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Three-dimensional track-ballast interaction model for the study of a culvert transition

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ABSTRACT

Transition zones corresponding to the passage from railway tracks on embankments to settlement free structures are frequently problematic for maintenance. Changing stiffness of the track and differential settlements are main causes for the degradation of tracks and foundations at transitions. This paper concentrates on a railway passage over a box-culvert, where significant settlements were observed in the transition zones. Previous research using a Winkler type model showed that this cannot be explained by ballast compaction due to trains passage only. The paper presents a 3-D model. It describes the behaviour of the rail track, ballast, embankment and approach slabs. This calculation shows that the stress in the soil close to the approach slabs exceeds the strength of the ballast. This leads to rolling of particles on the approach slab and explains the differences between the Winkler type model results and the observed settlements.

1. Introduction

Transition zones in railway tracks are built to mitigate damage and wear to tracks and trains, and discomfort to passengers, caused by structural and foundation discontinuities, such as those introduced by bridge approaches or culverts. However, current design still lead to frequent maintenance operations and sometimes speed restrictions [1,2].

Field monitoring campaigns in railway transitions has been made across the world towards a better understanding of the physical phenomena under study. For example in culvert transitions in the Netherlands [3], in bridge-approach transitions in the US [4,5] and in Portugal [6,7], and in ballast to slab tracks transitions in France [8]. These field campaigns have shown that the problem at railway transitions is complex, with different causes and mechanisms potentially involved [4,9].

There are frequently subgrade issues at railway transitions, for example triggered by insufficient or inadequate compaction of the embankments [9]. On the long-term, significant accumulated permanent deformation take place within these subgrade layers, resulting in a downward motion of the top surface of the ballast, referred to as settlement. As the stiff structure is normally well founded and therefore free of settlements, differential settlements arise between the approach section and the stiff structure. The rails, being connected to the sleepers which are laid over the ballast, see its centerline vertical position (referred to as vertical profile or level) being affected, and a bump arises at the extremities of the stiff structure. This will very probably result in unsupported (also called hanging) sleepers, which are sleepers suspended by the rails, with a void or gap between the top surface of the ballast and the base of the sleepers when the track is not loaded by a train [10,11].

Another cause of differential settlements is the permanent deformation due to ballast compaction. These are sensitive to the loading conditions, depending not only on the maximum vertical stress, but also on the confining pressure, and on the frequency content [12,13]. Due to the presence of hanging sleepers, the loading conditions on the ballast change significantly in the region, impacts on the ballast are also possible, and the settlements of the ballast may increase substantially [14].

Complementary to field campaigns at different kinds of railway transitions, numerical simulations are necessary to further understand this problem and to effectively test alternative solutions. Generally, the rails are modeled by a beam. The subsoil can be modeled by a spring-dashpot system (Winkler type model), or a 2-D or 3-D continuum.

Winkler type models used to analyze railway transitions can be found in [15,16,11]. These models require less computational effort compared with three-dimensional equivalents, but are mainly

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restricted to studies focused on the vehicle and track response well below critical-speed regimes. The works of Kouroussis [17,18] have shown the applicability of these spring-dampers models to represent railway track dynamics.

The work of Shan et al. [19] includes a complete state-of-the-art review concerning numerical modelling of railway transitions where the soil is modeled as a continuum. Despite recent advances by van Dalen et al. [20] in semi-analytical models representing inhomogeneous track support conditions, most of the developed models are based in the finite element method (FEM). One of the main advantages is that FEM models allow the consideration of complex non-homogeneous geometries, which is generally the case of railway transitions. Some examples of three-dimensional FEM models applied to study transition zones can be found in [21–24,19]. The model of Galvín [22] combines finite elements with boundary elements, and together with Ribeiro [21] and Banimahd and Woodward [23], it includes a simplified representation of the vehicle interacting with the track.

In the 3D FEM based models for railway transitions mentioned above, the uneven vertical profile due to differential settlements is not considered, as the rail-sleeper system is initially placed at horizontal position. In some of these models the possible existence of hanging sleepers is analyzed, either by artificially lowering the material stiffness of some elements representing the top ballast [23], or by including interface elements between the sleepers and the ballast [24]. Also, the constitutive law for the ballast and the sub-ballast layers is assumed linear-elastic, whereas these materials are known to behave non-linearly when loaded by passing trains. In railway transitions with uneven vertical profiles due to differential settlements and probably with hanging sleepers, the initial stress state in the ballast and sub-ballast will vary substantially from sleeper to sleeper, which enforces the need for the consideration of the non-linear nature of these materials in studies focused on their stress-strain response [25,26].

