A comparison of 2D, 2.5D and 3D BEM models for the study of railway induced vibrations

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Summary
The propagation of vibrations from surface or underground excitations due to tramways or trains is well described by FEM/BEM approaches where the different media can be modelled either by FEM or BEM. The MEFISSTO software developed at CSTB over the last 20 years exists in 2D, 2.5D and 3D versions. While certain configurations such as pile foundations must be handled with a 3D model, many situations, such as trains in tunnels, are well described by a 2.5D approach. In this paper, the effects of 2D versus 2.5D and 2.5D versus 3D are assessed through several applications. In many situations, 2.5D models come as a necessity over 2D models and can be showed to be also valid for structures of moderate length. The case of a tunnel imbedded in multi-layer soils is presented as a practical application.

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1 Introduction

The propagation of vibrations from railway excitations is a recurrent problem. The prediction of structure-borne sound requires a model which can handle the vibration transfer through the ground and into the foundations. Mobility techniques [1] allow the interfacing of the top of foundations and upper structures so that one has to concentrate on the underground part of the problem. Sources can be characterized from ground vibrations close to the railway lines [2]. One popular predictive method is the BEM/FEM approach which exists in 2D, 2.5D and 3D versions. The 2.5D approach was first introduced by Tadeu [3] and is an intermediate step between 2D and 3D approaches. In 2.5D, as in 2D, the geometry of the problem is assumed to be invariant in the direction (y) parallel to the tracks. However, contrary to the 2D model, the source is a point force and by extension can be the sum of correlated or uncorrelated forces. In this paper, we will use the MEFISSTO software developed at CSTB and compare 2D [4], 2.5D [5] and 3D [6,7] computations. First, we will see that, first due to high absorption in the ground it is often legitimate to use 2.5D models rather than the 3D approach; second, we will show that the simplest 2D model is not adequate.

2 The BEM/FEM approach

The MEFISSTO software is based on mixed BEM and FEM models where each finite sub-domain can be modelled either with BEM or FEM. In 2.5D, only BEM is employed its FEM counterpart would be spectral elements [8]. In [1] it was found that BEM has a faster convergence for massive structures whereas FEM should be preferred for slender ones. Massive platforms or foundations and thick tunnels are easily handled with BEM. As many sub-domains as wanted can be defined, which includes FEM regions. Each FEM region is condensed onto the nodes coupled with BEM so that the FEM contribution, for a given zone, to the global matrix is a dense sub-matrix. The meshing, both for BEM and

FEM sub-domains, can be remade automatically at each new frequency in order to optimize CPU's. A particular attention is given to points in contact with multiple domains and the addition of multiple tractions, which leads a priori to an insufficient number of equations, is compensated by the addition of extra nodes where the unknowns are interpolated from the two (or 3 in 3D) neighboring nodes. This technique was originally proposed in 2D in [9] and applied in 3D [6,7].

3. 2.5D versus 3D BEM

We show here through a very simple example that a structure does not have to be very long to be eligible to a 2.5D description. A 1x1 m^2 infinitely long concrete block is placed inside an infinite ground. A unit horizontal force is placed at (-5,0,0) and the horizontal displacement is computed at two points behind the structure (M_1 on the block and M_2 in the ground). Computations are made with the 2.5D model ($L_y=\infty$) and with the 3D model for a finite block of lengths L_y=4,8,12 m. We observe in Figure 1 that a length of 12 m is sufficient for a 2.5D approximation and that even the short 4-m long structure can reasonably be considered as infinite. Other simulations have been carried for other situations and similar results were obtained. As a consequence it can be considered that one may reasonably use a 2.5D model in many situations for structures of, say, a least 10 m of length parallel to train-like sources.

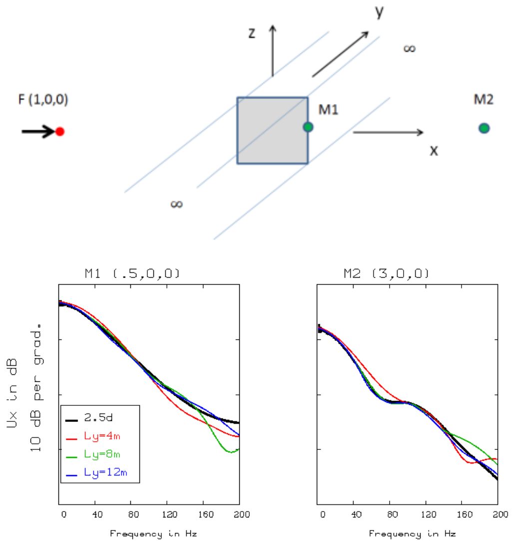

Figure 1. Comparison of 2.5D and 3D computations

4. The importance of 2.5D

4.1 Tracks on ground surface

Measurements carried on a free surface, at a given distance L_x from the track can be used to calibrate computations. For a given model (2D or 2.5D) we carry two computations at L_x (without and with a foundation) in order to estimate H the insertion loss of a structure prior to its construction.

$$H=L_V(no\ structure)-L_V(structure)$$

where L_V is a velocity level.

