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INDUCED VIBRATIONS DUE TO HIGH-SPEED TRAINS: CÓRDOBA-MÁLAGA HIGH SPEED LINE

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ABSTRACT

Numerical models to obtain ground vibrations induced by the passage of HST, based on finite element method and boundary element method, have been developed in the last years. A few models have been validated, comparing the results obtained from numerical models and those obtained from experimental measurements. Most of these models contain important simplifications, i.e; the ground geometry around the track is not considered or close structures can not be taken into account. Other models only produce the vertical displacements of the ground.

In this paper, a three-dimensional BEM-FEM model based on time domain formulation to solve wave propagation problems is presented. The soil is assumed to be a uniform half-space with viscoelastic properties, and the structures can be represented by FE or BE. From the proposed numerical model, vibrations induced by the passage of HST have been obtained. The geometry and the properties of the ballast have been also considered.

The numerical results obtained from the proposed model have been compared with in situ measurements performed during the passage of AVE high speed trains on the track between Córdoba-Málaga. The agreement between both sets of results is quite good.

INTRODUCTION

High speed trains are becoming a usual mean of transportation for intermediate distances in many countries. New lines have been constructed in recent years. Factors such as: vibrations in the train, wave propagation in soil next to the track and dynamic effects in nearby constructions, are much more important in high speed trains than in conventional ones. These effects require a deep analysis in order to maintain security and comfort in the trains and to avoid problems in nearby constructions due to vibrations induced by waves transmitted through the soil. Particularly serious would be situations in which the train speed may be higher than that of the surface waves in the underneath soil. This possibility was completely unthinkable in conventional trains but it is now something that should be taken into account when high speed trains operate at locations with particularly soft soils or underground discontinuities that may result in relatively low surface wave speed.

The study of these problems require of comprehensive models that take into account many factors related to the characteristics of the train, the track, and the particular soil properties. Nearby structures should also be modelled in case the effects on these structures are being analyzed. Different analytical, semi-analytical or numerical methods have been developed in recent years. Numerical methods are intended to reproduce more precisely the particular conditions of the problem taking into account the important dynamic interaction effects. Finite Element Method (FEM) and Boundary Element Method (BEM) have been used for the study the problem of high speed train passing taking into account propagation of waves in the soil and dynamic soil-structure interaction [1,2]. The main differences between these models are based on the way in which excitation and interaction effects are considered.

It is known that Boundary Elements are very well suited for dynamic soil-structure interaction problems. They are able to represent unbounded regions in a natural way due to the fact that the fundamental solution and, therefore the solution of the problem at hand, satisfy the radiation conditions. In the case that a full space fundamental solution is used for soil problems, the whole soil surface extending to infinity should be represented. Nevertheless, the discretization can be truncated at a short distance from the zone of interest without lost of accuracy [1]. These properties, in addition to the fact that, in most cases, propagating waves produce deformations that can be assumed to be linear elastic or viscoelastic, make BEM an adequate tool for the analysis of dynamic effects induced by high speed trains.

The study presented in this paper has been carried out using the time domain formulation of the BEM and the FEM. As opposite to frequency domain formulations, time domain analysis allows for an efficient and accurate solution of transient problems and permits to include non linear effects in the response of structures which are connected to the soil. Time domain formulations of the BEM have been in the literature since the early eighties [1,3,4]. In the present work, a three dimensional time domain formulation of the BEM with a full-space fundamental solution is used. The formulation and numerical implementation follows the work of Marrero and Domínguez [5,6]. Nine node quadrilateral and six node triangular quadratic elements are used. Piecewise linear and piecewise constant time interpolation are used for displacements and tractions, respectively. Special attention is paid to stabilizing algorithms and element subdivision to improve efficiency, stability and accuracy of the procedure. A decaying law for wave amplitude is introduced in order to represent internal damping in the soil.

The soil is assumed to be a uniform half-space with viscoelastic properties and its surface is discretized in a zone around the points of interest, and the structures can be represented by FE or BE. Both methods are couple by an iterative algorithm [7]. Induced motion at several points of the soil surface near the track is evaluated. The model is validated by comparison of the computed results with actual values measured during the passage of AVE high speed trains on the track between Córdoba-Málaga. The agreement between experimental and numerical values is good.

