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EFFECTS OF TRAFFIC LOADS ON REINFORCED CONCRETE RAILROAD CULVERTS

Lutz Hermanns*, Javier Fernández, Enrique Alarcón, Alberto Fraile

Technical University of Madrid (UPM), School of Industrial Engineering (ETSII)
c/ Jose Gutierrez Abascal, 2
28006 Madrid
{lhermanns,jfernandezm,alarcon,afraile}@etsii.upm.es

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Abstract. *In the context of the present conference paper culverts are defined as an opening or conduit passing through an embankment usually for the purpose of conveying water or providing safe pedestrian and animal crossings under rail infrastructure. The clear opening of culverts may reach values of up to 12m however, values around 3m are encountered much more frequently. Depending on the topography, the number of culverts is about 10 times that of bridges. In spite of this, their dynamic behavior has received far less attention than that of bridges. The fundamental frequency of culverts is considerably higher than that of bridges even in the case of short span bridges. As the operational speed of modern high-speed passenger rail systems rises, higher frequencies are excited and thus more energy is encountered in frequency bands where the fundamental frequency of box culverts is located.*

Many research efforts have been spent on the subject of ballast instability due to bridge resonance, since it was first observed when high-speed trains were introduced to the Paris/Lyon rail line. To prevent this phenomenon from occurring, design codes establish a limit value for the vertical deck acceleration. Obviously one needs some sort of numerical model in order to estimate this acceleration level and at that point things get quite complicated. Not only acceleration but also displacement values are of interest e.g. to estimate the impact factor. According to design manuals the structural design should consider the depth of cover, trench width and condition, bedding type, backfill material, and compaction. The same applies to the numerical model however, the question is: What type of model is appropriate for this job? A 3D model including the embankment and an important part of the soil underneath the culvert is computationally very expensive and hard to justify taking into account the associated costs. Consequently, there is a clear need for simplified models and design rules in order to achieve reasonable costs. This paper will describe the results obtained from a 2D finite element model which has been calibrated by means of a 3D model and experimental data obtained at culverts that belong to the high-speed railway line that links the two towns of Segovia and Valladolid in Spain.

1 INTRODUCTION

Culverts are often used to reduce the fragmentation effects of linear infrastructure systems. For example along the 180 km long rail link between Segovia and Valladolid 131 crossing structures exist. Historically, these small infrastructures have never deemed worth an in-depth structural analysis, except for the so-called soil-steel bridges [1-2], where the flexibility of the conduit wall presents an interesting challenge to the designer due to the presence of soil-structure interaction.

Bridge design rules in accordance with Eurocode [3] involve checks on stresses according to dynamic loading. These checks are often performed based on the impact factor. There are bridge typologies for which the Eurocode provides simplified expressions however, in other cases, there is no such guidance. In the latter cases a comprehensive set of dynamic analysis is necessary if the speed is higher than 220 km/h. This also applies to culverts.

Reinforced concrete (RC) culverts are self-supporting but rely on some degree of interaction with the surrounding soils. Indeed, it is this interaction that complicates the study of the structural response to train loads. Most culverts can be considered embankment-supported structures where the quality of the backfill and degree of compaction affect the side support and foundation support. The soil-structure interaction is thought to be responsible for a significant contribution to the overall damping of the structure as vibrational energy can be transmitted through the contact surfaces. High damping ratios are desirable in order to limit vibration levels in case of resonance effects preventing thereby ballast instability from occurring.

When it comes to modelling the dynamic response of RC culverts a variety of options exist. An important question the designer faces is whether the surrounding soil has to be included in the model and if yes how this should be done. If the soil is modelled using solid Finite Elements (FE) the number of additional nodes rapidly increases rendering the model impractical for parametric studies of transient dynamic analysis.

2 OBJECTIVE

The objective of the present paper is to propose a simple method to set up a 2D FE model that can be very useful for parametric studies which are valuable in order to derive simplified formulas for the estimation of the impact factor for culverts. To this end a 3D FE model that has been validated against experimental data is used as starting point. The interested reader is referred to [4-5] for more information on the 3D model.

3 FINITE ELEMENT MODEL

It is important to note that a 2D model is only capable of representing beam-like vibration modes. As a consequence, this type of model will, in general, give reasonable results only up to frequencies around the first mode. The corresponding frequency depends on the dimensions of the culvert and is generally much higher than the fundamental frequency of short span bridges.