The combination of the measured surface velocity with H allows the estimation of the velocity at the top of the foundation. In Figure 2, we compare the spectra of H estimated with 2D and a 2.5D models. As mentioned before, the 2.5D approach allows the excitation to be made of sums of uncorrelated vertical point forces distributed over different lengths, thus representing different train lengths. In Figure 2, the 2D results are compared to a single force situation and to 80 or 320 m long (L_y) force distributions (one force every meter). The top and lower graphs give respectively the horizontal and vertical components of H. Three values of L_y are considered (29, 13 and 4 m). It clearly appears that (i) the coherent (2D) model underestimates the attenuation provided by the foundation, (ii) the single point force has the opposite effect, (iii) 160 and 320 m excitations lead to identical results (green and blue curves superimposed) (the source length L_y is then much longer than L_x).

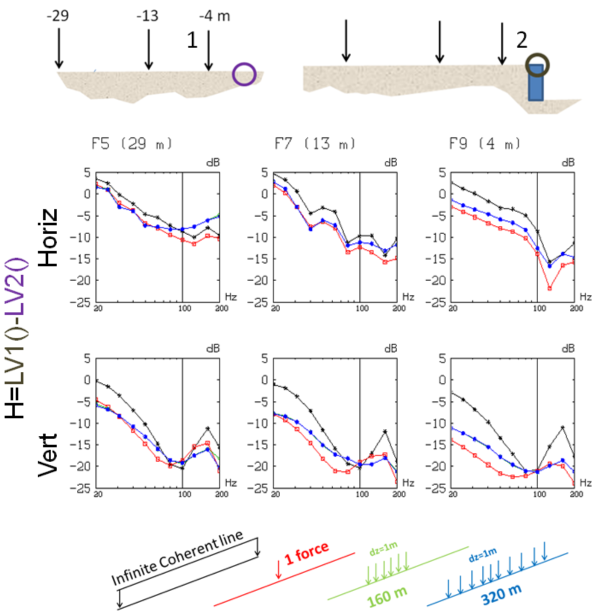

Figure 2. Surface insertion loss. 2D versus 2.5D

4.2 Tracks in tunnels: 2D versus 3D

The case of train tunnels is now considered. The tunnel modelled has a radius of 4.5 m and walls 40 cm-thick; it has its center at z=-25 m. Four cases of soil compositions are modelled as summarized in Table 1. For instance in *case 1* the soil is semi-infinite and is considered “average”. The two other soils are made of two top layers and a lower semi-infinite chalky medium. The underlined data correspond to the layer containing the tunnel. Note that in *case 2* the tunnel is set in a hard layer (chalk), in *case 2* the tunnel is in a softer soil (clay) and in *case 4* the tunnel has its lower half imbedded in chalk and its upper half in clay. In this last case, the tunnel’s boundary intersects an interlayer so that special care must be taken when defining the tractions; at the nodes of intersection (which belong to 3 different domains) one has to define 3 tractions.

Table 1. Soils data

		1	2	3	4
E MPa	269	200	2500	7500	1000
ρ kg/m³	1550	2000	2000	2000	2400
type	average	Sand/alluvium	Marl / clay	chalk	
Case1	< 0m				
Case 2		[-10 ,0]	[-19 ,-25]	[-31 ,-19]	<-31 m
Case 3		[-10 ,0]	[-31 ,-25]	[-40 ,-31]	<-40 m
Case 4		[-10 ,0]	[-40 ,-25]	[-40 ,-25]	<-40 m

The excitation is made by two identical forces representing two trains as showed in Figure 3.

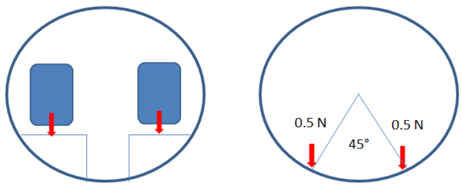

Figure 3. A tunnel with two trains and the corresponding excitations.

We compute the velocity difference $H_V = L_V$ (surface)-L_V (tunnel bottom) which characterizes the increase of attenuation due to the medium. Figure 4, compares the 2D results and 2.5D results for different train lengths in *case 1*. The 2D model underestimates the attenuation by 3 to 15 dB.