THE TIME DOMAIN BEM FOR 3-D ELASTIC PROBLEMS

The 3-D BE formulation for transient problems is briefly summarized in this section. A complete treatment can be found in the work of Domínguez [1], and Marrero and Domínguez [6]. Starting from the integral representation of displacement u at a point i on the boundary of a elastic body, after space and time interpolation of the boundary variables, piecewise integration in space and time of the fundamental solution kernels and once the boundary conditions are applied, a system of equations can be solved step-by-step to obtain the time variation of the boundary unknowns, i.e., displacements and tractions. In the present paper, piecewise constant time interpolation functions are used for tractions and piecewise linear functions for displacements, the fundamental solution displacement and traction are evaluated analytically without much difficulty, and nine node rectangular and six node triangular quadratic elements are used for spatial discretization. Each side of the element is divided into equal parts in the natural coordinates domain, yielding an element subdivision which is used for numerical integration.

The spatial integration extends only to those subdivisions whose midpoint is under the effects of the fundamental solution waves according to the causality condition of each term of the fundamental solution.

SOIL MOTION DUE TO TRAIN PASSAGE

The analysis of the soil vibrations induced by a high speed train on a viscoelastic half-space is now carried out using the BE mesh of Figure 1 which has a total length of 86.4 m, a width of 25 m and elements for the track zone of the same type as those in [8]. The train is represented by an array of loads corresponding to the axles location and load values of trains Alstom (AVE) as shown in Figure 2.

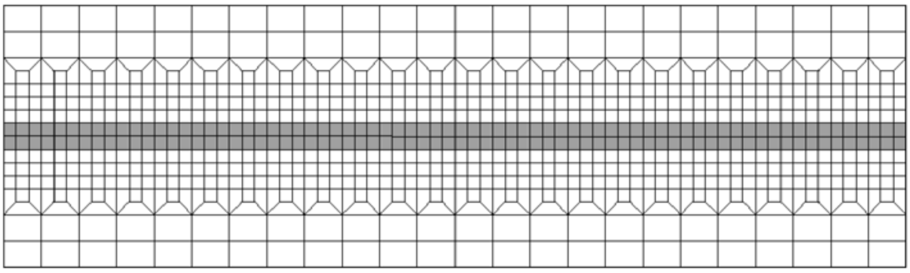


Figure 1.- Soil surface discretization

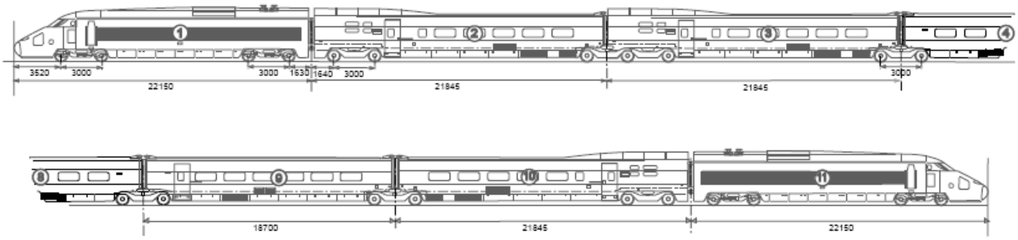


Figure 2.- Configuration of the Alstom (AVE) high-speed train.

Galvín [9] carried out in 2006 a series of experimental measurements for this train just before the inauguration of the high-speed train track between Córdoba y Málaga. These valuable data will be used in the present paper to compare with numerical results obtained using the proposed numerical technique.

The train characteristics, and the rail and sleeper properties, are as given in references [9]. The soil is assumed to be an uniform viscoelastic half-space with shear-wave velocity c_S=150 m/s, a Poisson's ratio ν=0.3 and a mass density ρ=2000 kg/m^3. These equivalent soil properties coincide with those measured by Galvín [8] for a layered soil.

Numerical studies carried out by the authors for a point load travelling at constant speed, within the train speed range considered, on the surface of a stratum with the properties reported by Galvín [9] (h_1 = 1.2 m, c_{s1} = 150 m/s; h_2 = 2.5 m, c_{s2} = 408.4 m/s; and bedrock c_{s3} = 635 m/s), show that surface motion is almost identical as for a uniform half-space with c_s = 150 m/s. A viscous damping ratio ξ= 0.02 was estimated in [9]. Train speed values v=298 km/h y v=250 km/h were assumed for the numerical analysis. Experimentally recorded values are available for these train speeds. The load transmitted to one of the sleepers by a unit axle load is obtained from Krylov´s analytical prediction model [10].

