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Identification of soil-structure interaction effect in a portal frame railway bridge through full-scale dynamic testing

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ABSTRACT

This paper is devoted to identify the effect of soil-structure interaction on the dynamic response of a portal frame railway bridge. The study aims to validate the accuracy of numerical models in evaluating the dynamic stiffness and modal properties of the bridge–soil system. To achieve this aim, a controlled vibration test has been performed on a full-scale portal frame bridge to determine the modal properties of the system through measuring Frequency Response Functions. The results of the dynamic test provide reference data for FE model calibration as well as valuable information about the dynamic behavior of this type of bridges. Using the experimental data, an FRF-based model updating procedure was used to calibrate a full 3D solid model involving the entire bridge-track-soil system. Both measured and computed responses identify the substantial contribution of the surrounding soil on the global damping of the system and highlight the importance of the soil–structure interaction on the dynamic response of this type of bridges. The identified modal damping ratio corresponding to the fundamental bending mode of the studied bridge was nearly 5 times higher than the recommended design values. A simplified model for the surrounding soil was also proposed in order to attain a less complicated model appropriate for practical design purposes.

1. Introduction

Short span portal frame (integral) bridges are the most common type of underpasses along modern railway lines. This type of bridge is designed as a reinforced concrete rigid frame with integral wing walls and is surrounded by an embankment reasonably longer than its length. Although it is well known that the dynamic response of these partially-buried rigid structures is governed by the surrounding soil, the effect of the soil is typically neglected in the train-induced vibration analysis due to the high computational cost and lack of reliable simple models.

According to Eurocode 1991-2 [1], the damping ratio of reinforced concrete railway bridges should be taken as 1.5–2.5%. However, several numerical investigations [2–5] have shown that the modal damping ratio of the fundamental bending mode of short-span railway bridges is much higher than the values recommended in the codes. This fact is primarily due to the considerable energy dissipation at the boundaries. Particularly, in the case of short span integral bridges, the dissipative capacity of the backfill soil could lead to an increase in the global damping of the system and consequently reduce the amplitude of the resonant response of the bridge [6,7]. Therefore, neglecting the effect of the soil-structure interaction in the train-induced vibration analysis of short-span integral bridges, may lead to conservative and unrealistic results at resonance regime.

Despite several attempts to develop advanced numerical models aimed to identify the soil-structure interaction effects on the dynamic response of railway bridges [2,6,34], the lack of reliable validation of the theoretical results against in-situ measurements is still noticeable. Identification of the modal properties of existing railway bridges through full-scale measurements is commonly carried out by monitoring the response under wind-induced ambient vibrations or excitation due to train passages [8–11]. However, in the case of short-span railway bridges, wind-induced ambient vibrations have significantly lower amplitudes and are of a totally different nature than the ones induced by passing trains. Moreover, in the case of using high-amplitude train-induced vibrations, challenges arise with the short duration of excitation and the train-bridge interaction [12].

To overcome these challenges a hydraulic bridge exciter has been developed with the aim of performing controlled vibration tests on the

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short to medium span railway underpasses. This work is part of an ongoing research project developed in collaboration with Swedish Transportation Administration aimed at assessing the possibility of upgrading the speed limits of existing Swedish railway lines. The objective is to understand the dynamic behaviour of railway bridges, especially bridge-soil interaction through numerical and experimental investigations. For this purpose, a certain number of bridges which are located along high-speed railway lines in Sweden have been selected for an experimental campaign [7,12,13].

In this paper, the effect of the surrounding soil conditions on the vertical dynamic response of a portal frame bridge is investigated both numerically and experimentally. The main objective is to validate the reliability of numerical models in evaluating the dynamic stiffness and modal properties of the bridge-soil system. To this end, the controlled vibration tests have been performed on a full-scale portal frame bridge to determine the modal properties of the bridge-soil system through measuring Frequency Response Functions. Then, a FRF-based FE model updating procedure is used to calibrate the numerical FE model using experimental data. The reliability of the calibrated FE model was verified against another set of dynamic tests as well as monitored acceleration signals due to passing train. A simplified model for the surrounding soil is also proposed in order to obtain a less complicated model suitable for practical design purposes as well as parametric studies. Finally, the calibrated models are used to underline the influence of the soil–structure interaction on the dynamic response of this type of structures.

