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Road and Rail Infrastructure III

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FEM ANALYSIS WITH SPECIAL FOCUS ON SOIL-STRUCTURE INTERACTION OF FLOATING SLAB-TRACK INFRASTRUCTURE IN HIGH SPEED RAILWAY EMBANKMENTS

Paulina Bakunowicz, Hasan Emre Demirci, Isfendiyar Egeli
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Abstract

Use of Floating Slab Track (FST) type infrastructure systems in high speed railway (HSR) embankments is becoming increasingly popular in the world today as well as a mean of vibration isolation and safe and fast rail travel. The main emphasis of this study is on the application of non-ballasted concepts for high-speed operation used in the design of Far Eastern HSR embankments and a manufactured floating slab track system. In this paper, finite element method (FEM) is used to model soil-structure interaction. Effects of soil stiffness (k_s) are carefully investigated. Longitudinal settlements are obtained and checked against allowable values. The study has confirmed the quality and reliability of the FST systems, which continue to have huge use in high speed rail design-construction projects nowadays.

Keywords: soil-structure interaction, coefficient of subgrade reaction, High Speed Railway embankments, slab track

1 Introduction

New slab track designs are being developed in the world today, in order to come across with a need for safe and fast passenger-load carriage along heavy transportation service lines that will operate with low maintenance costs. The so-called slab track is a concrete or asphalt surface made of stiff and brittle materials with resilient components to provide the required elasticity. Factors like ground conditions, life cycle duration, cost, construction time, availability and durability are the main factors in designing railway lines nowadays. With regard to the specified factors, modern slab-tracks are replacing the traditional ballasted track designs nowadays. The significant increase and popularity is mainly due to the low maintenance and efficient life-cycle costs. However both ballasted and unballasted track designs have their advantages and disadvantages and in some cases still standard ballasted track designs may have more advocates, as they are widely used in high speed operation areas, especially when embankments are built on soft clays or soft peat layers, as well as in earthquakes areas. There are basically 2 types of embankment lateral-sections, namely The European type – ballasted and the Far-Eastern type – slab track (Fig. 1) though the longitudinal sections are very similar. The trend shows that; although the standard ballasted concepts are still popular in general, they will lose their attractiveness in favour of slab tracks systems, due to this new attitude. In this study we have analyzed the Far-Eastern case. In the Far-Eastern slab track type embankment one fill strata called ‘Uncemented-Prepared Subgrade Layer (U-PSL)’ is replaced with a cemented one called ’Cemented-Prepared Subgrade Level’ (C-PSL) (Fig. 1a) [1].

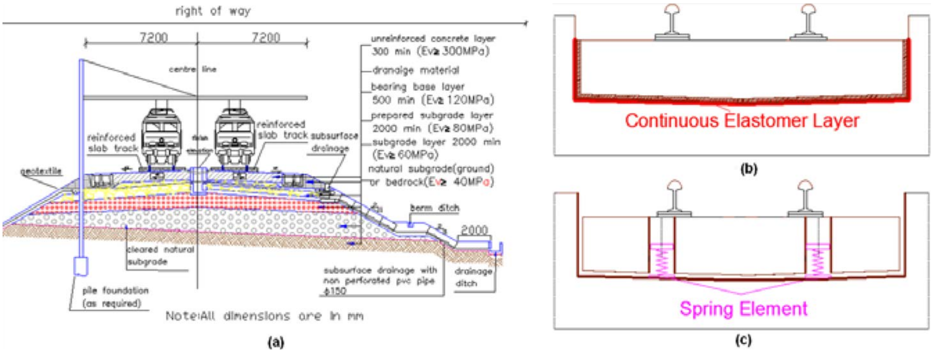

Figure 1 (a) Cross-section of a HSR embankment (Far-Eastern type) [1], (b) FST Type 1, (c) FST Type 2