The free-field time response for a train passage was obtained using the 3-D time domain technique presented above using the discretization shown in Figure 1 and a time step Δt= 0.003 s. The response to a single axle load, producing a surface load at each sleeper of the type shown in Figure 1, was obtained for each velocity. Then the response for the complete train was obtained by superposition. It is worth to mention that to validate the mesh in Figure 1, the problem of a point load travelling at constant speed on the surface of half-space without track was studied first using the same mesh. A good agreement between numerical and analytical solution was obtained for the same velocities and properties of the present study. Results of that experiment can be seen in [8]. The size of the elements used in Figure 1 discretization is small enough to represent the soil surface motion of the problem at hand for an axle load at the speeds of interest. It should be taken into account that the frequency content is as shown in Figure 4 and that a 10x10 element subdivision is used to carry out numerical integration over the boundary elements. The time step used in the analysis is short enough to produce accurate BE results for one axle load and to preserve accuracy in the superposition process. Previous BE analysis of soil vibration problems show that a mesh several times as wide as the loading zone is enough to obtain accurate results in an area around to the loading zone. In the present study, a mesh width of 25 m was chosen in order to be able to measure soil surface displacements up to 10 m from the track axis. A good representation of the soil surface displacements at larger distances would require of a wider mesh. Displacements records at any point on the boundary element mesh are obtained from the numerical analysis. Points on the cross symmetry axis of the discretized zone are taken as reference. Figure 3 corresponds to the time records of the vertical component velocity at a surface point located at 11.8 m from the track axis and the four speed values mentioned above. Experimental data and time-domain BE computed values are shown in the figure for the four train speed values. A high frequency pass filter with a roll-off termination frequency f_t = 2.5 Hz and a cut-off frequency f_c = 3.0 Hz has been applied. This filter was used in order to compare numerical results with the experimental values reported by Galvín [8] who used the filter to compute velocity values from recorded acceleration data. Frequency spectra for the BEM numerical results were obtained using the Fourier transform. Frequency spectra are shown in Figure 4 for distance 11.8 m to the track axis. It can be observed from these figures that numerical results are dominated by bogie and axle passage frequency (low frequency). This part of the numerical results spectra is in good agreement with the experimental results spectra. However, the intermediate frequency content of the experimental results spectra, corresponding to wheel and rail irregularities, are not shown by the time records and frequency spectra of the numerical results as they are not included in the load model. A good representation of damping is important to numerically calculated ground vibrations. Radiation damping plays a key role in the system motion. This damping mechanism is very accurately represented in the BEM since it is exactly included in the fundamental solution. An attenuation law is assumed to taken into account the material damping effect.

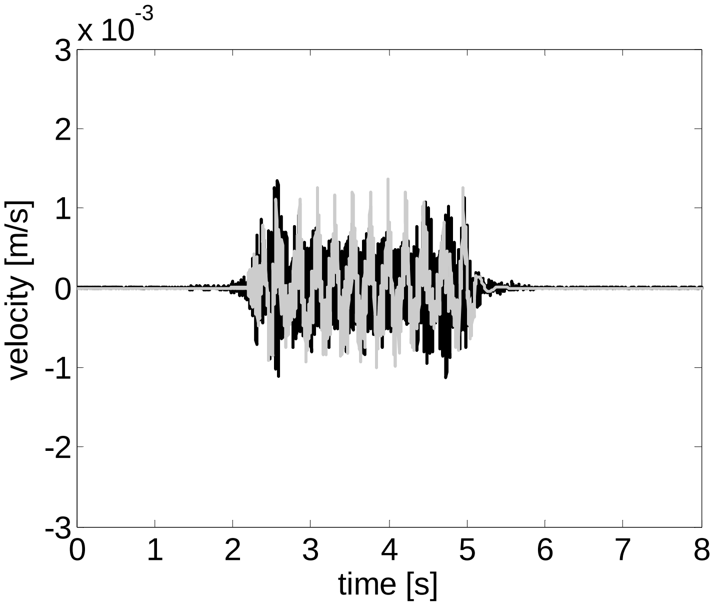


Figure 3.- Vertical velocity at a point 11.8 m from the track: *v* = 298 km/h. Experimental (black line) vs. Numerical (grey line).