2. Experimental testing

2.1. Introduction to the bridge

The Degersmyran Bridge (Fig. 1), located on a single track railway line in the North of Sweden, is a short-span portal frame railway underpass and has a single span of 7 m. The bridge is a reinforced concrete rigid frame with integral wing walls and was designed for both freight trains (33 ton/axle) and high-speed trains with a maximum speed of 250 km/h. The basic information about the geotechnical properties of the geo-materials at the site, such as type of backfill material, elevation of bedrock and ground water level, were found in the geotechnical reports and as-built drawings of the project (see Fig. 2b). According to the geotechnical data, the foundation slabs were placed on a layer of compacted crushed rock, approximately 0.5–1 m thick and laid directly on the bedrock. The abutments are surrounded by compacted layers of crushed rock and the ground water level is always kept lower than the bottom of foundation slabs. No geotechnical tests have been performed to estimate the shear and compression wave velocities of the soil layers at this site. A general view of the bridge and surrounding soil is presented in Fig. 1.

2.2. Forced vibration tests: Instrumentation and loading

The controlled vibration test was performed on the bridge deck by using of a hydraulic bridge exciter [12] in the vertical direction (see Fig. 1b). Fig. 2 shows the locations of the exciter and arrangement of accelerometers. Based on the results of pre-test FE analyses, it was decided to locate the exciter at two different points (P1 & P2), as shown in Fig. 2a, in order to excite several modes of vibration. Specifically these modes are: the 1st vertical bending mode and the 1st torsional mode by exciting point P1 and the 2nd bending mode of the deck by exciting point P2.

Sixteen uniaxial accelerometers (SiFlex-SF1500S) denoted as a_1 to a_{16} were installed on the bridge in such a manner that the bending, torsional and plate modes of the deck could be captured with reasonable accuracy. The linear output range of the accelerometers is ± 3 g with a corresponding sensitivity of 1.2 V/g. The accelerometers were installed in one setup only.

In each dynamic test, the force amplitude was constant and a linear frequency sweep was carried out at an adequately small rate to achieve steady-state response. A HBM MGCPlus data acquisition system was used for collecting data with a sampling frequency of 1200 Hz. A low-pass filter at 80 Hz was used to remove the high frequency contents from the measured signals.

In this paper, only a part of the vibration test results with force amplitude equal to 1 kN, denoted as Test P1 and Test P2 in Table 1, is presented. Initially the experimental program also included tests with higher amplitudes to investigate the potential amplitude dependency of the experimental results. However, due to some technical problems only two successful tests with higher applied loads (10 kN and 15 kN) have been performed at point P1 in the frequency range between 40 and 55 Hz.

2.3. Forced vibration tests: post-processing of the experimental results

The measured Frequency Response Function vector ($\mathbf{H}_i^{\mathrm{X}}$) at sensor i was obtained from Eq. (1), where $\mathbf{a}_i^{\mathrm{X}}$ and $\mathbf{F}^{\mathrm{X}}$ denote the Fourier transform of the measured acceleration signal at sensor i and corresponding input force signal.

$$\mathbf{H}_i^{\mathrm{X}}(\omega) = \frac{\mathbf{a}_i^{\mathrm{X}}(\omega)}{\mathbf{F}^{\mathrm{X}}(\omega)} \tag{1}$$

A simple peak-picking technique [14] was used to estimate the modal properties of the system. Fig. 3a shows the measured frequency response function at sample sensor 2 obtained in tests P1, P1–10 and P1–15. Within the studied frequency range, four visible peaks were detected (see Table 2). These correspond to the 1st vertical bending of the deck at $f_1 = 31.6$ Hz; the 1st torsional mode at $f_2 = 47.7$ Hz and two additional plate modes at $f_3 = 66.7$ Hz and $f_3 = 71.5$ Hz, respectively. Here the term “plate mode” is used to denote the fact that these modes involve bending in two directions whereas the first vertical bending mode involves bending in one direction only. It should also be


(a)
(b)

Fig. 1. View of the case study bridge, (a) during train passages, (b) view of the hydraulic exciter.