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Research Paper

Evaluation on the dynamic performance of bridge approach backfilled with fibre reinforced lightweight concrete under high-speed train loading

Kaiwen Liu[a,b], Qian Su[a,b], Pengpeng Ni[c,*], Chuanbin Zhou[a], Wenhui Zhao[a], Fei Yue[a]

[a] School of Civil Engineering, Southwest Jiaotong University, Chengdu, Sichuan 610031, China
[b] Key Laboratory of High-Speed Railway Engineering, Ministry of Education, Southwest Jiaotong University, Chengdu, China
[c] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore

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ABSTRACT

In China, high-speed rails are often constructed over bridges in the region of soft soils. Differential settlement could occur in the foundation soils between bridge abutment and approach embankment that causes “bumps” to affect the smoothness at the end of a bridge. A three-dimensional finite element model is developed to investigate the use of fibre reinforced lightweight concrete in the transition zone of bridge approach for high-speed railways. Time-frequency analysis is performed using the method of Fast Fourier transform. The sensitivity analysis of rail speed, density of backfills, and the structural type of the trapezoidal shaped transition zone is conducted.

1. Introduction

In China, rail transport is an important transportation mode, forming a network with more than 120,000 km railways, among which China has the longest high-speed rail network of approximately 19,000 km. Bridges have been extensively used for the rail network, especially in the region of soft soils. For high-speed rails, it is imperative to minimize the differential settlement along the line at bridge approaches. This is because the approach embankment over soft clays could settle with time excessively, exceeding the settlement of bridge abutment, which is usually sited on piles. The differential settlement between bridge abutment and approach embankment will result in “bumps” at the end of a bridge [53]. The bridge bumps could endanger the operation of high-speed rails, and in turn, amplify the dynamic response of the bridge to reduce its service life.

There are, in general, three types of treatments to mitigate the occurrence of bumps at bridge approaches [38]. As illustrated in Fig. 1a, a reinforced concrete slab can be casted *in situ*, with one end supported on the abutment. A suitable thickness of the approach slab needs to be designed to increase the flexural resistance of the track. Secondly, the soft soil zone can be improved by grouted gravel columns, or deep cement mixing piles in combination with geosynthetics as depicted in Fig. 1b. The reinforcement technique can essentially increase the soil resistance to consolidation settlement. Alternatively, high performance materials can be used as backfills in the zone behind the abutment as shown in Fig. 1c, such as high performance lightweight concrete (LWC) [15], expanded polystyrene geofoams [14] and tire derived aggregates [29], to decrease the overburden stress.

The approach slab technique has been used extensively in the past. For example, Ha et al. [10] conducted survey and site investigations for 18 sites in the Houston District, focusing on the performance of bridge approach slab expansion joints. Similarly, Bakeer et al. [1] reported a field study on 63 pile-supported and 21 soil-supported approach slabs in southeastern Louisiana, and they found that the design and the field performance were inconsistent. White et al. [50] performed field survey for 74 bridges in Iowa, and revealed that poorly graded sandy backfills could settle by 5–18% to cause bumps. Some numerical investigations [2,19,32,43] also confirmed that the settlement of backfills has an adverse effect on the performance of bridge approach slabs.

Different types of soil reinforcement have been employed over past several decades, such as geogrids [7,24,30,51,57], geosynthetic-wrapped face embankments [13,16,42,52,59], grouted gravel columns [23], reinforced floating columns [26] and coupled prefabricated vertical drains and deep cement mixing piles [11,21,27,63]. Given the bridge approach sustaining cyclic loads induced by high-speed rails during its whole service life, the repeated loads could cause distress in the reinforced soil-structure system. In addition, geosynthetics employed in most applications present the high nonlinearity and the stress relaxation behaviour, which may make the long-term performance of reinforced bridge approach become questionable.

The techniques of approach slab and soil reinforcement are all implemented to increase the capacity of the system. On the contrary,

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* Corresponding author.
E-mail address: pengpeng.ni@ntu.edu.sg (P. Ni).

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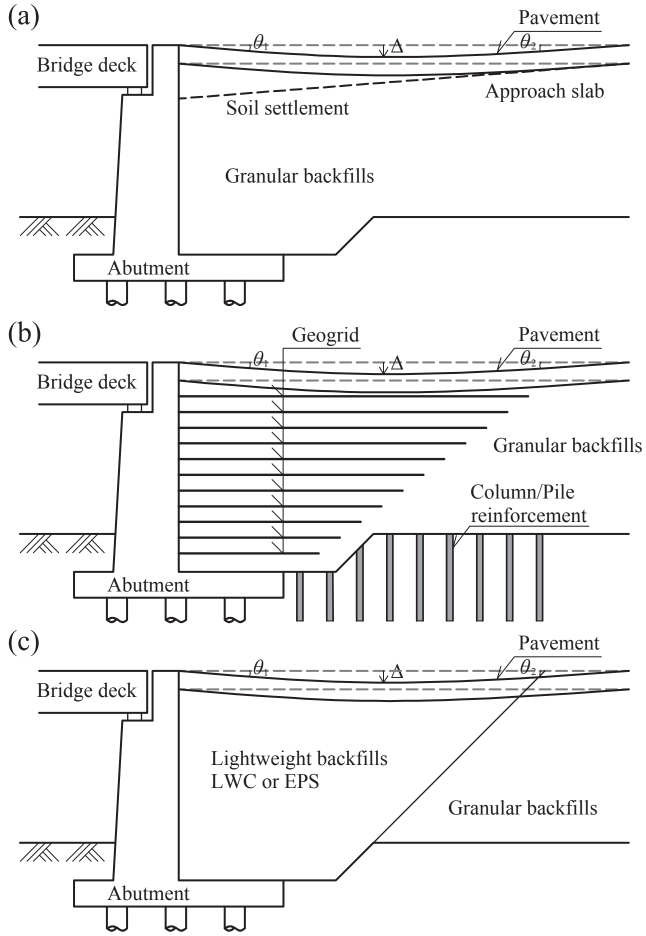