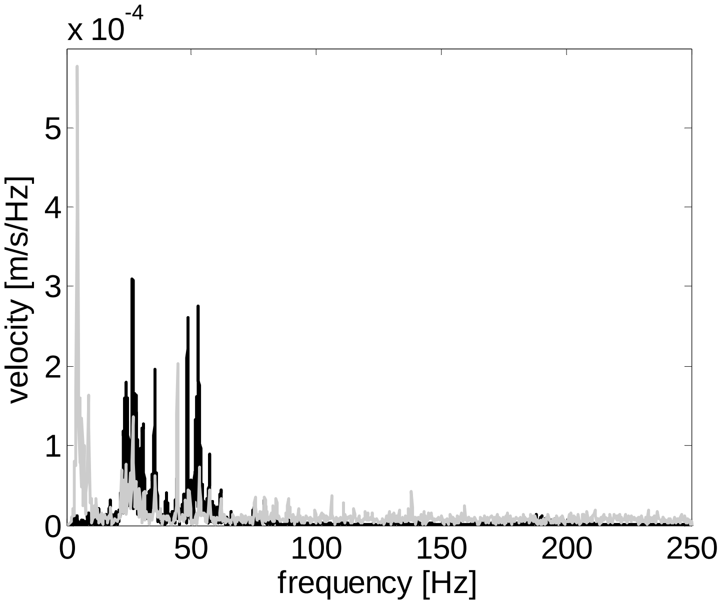


Figure 4.- Frequency content of the vertical velocity at a point 11.8 m from the track: *v* = 298 km/h. Experimental (black line) vs. Numerical (grey line).

DYNAMIC INTERACTION WITH A CONCRETE UNDERPASS STRUCTURE

The geometry of the problem and BE discretization for soil and structure are shown in Figure 5. The train passes along an embankment on a uniform half-space. Both half-space and embankment have the same properties: shear-wave velocity c_s=100 m/s; Poisson's ratio ν=0.3; density ρ=1850 kg/m^3 and viscous damping ratio ξ=0.02. The underpass is a concrete plate type structure with the geometry shown in Figure 5. The concrete is assumed to be a uniform linear elastic material with the following properties: shear modulus μ=0.8x10^{10} N/m^2; Poisson's ratio, ν=0.2 and density, ρ=2500 kg/m^3.

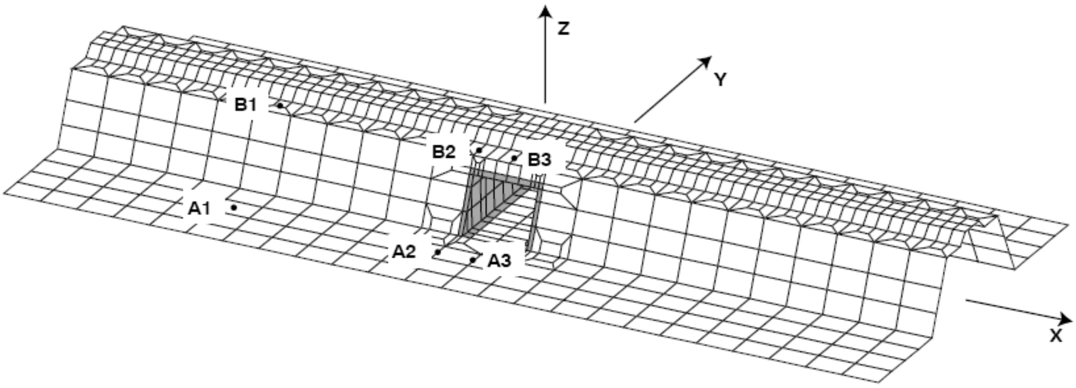
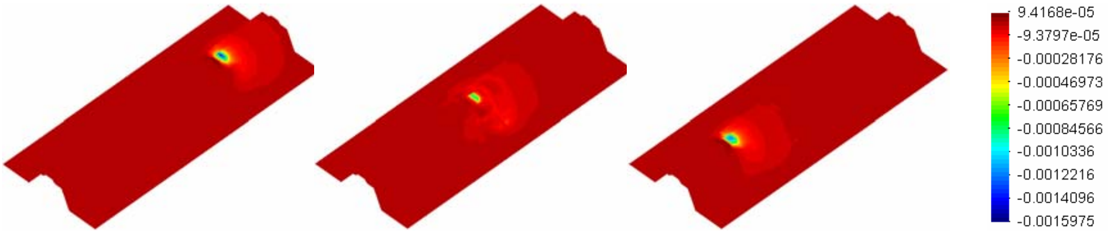