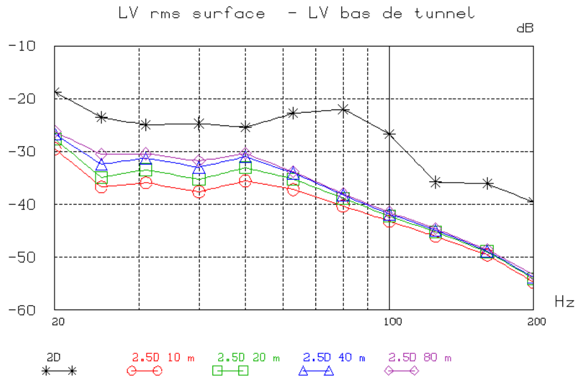

Figure 4. Case 1: soil attenuation for 2D and 2.5D models (1/3 octave bands).

Figure 5 shows the results for the 4 cases considered. It shows that the 2D computation always underestimates the ground attenuation. The 2.5D effect also depends on the soil characteristics. The function H_V itself, as expected, also depends on the soil characteristics.

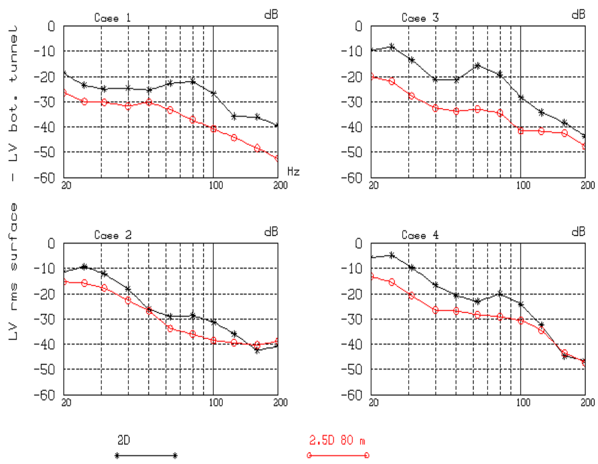

Figure 5 . 4 cases: soil attenuation for 2D and 2.5D models.

The modal behavior of the tunnel is illustrated in Figure 6 obtained from a 2D computation.

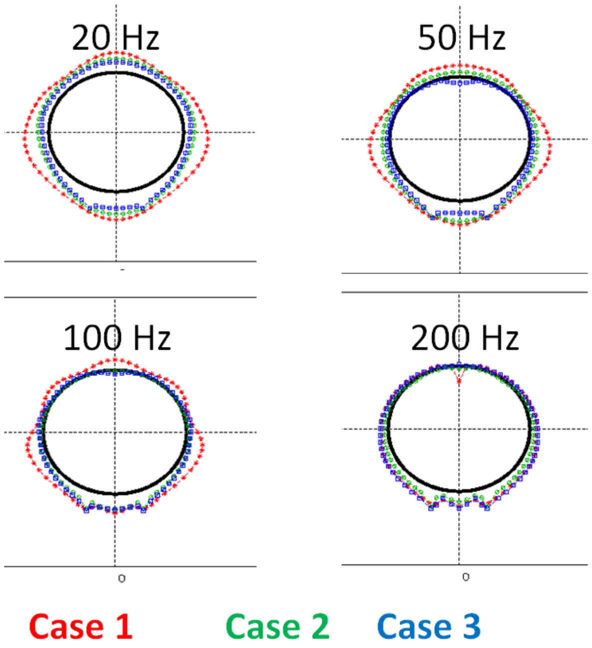

Figure 6. Modal behaviour of the tunnel (2D)

Figure 7 shows the influence of the inclusion of the platform in the tunnel's model. A few dB's difference may be observed but the general behavior is not significantly modified.

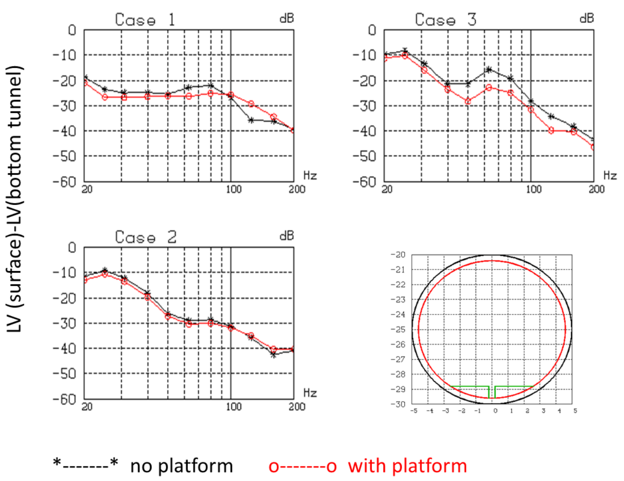

Figure 7. Influence of the train platform (2D).

Figure 8 compares the spectra of H_V obtained for two thicknesses of the tunnel's walls (40 and 60 cm) for *cases 1 and 2*. The incoherent line is 80 m long. The effect in *case 1* (tunnel in softer soil) is more pronounced than in *case 2*.