For the present study the dynamic response of the structure has been calculated using a 2-step approach. First, the contact forces at the sleeper soffit are determined with the FE model presented in Figure 1. In the second step the dynamic response of the culvert to these contact forces is calculated using a FE model representing the sub-ballast layer, the culvert, the embankment and the subgrade. As the FE model used in the second step is linear the analysis is performed in the frequency domain. After that the results are transformed back to the time domain.

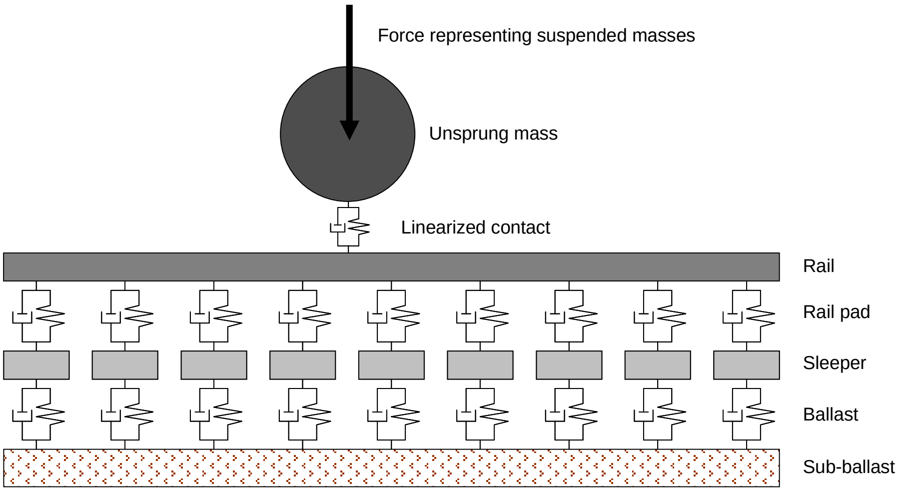

Figure 1: FE model used to determine the force boundary conditions for the second analysis step.

In Figure 2 part of a 3D FE model that has been used to calibrate the corresponding 2D FE model is displayed. Different colors indicate different materials.

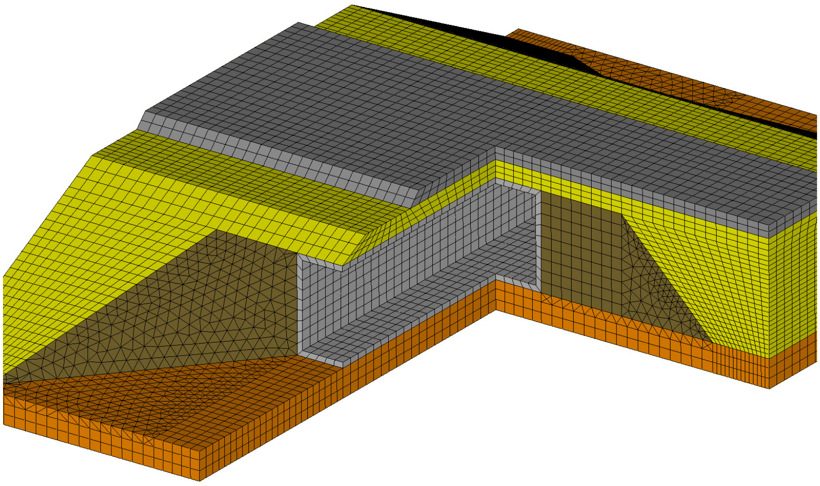

Figure 2: Part of a 3D FE model that has been used to calibrate the corresponding 2D FE model.

In order to adequately capture wave propagation phenomena that take place in the soil and embankment regions, the element size has to be chosen accordingly. As a consequence, the high number of small elements of the soil and embankment regions results in quite large FE models which are impractical to deal with.

The lateral and base boundary conditions for the computational soil domain have been modelled using Lysmer transmitting boundaries [6].

In Figure 3 a photo of a 3m x 3m box culvert and the results obtained with the 3D model at the centre of the top slab are displayed.