Fig. 5. Underpass. BE discretization and geometry.

Soil surface displacements in the vertical direction *Z* due to a 15x10^4 N axle load travelling at 300 km/h are represented for three instants of time in Figure 6. underpass displacements are shown in Figure 7. The coordinates origin is located at the point of the underpass half-space surface located on the two planes of symmetry of the problem. The three instants t=0.267 s, t=0.537 s and t=0.804 s correspond to distances X=-2.45 m, X=0.05 m and X=22.30 m, respectively. It can be seen from the figures how the influence of the underpass on the soil surface displacement is small for t=0.267 s and t=0.804 s. Vertical displacements are almost symmetric and their values are almost the same as for greater distances to the underpass. At t = 0.537 s the load is over the underpass and, as compared to the other two cases, the *Z* displacements values under the load and its vicinity are smaller due to the stiffening effect of the concrete plate close under the loaded surface.



(a) (b) (c)

Fig. 6. Vertical soil surface displacements for the passage of a 15x10^4 N axle with v=300 km/h: (a) t = 0.267 s (b) t = 0.537 s (c) t = 0.804 s.

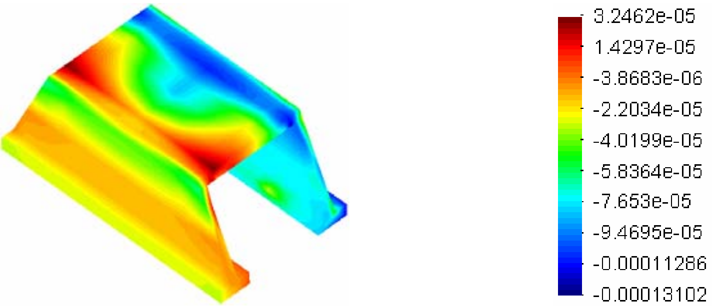


Fig. 7. Vertical underpass displacements for the passage of a 15x10^4 N axle with v=300 km/h: t = 0.537 s.

CONCLUSIONS

A three-dimensional time domain model for viscoelastic solids has been applied to the analysis of soil motion due to high-speed train passage. As compared to frequency domain formulations, the present BE formulation permits to consider coupling with nearby structures that may have a non linear behaviour. As compared to formulations based on direct integration of half-space Green's functions, it is able to consider the actual geometry, embankment and ballast effects, and other local effects. As compared to 2.5-D solutions the present formulation can take into account local soil discontinuities, underground constructions such as underpasses, and coupling with nearby structures that brake the uniformity of the geometry along the track line.

Some of the conclusions drawn from the computed numerical results for the particular situations for which there are in situ measurements of soil surface motion due to high-speed train passage are:

(1) In all studied cases, the time length of the main perturbation, the normal peak particle velocity (PPV) values and the dominant frequency corresponding to bogies and axle passage are accurately represented in the numerical model. There is a good agreement between numerical results and experimental measures.

(2) The present time domain boundary element approach is able to represent properly the soil surface motion time history at a significant area around the track, including the attenuation effects, for different train speeds.

(3) The most significant difference between experimental and BE computed values is that experimental values contain intermediate frequency peaks, superimposed to the dominant bogie and axle passage peaks, which are not obtained in the numerical solution. These peaks are due to excitation mechanisms, such as rail or wheel irregularities, which are not included in Krylov's load model. Nevertheless, the PPV and the most significant frequencies are accurately represented by the present numerical approach.

ACKNOWLEDGEMENTS

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