Moreover, vibration isolation and sound effects' reduction play an increasingly important role during design and performance evaluation of a HSTR. With the increase in traffic intensity, it becomes more and more difficult to ensure comfort, security and to avoid problems, due to vibrations induced. For the slab track design, inserting elastic materials like elastomer layer is an effective method for reducing vibrations transmitted into the soil and to surrounding buildings (Fig. 1b-c). There are basically two most commonly used Floating Slab Track (FST) types, built within the unreinforced concrete layer. These are: FST sitting on a continuous elastomer layer-Type 1 (Fig. 1b) and FST sitting on spring units – Type 2 (Fig. 1c). The groundborne noise and vibration mitigation performance of a (FST) is determined by its first natural frequency. The vibration mitigation performance of a FST can be increased by lowering its resonance frequency; either by increasing the mass of the concrete slab or by increasing the resiliency of the elastic layer. Xin and Gao have investigated the problem of vibration transmission from a slab track structure into a bridge in a HSR by a theoretical analysis [2]. They have confirmed the great influence of stiffness of a slab mat on both rail and slab displacements, as well as on bridge and rail accelerations. There, total settlements have decreased and, but train accelerations also have suffered. Hence, many researchers and engineering institutions suggest optimizing the stiffness, by selecting an appropriate thickness of elastomer membrane, along with an appropriate choice of material [2]. However, in this study we did not consider to include such a slab mat layer, because of its minor impact on the total settlements.

The complexity of design of HSTR requires performance of a detailed analysis in order to maintain security and ride comfort in the trains and to avoid problems, due to vibrations induced in nearby buildings by waves transmitted through the soil. In recent years, there has been a huge expansion in the power and availability of numerical analysis techniques with a particular popularity of finite elements methods (FEM), with which both non-linear and linear elastic models are widely used in engineering practice. However, there are many researchers, who also favour to use soil structure interaction methods (SSI). In contrary to standard application of Elasticity modulus (E_s) and Poisson ratio (ν), the concept of modulus of subgrade reaction (k_s) is adopted. This widely used SSI concept refers to the relationship existing between soil pressure and deflection. It is applicable for various geotechnical problems, including continuous footings, mats, piles etc. k_s is described as the ratio of the increment of contact pressure ($\Delta\sigma$) to the corresponding change in settlement or deformation ($\Delta\delta$). Commonly plate load test is performed to obtain and plot values of σ versus δ to estimate a laboratory value of k_s. Results are usually non-linear and k_s needs to be obtained as a slope of either a tangent or secant line with preference of using the initial values. Thus, k_s is not an input parameter, but a determined value, whose magnitude must be calculated beforehand, based on current knowledge and available models. This fact was used subsequently by us, as one way of evaluating the accuracy of various subgrade models, where it is necessary to assume k_s as part of the analysis.

Bowles [3] has suggested that using SSI method over the FEM approach is preferable because of greater ease of use and more efficient computation time. Some scientists have tried to find a direct relationship between E_s and k_s. Terzaghi [3] was one of the first contributors, who attempted to make a correlation from plate load tests to estimate a numerical value of k_s. He has suggested an empirical method for k_s as an input value for the structural analysis of slab foundation design. However, the relationships found by Terzaghi are dependent on results from the plate load tests and they are exposed to size effects [3]. So the contribution by Terzaghi is mentioned only for historical reasons and it is not used in our analysis.
Earlier, Winkler (1867) has proposed a more specific formulation of the concept [4]. Thus, thanks to this significant contribution, the term 'Winkler foundation' or 'Winkler method' has been established. To describe this concept briefly; the coefficient k_s is transformed into a discrete spring element or support. In this concept of subgrade reaction, the foundation slab is assumed to act as an element, capable only of bending behaviour, as a plate or a beam [5]. The term 'elastic foundation' refers to the Winkler foundation model, and therefore analyses of this type are known as 'beams on elastic foundation (BOEF)' analyses. Although BOEF is widely used in geotechnical engineering practice, Winkler's assumptions cause some errors, as the model cannot transmit the shear stresses. It is because of the lack of spring coupling. Although various researchers have tried to deal with this limitation, those mitigation methods did not gain much popularity among majority of designers. Scientists like Filonenko and Borodich, Pasternak, Kerr and Hetenyi in their modified models found connectivity between individual Winkler springs by merging an elastic plate, which sustains some flexural or transverse shear deformations [6]. However during the settlement analysis, shear stresses do not play important roles, though in our study Winkler model was still employed. Numerical simulations of the static behaviour of a HSR were conducted in this study, but further dynamic and seismic analyses, together with numerical modelling of the vibration mitigation were not included.

