future work should extend the analysis to dynamic train loading, long-term consolidation settlement, and a broader range of subgrade/structure stiffness combinations to test the generality of the relative-stiffness explanation proposed here.

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