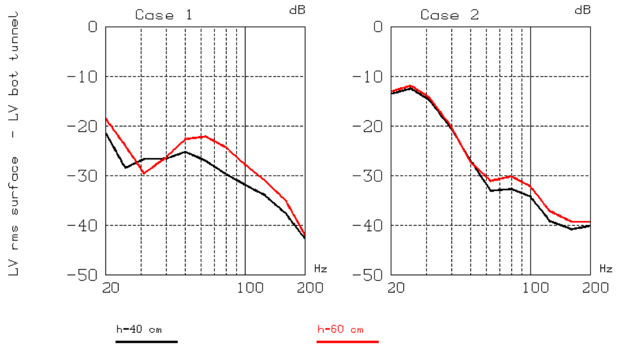

Figure 8. Effect of the tunnel's walls' thickness (2.5D).

Finally, we want to illustrate the advantage of color maps which can help to understand the complex propagation of vibrations in the ground. A tunnel is excited by one force. The soil has 3 layers with values of Young's modulus of 200, 2500, 7500 MPa from top to bottom. Interferences between the free surface and the tunnel can be seen. Due to lack of time, the calculations were done in 2D; 2D results tend to amplify standing wave patterns as compared to 2.5D.

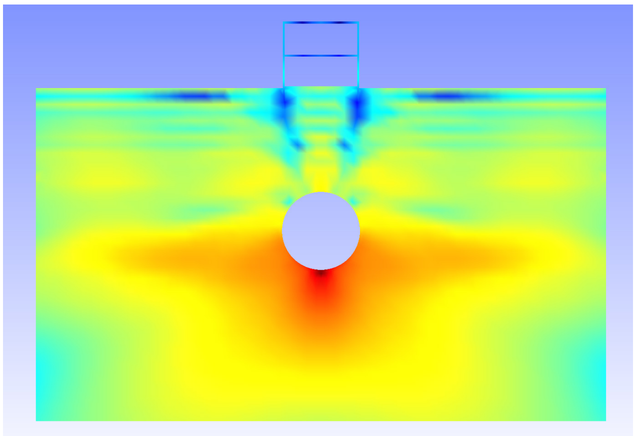

Figure 9. Total displacement at 100 Hz. Color span of 38 dB (2D)

This map is obtained by combining the values obtained at the BEM and BEM nodes and values obtained at a selection of points in the soil (post-treatment). Figure 10 shows a zoom of Figure 10, together with the computations meshes (BEM and FEM) and the post-treatment mesh.

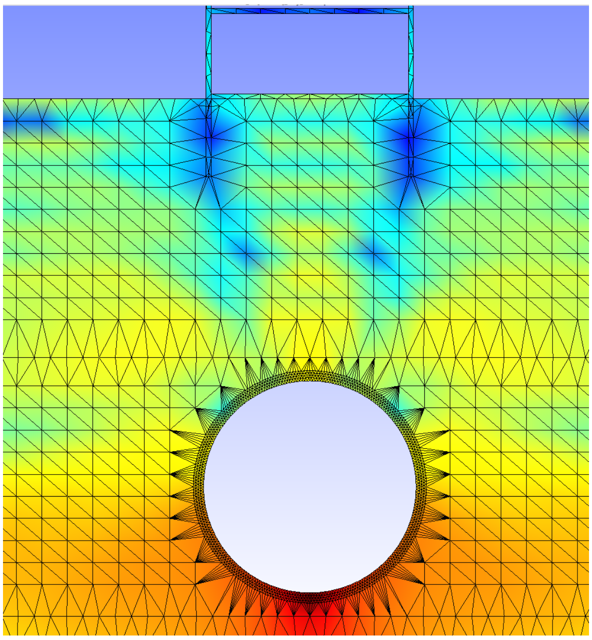

Figure 10. zoom with calculation and post-treatment meshing (2D)

5 Conclusion

A comparison between 2D, 2.5D and 3D FEM/BEM models for the study of propagation of vibrations from railway excitations has been presented. First, one can correctly approximate 3D problems with a 2.5D model provided that the structure is several meters long parallel to the tracks and assuming that transverse geometrical aspects can be neglected. This is often the case for foundations. Upper structures can eventually be coupled to the foundations via mobility techniques. Secondly, one should avoid the use of 2D (infinite coherent line source) models since source effects are not correctly handled in 2D. Railway sources are better approximated by uncorrelated forces thus requiring a 2.5D model. Comparing 2D and 2.5D models for tracks on the surface but also for tracks in tunnels clearly shows the necessity to use the 2.5D approach. The case of propagation from tunnels to the surface or to foundations has been illustrated showing the influence of the ground's composition.

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