2 Methodology

2.1 Soil-Structure Interaction

The soil-structure interaction (SSI) analysis evaluates the behavior of three linked systems. These systems include; the structure, the foundation and the soil underlying, as well as surrounding the foundation. The determination of the coefficient of subgrade reaction (k_s) is crucially important to obtain reliable results in the SSI concept. There are various relations proposed by some researchers in order to specify the k_s. The most common relations suggested for the coefficient of subgrade modulus are given in Table 1 [7].

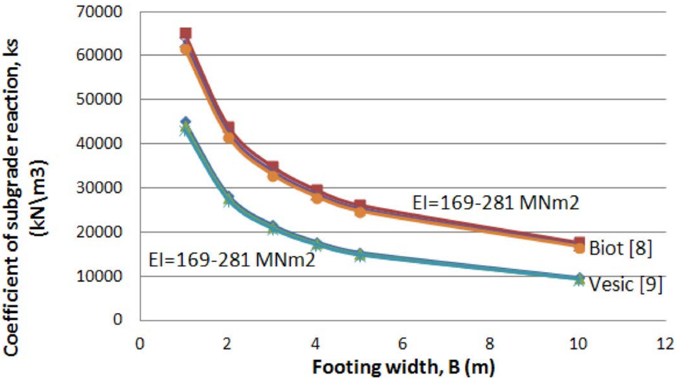

Figure 2 The variation of the coefficient of subgrade reaction depending on width and flexural rigidity of footing

In this study, Biot (1937) and Vesic (1961) findings are used, in order to determine the k_s [8, 9]. For various widths of footings (B) and various flexural rigidities of footings, k_s is calculated and these results are illustrated in Figure 2. According to these results, the k_s values of the Biot relation are greater than the k_s values of the Vesic relation for different values of widths of footings (B). With increase of B, k_s decreases significantly, whereas any significant increase in the k_s is not observed, despite substantial increases in flexural rigidity of footings.

Table 1 Common relations suggested for the k_s [7]

No.	Investigator	Proposed expression
1	Terzaghi	For sands $k_s = k_{s1}\left(\frac{B+1}{2B}\right)^2$ For clays $k_s = k_{s1}\frac{1}{B}$
2	Biot	$k_s = \frac{0.95E_s}{B(1-v_s^{\,2})EI}\left[\frac{B^4E_s}{(1-v_s^{\,2})EI}\right]^{0.108}$
3	Vlassov	$k_s = \frac{E_s(1-v_s)}{(1+v_s)(1-2v_s)}\left(\frac{\mu}{2B}\right)$
4	Vesic	$k_s = \frac{0.65E_s}{B(1-v_s^{\,2})}\sqrt[12]{\left(\frac{E_sB^4}{EI}\right)}$
5	Meyerhof and Baike	$k_s = \frac{E_s}{B\left(1-v_s^{\,2}\right)}$
6	Klopple and Glock	$k_s = \frac{2E_s}{B\left(1+v_s\right)}$
7	Selvadurai	$k_s = \frac{0.65}{B}\cdot\frac{E_s}{1-v_s^{\,2}}$
8	From Theory of Elasticity	$k_s = \frac{E_s}{B'\left(1-v_s^{\,2}\right)mI_sI_F}$

where:

E_s	modulus of elasticity of soil;	k_{s1}	the coefficient of subgrade reaction for a plate 1 ft wide;
v_s	Poisson's ratio;		
B	width of footing;	I_s and I_F	influence factors which depend on the shape of footing;
EI	flexural rigidity of footing;		
μ	non-dimensional soil mass per unit length;	m	takes 1, 2 and 4 for edges, sides and center of footing respectively.
B'	least lateral dimension of footing;		