Fig. 1. Treatments for bridge approaches: (a) approach slab, (b) soil reinforcement, and (c) lightweight backfills.

lightweight backfills can be used to reduce the demand on the foundation soil, where the decrease of overburden stress will result in less amount of consolidation settlement. Jamnongpipatkul et al. [17] presented a case study of using air foam stabilized soils in a bridge approach in Thailand, and observed the satisfactory short-term performance with minimal settlement. Similarly, de Paiva and Trentin [5] studied the response of flexible pavement for bridge approach subjected to static loads, and confirmed that enhanced compaction on flexible pavement cannot alleviate the magnitude of differential settlement at the end of a bridge. The application of lightweight treated soils for other engineering projects can also be found in Satoh et al. [44], Otani et al. [37], Watabe and Noguchi [49] and Kikuchi et al. [20]. However, the stability of treated soil may degrade in a seawater environment subjected to sulfate attack [41]. Given that high-speed rails could operate along the coastline, lightweight concrete can be a promising solution to bridge approaches.

The mechanical properties of lightweight concrete have been studied extensively [40,41,60]. Zhang and Yang [62] reported a successful experimental program on the performance of runway for an aircraft arresting system using foamed concrete. Huang et al. [15] initially investigated the efficacy of using foamed concrete for subgrade bed filler of ballastless track using model-scale experiments. The abrasive resistance of LWC may be of concern for bridge approaches. Hence, fibre can be mixed with foam to cast lightweight concrete following the idea of Gray and Ohashi [8] and Wang et al. [48]. The dynamic response of bridge approach treated with fibre reinforced lightweight concrete (FRLWC) backfills behind the abutment will be studied in this investigation.

Researchers often study the dynamic response of bridge approach using simplified beam-spring mass models [9,12,28,31,46,55,56,58]. Zhang et al. [61] utilized a two-dimensional ballasted railway tracks model based on the discrete element method to analyze the dynamic behaviour of concrete sleeper, clustered ballast stones and silty clay subgrade subjected to irregular vibrations due to a passing train. Nsabimana and Jung [36] developed a two-dimensional (2D) numerical model to consider the interaction between the vehicle, rail, track and subsoil. Shan et al. [45] proposed a plane stress finite-infinite element model to analyze the performance of a high-speed railway subgrade-bridge transition zone. However, there are few full three-dimensional (3D) numerical analyses on this issue [4,54]. Furthermore, the backfill material in the transition zone was adopted as graded gravel mixed with/without cement in those previous studies.

In this study, a full 3D numerical model is developed to simulate the behaviour of bridge approach with treatment in the transition zone using fibre reinforced lightweight concrete backfills. The dynamic response of bridge approach is analyzed by applying the time history of live load induced by a CRH380A electric high-speed train on all track fasteners. The impact of four densities of FRLWC at the optimum fibre content is investigated. The influence of rail speed, backfill materials in the transition zone, and the configuration of the transition zone on the magnitude of acceleration, stress and displacement in the embankment is studied.

2. Numerical simulation

2.1. Overview of the bridge approach

In this study, a bridge approach connecting a U-shaped abutment and the approach embankment for double track electric railways is studied. Fig. 2 illustrates the cross section view of the bridge approach. The bearing seat of the U-shaped abutment has a length of 3 m along the railway. The height of the abutment is 7 m. The low-cap pile foundation has a length of 9 m along the railway and a height of 1.5 m, below which a 3 × 4 (longitudinal × transverse) pile group is used to provide pile end resistance. Each pile has a diameter of 1.2 m. The spacing between piles is 3.5 m and 4.0 m in the longitudinal and transverse directions, respectively. Wing walls are neglected, since the embankment can be formed easily using FRLWC rather than granular backfills. Hence, the embankment is similar to a cantilever retaining wall.

The approach embankment is 6 m high, with an inverse trapezoidal shaped zone of fibre reinforced lightweight concrete backfills. In the transverse direction, the slope angle of the embankment is 1:5. The transition zone has a total length of 20 m and an inclination angle of 1:2. Above the subbase layer with FRLWC backfills, a base layer of

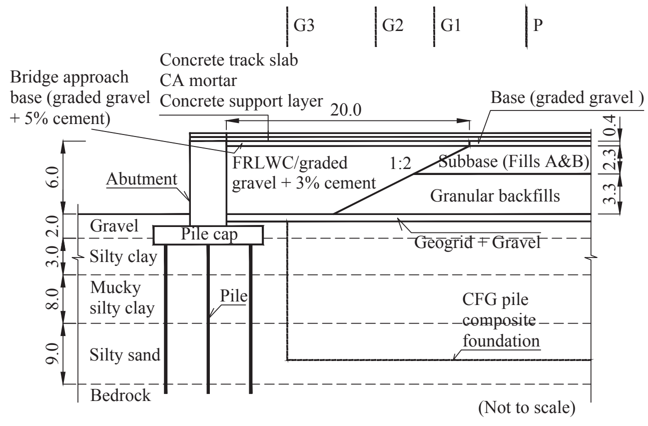

Fig. 2. Cross section of bridge approach backfilled with fibre reinforced lightweight concrete (unit: m).