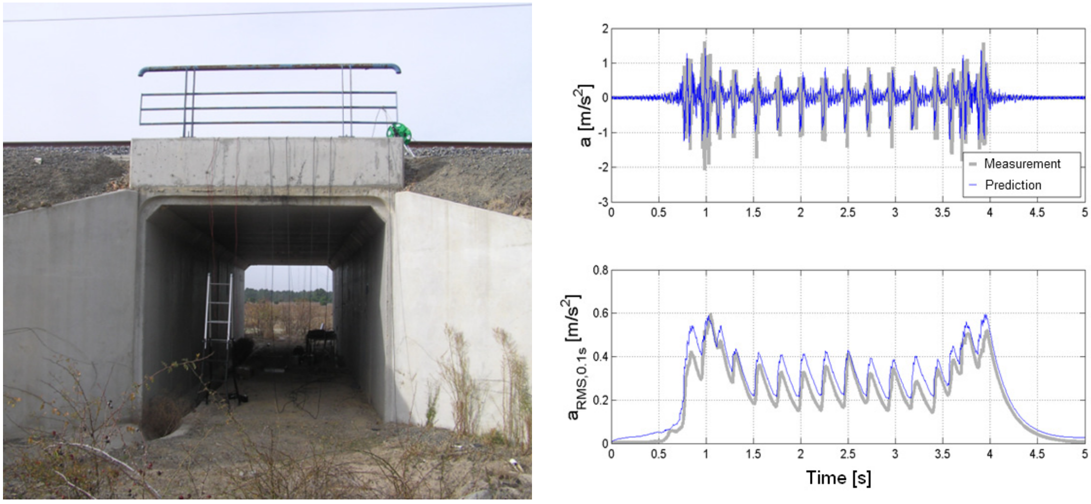

Figure 3: Comparison of acceleration time histories at the centre of the top slab of a 3m x 3m culvert.

For the 2D FE models plane stress elements have been used. In Figure 4 part of the mesh of a 2D FE model is displayed.

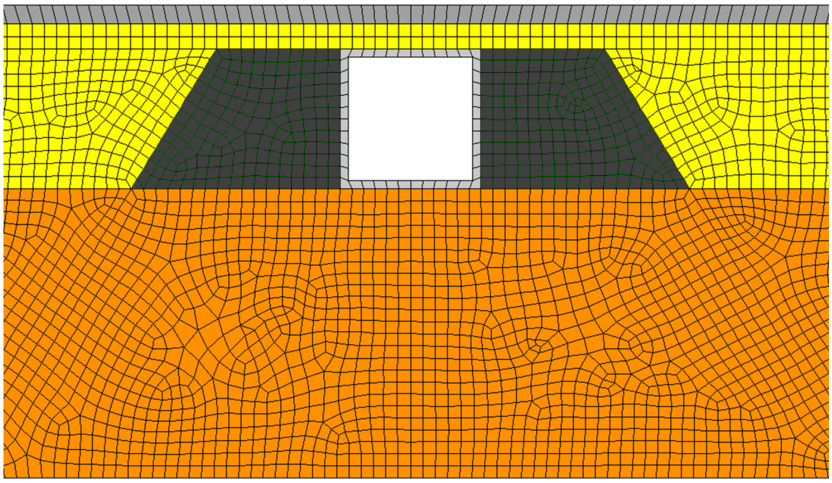

Figure 4: Part of a 2D FE model that has been calibrated to the results of a 3D model.

The element thickness varies with distance to the sleeper soffit. At the sleeper soffit, the thickness corresponds to the effective length of the sleeper i.e. approximately 2.3 m. The thickness of the elements representing the embankment, the backfill and the soil increases at a slope of 1 to 4 as shown in Figure 5.

The elements representing the culvert are of thickness U_w which has been determined by comparison of 2D and 3D model results. However, a modelling approach that involves the use of a 3D FE model in order to calibrate a 2D FE model is not very helpful.

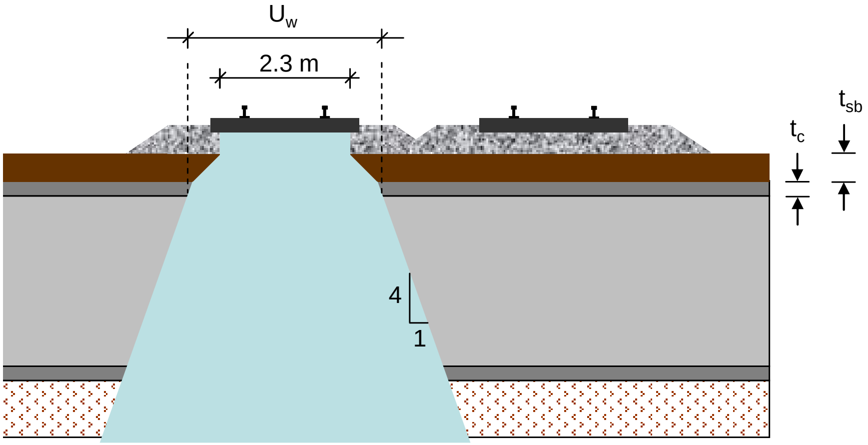

Figure 5: Variation of element thickness with distance to the sleeper soffit.