As seen in Table 1, the coefficient of subgrade reaction is related to the elasticity modulus of soil, which directly affects the coefficient of subgrade reaction. In order to accurately specify k_s values, it is required that realistic values of E_s of soil must be determined. The selection of the elasticity modulus of soils depending on only first soil layer beneath the footing will not give realistic results. Therefore, the effects of stratification on elasticity modulus of soil must be taken into consideration. Approach of an equivalent modulus of elasticity which includes the mechanical properties of soil layers within the influence depth is used in this study [7]. To explain this with respect to the Boussinesq theory, the contribution of external load to the increment of soil stress decreases with depth. Therefore, the upper layers have an important role for settlement of footings subjected to external loadings. Therefore, the equivalent elasticity modulus of soil (E_{eq}) is calculated by considering thicknesses of each layer and the depth factor (I_z) [7]. The equivalent elasticity modulus is calculated with the aid of Equation 1.

$$E_{eq} = \frac{\sum_{i=1}^{n} E_{si} I_{zi} H_i}{\sum_{i=1}^{n} I_{zi} H_i} \tag{1}$$

where:

E_{si}	elasticity modulus of soil at mid-point of each layer;
I_{zi}	depth factor at midpoint of each layer;
H_i	thickness of each layer;
n	numbers of layers.

The equivalent elasticity modulus of soil is calculated as 68144 kPa by using the data given in Table 2.

Table 2 Equivalent elasticity modulus parameters for High Speed Train Embankments

Number of Layers	Unreinforced Concrete Layer	Bearing Base Layer	Prepared Subgrade Layer	Subgrade Layer	Natural Subgrade Layer
E_{si} (kPa)	300000	120000	80000	60000	40000
H_i (m)	0,30	0,50	2,00	2,00	5,00
I_{zi}	0,99754	0,9918	0,9713	0,9308	0,73175

The coefficient of subgrade reaction is calculated by using both the Biot [8] and Vesic [9] relations, existing between E_s and k_s. The k_s values for these two relations are given in Table 3.

Table 3 The coefficient of subgrade reaction values for Biot [8] and Vesic [9] relations

Relation	k_s (kN/m^3)
Biot [8]	36645
Vesic [9]	23480

As seen in Figure 2 and Table 3, the Biot [8] relation gives greater results than the Vesic [9] relation. Thus, it is clear that the total settlements of slab track will be lesser, when the Biot [8] relation values of k_s are used in the Winkler model. In other words, critical settlement values will occur, when the Vesic [9] relation values for the k_s are used in the Winkler model.

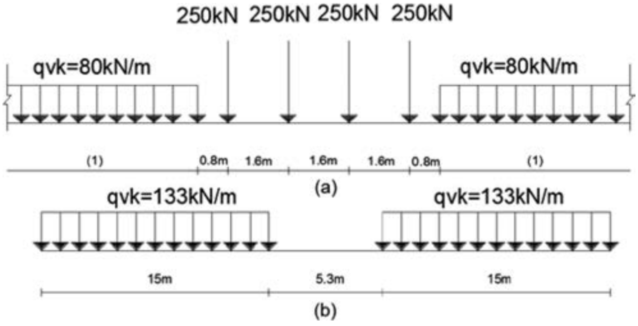

Figure 3 (a) Load Model 71, (b) Load Model SW/0 [10]

Another point is to determine external loadings on footings in the SSI concept. Rail traffic loads can be defined by means of load models. General rules about these load models are given for the static load condition of a High Speed Train load in the EN 1991-2 standards [10], where there are two different load models; as the Load Model 71 and the Load Model SW/0. These 2 load models represent the static effect of the vertical loads, due to normal HSR traffic. These load arrangements are shown in Figure 3a-b. In the EN 1991-2, the designated distance (1) varies, but it was taken as 20m in this study [10].