In soft soils regions the problem with transition zones is particularly severe [27]. This is the case in the Netherlands, where existing very soft soil layers, composed of organic peat, are gradually settling at a high rate, reaching 1 mm/month. Stiff constructions built along the track and supported on piles, such as culverts, will remain in a higher level, resulting in permanent differential settlements between the approach section and that on top of the stiff structure.

Due to this, a cooperative research project devoted to transition zones was supported by ProRail and conducted between the years 2007 and 2010 [3]. The research program focused on a culvert box transition located in a soft soils region near the city of Gouda, and included an extensive monitoring campaign comprising both short-term and long-term measurements. The selected culvert was associated with a bump in the vertical profile of the track, and the existence of hanging or unsupported sleepers were evident by visual observation.

Within this project, a 3-D numerical program was specifically developed to study railway transitions, and then applied to analyze the culvert transition. Important aspects considered in the numerical program were (i) the rail unevenness caused by differential settlements, with the possibility of introduction of voids between the sleeper soffit and the ballast surface with prescribed height per sleeper; and (ii) the non-linear constitutive behaviour of the ballast and sub-ballast layers, for a realistic determination of the stress-strain field inside these layers. This program is innovative by integrating these aspects in a single three-dimensional analysis tool.

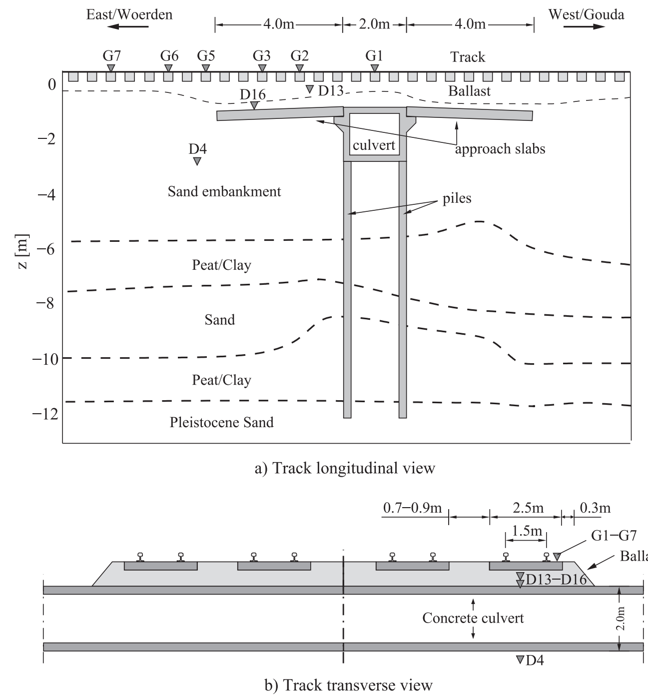

Fig. 1. Representation of the track passing over the box-culvert. (a) Longitudinal view; (b) Transversal view. Modified from [14].

2. Description of case and research questions

2.1. Case description

Fig. 1 shows a schematic representation of the track passing over the culvert. The railway line is here composed of four parallel ballasted tracks, with wooden sleepers. Two of the tracks were built in 1855 and the other two in 1995. The track is straight over the culvert, and about 100 m before the culvert a high-speed switch is located. The measurements and the following analyses were concentrated on the newer segment, on the track closer to the edge of the ballast embankment. Fig. 1(b) shows the location of some of the sensors used during measurements, which will be addressed further in the validation section.

Fig. 1(a) also depicts the soil profile at the culvert area, which is characterized by the existence of soft soils (clay and peat) underlying a stiffer sand embankment that supports the railway track itself. These layers were identified by CPT and characterized with VSPT tests, see [24,26] for more information.

The culvert itself consists on a square concrete box 2 m by 2 m, approximately 60 m long. The culvert is founded on piles. At each side, approach slabs simply supported on the culvert of 4 m length and 30 cm thickness form the transition zones.

An important finding at this culvert transition was the existence of significant voids under the sleepers located in the transition zones, above the approach slabs. The height of these voids was measured and it was found that after seven months since maintenance the height of the voids could reach 10 mm.

2.2. Observations from previous research

Numerical simulations for both dynamic response and long-term settlement of the track were previously performed using a Winkler type model for the track-soil system, that were validated with the collected data from the culvert monitoring program, and presented in [11,14].

The long-term settlement analyzes were performed