To avoid having to set up a 3D FE model a parametric study including 5 culverts with clear spans ranging from 2.3 to 10 m has been performed. A linear relation has been found between the equivalent inertia of a 1 m wide section of the top slab and the layer located between ballast and culvert and the thickness U_w. The equivalent bending stiffness EI of this 1 m wide section is then obtained by multiplying I_{eq} by the Young's modulus of concrete. The obtained fit is displayed in Figure 6.

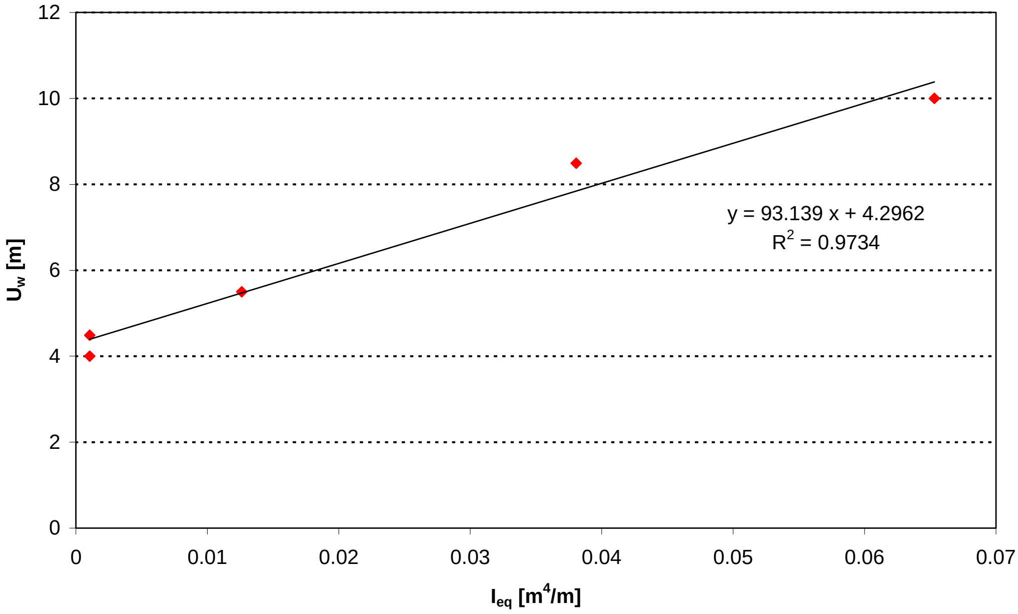

Figure 6: Linear regression fit for $U_w(I_{eq})$.

The following expression may thus be used to estimate the thickness U_w:

$$U_w = 4.3 + 93 \cdot I_{eq} \tag{1}$$

with U_w in m and I_{eq} in m^3. It is important to note that expression (1) is only valid for culverts with thickness ratio t_{sb} / t_c lower than or equal to 4.

4 CONCLUSIONS

In the present study experimental results and numerical predictions of a 3D FE model have been used to calibrate a 2D FE model that can be used to estimate the maximum top slab displacement of a RC box culvert.

The dynamic response of the structure has been calculated using a 2-step approach. In the first step, the contact forces at the sleeper soffit are determined, and the second step consists in calculating the dynamic response of the culvert to these contact forces.

The dynamic response of the culvert is dominated by plate vibration modes. If the primary concern is to estimate maximum displacements, the frequency range of interest is limited. Therefore the use of a 2D FE model is appropriate because this type of model gives, in general, reasonable results only up to frequencies around the first mode.

For the 2D FE models plane stress elements have been used. The element thickness varies with distance to the interface between ballast and sub-ballast layer. A simple method to estimate the element thickness has been proposed. As input data only a few geometrical characteristics and material properties are needed.

This type of model may be very useful for parametric studies aimed at deriving simple expressions for the impact factor for RC box culverts.

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