3 Results

Various load combinations are taken into account, while conducting settlement analyses. The total longitudinal settlement and contact pressure diagrams of HSR embankments for the model 71 and SW/0 are presented in Figures 4-5. Contact pressures obtained by Biot [8] and Vesic [9] relations are fairly the same. However, there is a slight difference in the total settlements computed by both approaches. The load combination SW/0 gives 10% greater contact pressures, than the load model 71. Contrary to the contact pressure diagrams, there is a significant difference in the total settlements by the Biot and the Vesic formulas. The reason of this different results lies with the k_s parameter, which is significantly greater for the Biot than the Vesic formula. The load model 71 gives 12% greater total settlements, than the load model SW/0 for the Vesic and 14% for the Biot formulas. For these investigated concepts, the total settlement does not exceed the limiting value of 0.01m per any 20m of embankment length, which is widely accepted criterion for any track design of an HSR in the Far East. Egeli and Usun [1] calculated the total settlement for the load model SW/0 by Plaxis (FEM) and obtained the value of 0.0075m, which is in agreement with our SSI analysis' results, obtained by using the Vesic equation.

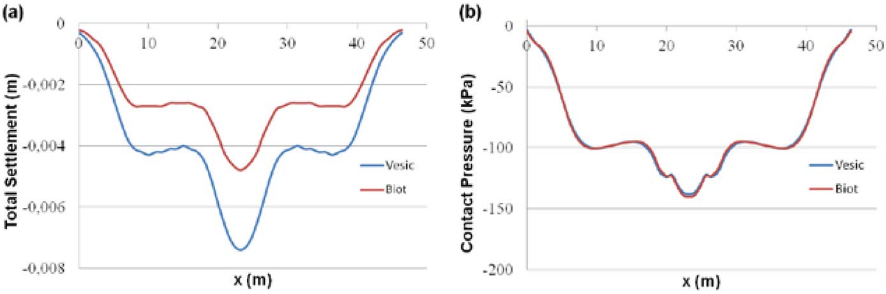

Figure 4 Calculations of (a) total settlement, (b) contact pressure, using the load model 71

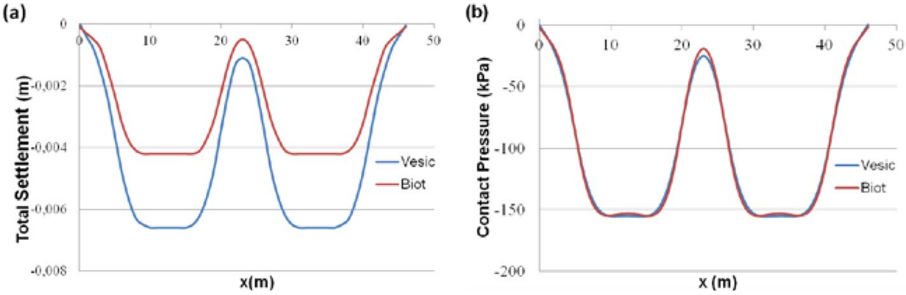

Figure 5 Calculations of (a) total settlement, (b) contact pressure, using the load model SW/0

4 Final conclusions

Numerical test methodology presented in this work and applied to the SSI model allows examining of the total settlements and contact pressures under a typical slab track subjected to HSR loads. Analyzed parameters (k_s, E_s, E_{seq}) estimate the amount of total settlements. Stratification effects of soil layers are taken into account thanks to considering the concept of equivalent elasticity modulus. In this study, it is proven that E_{eq} approach is a convenient tool to predict such critical total settlements. Numerical tests have been performed using different load arrangements and obtained results allow to evaluate the accuracy of different SSI approaches. Because implementation of the Vesic formula always produces the higher and more critical total settlements and the convergence of such results with the traditional FEM approach shows the usefulness of the approach used in engineering practice. Furthermore, the SSI concept has another distinct advantage above the standard finite element method, which is a timewise computation efficiency. Thus the study conducted has shown that the Floating Slab Track (FST) systems can be used successfully in HSR embankments without endangering passenger/load safety and with increased ride comfort. All these improvements have opened a new era in the analysis, and design of modern HSR infrastructures with variety of applications

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