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VibraSIG - Modeling railway structure-borne noise and vibrations and implementation in QGIS geographic information software

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ABSTRACT

In the context of engineering studies for passenger rail line projects, a method for predicting vibration and structure-borne noise levels in buildings close to the line is needed on the scale of a town or territory.

ACOUSTB has developed VibraSIG, a method for calculating railway vibration and structure-borne noise, based on two numerical models (VibraFer, CSTB and MEFISSTO, CSTB). A numerical model in VibraFer is used to define a railway excitation source term. A numerical model in MEFISSTO is used to calculate the vibratory response of the tunnel and the ground up to the building on a cross-section. A statistical building response model is used to estimate structure-borne noise and floor vibration levels.

Finally, the method for predicting vibration and structure-borne noise levels is extended to the entire project route, and the results are visualized for each building on a Geographic Information System (GIS).

Keywords: *vibrations, ground-borne noise, prediction, metro tunnel, railway.*

1. INTRODUCTION

Urban rail traffic is one of the strategic development axes for metropolises, thanks to its high transport capacity, regularity of service and reduced environmental impact compared to road transport.

One of the problems associated with railway tunnel construction projects in built-up areas is the vibrations induced by train movements on the track, propagating through the surrounding soil to the ground and nearby buildings. These vibrations are the source of complaints from many local residents, and restrictive limit values are applied to new construction projects to limit the disturbance caused by railway vibrations.

It is therefore necessary to have a model that can predict the vibrations transmitted by the surrounding ground to buildings located near the tunnel along the project route, and to determine the environmental vibration reduction measures required to comply with the limit values.

Since the 2000s, CSTB has been developing numerical calculation codes to tackle this complex problem, from the generation of the force applied when a train passes through to propagation in neighboring buildings. These include VibraFer [1], which estimates the equivalent force density during a train pass-by in a tunnel, and MEFISSTO [2], which calculates transfer mobilities between the tunnel and the ground. Based on a large number of transfer function measurements carried out by ACOUSTB or from the literature (cf. RIVAS [3]), ACOUSTB has implemented a calculation method that combines the results of Vibrafer, Mefissto and building-related transfer functions, in order to predict vibrations in buildings over an entire rail tunnel construction project.

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2. PREDICTION METHOD

2.1 Description

A prediction method is proposed for estimating ground-borne noise and vibration levels on a receiver located on the second floor of a building close to a railway tunnel.
The predictive calculation data are obtained for each calculation receiver by combining the results obtained are VibraFer for tunnel excitation forces, the results of vibration propagation to the ground surface under MEFISSTO, and the statistical ground-foundation-floor transfer functions chosen for the category to which the receiver belongs. Predictive levels are obtained in the form of floor-center vibration spectra and room-radiated solid-borne noise spectra.
The following figure describes the application of the FTA guide to the problem at hand, and the proposed implementation using Vibrafer, Mefissto, and the Rivas / FTA recommendations.

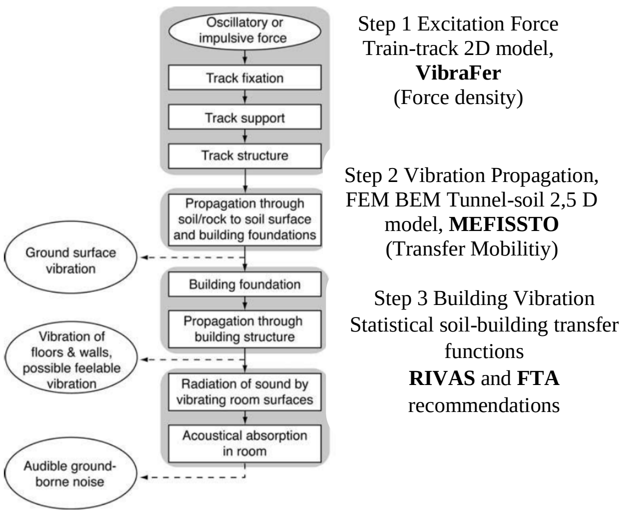

Figure 1 : Groundborne Noise and vibration model, left FTA diagram from [4], right implementation of the FTA procedure in VibraSig proposed by ACOUSTB

The proposed method includes 3 main steps, inspired by the recommendations of the FTA guide [4], and based on a calculation of the force density applied by the train to the tunnel invert and a calculation of transfer mobility to estimate the resulting vibration level at the ground surface. Then, the appropriate transfer functions are used to estimate the resulting vibration level in the building on the second floor (center floor), as well as to estimate the structure-borne noise. The three stages can be summarized as follows :

- Step 1: Calculate force density based on wheel/track roughness and train-track parameters using Vibrafer.
- Step 2: Calculate line-source transfer mobility from the tunnel invert to the ground surface, based on soil parameters and tunnel geometry using MEFISSTO,
- Step 3: Project ground-borne vibration and ground-borne noise inside buildings based on calculated ground surface vibration and statistical building propagation transfer functions using RIVAS and FTA recommendations.

We recall here the principle and equations proposed by the FTA guide [4], quoting the manual's formulations and applying them to the case of a railway tunnel.
The following equations are the basis for the prediction procedure on a receptor, where all of the quantities are one-third octave band spectral levels in decibels with consistent reference values:

$$L_v = FDL + LSTM + C_{build}$$

$$L_A = L_v + K_{rad} + K_{A-wt}$$

where:

L_v = rms vibration velocity level in VdB
FDL = force density level in dB for a line vibration source such as a train
$LSTM$ = line-source transfer mobility level in dB from the tracks to the sensitive site
C_{build} = adjustments to account for ground-building foundation interaction and attenuation of vibration amplitudes as vibration propagates through buildings
L_A = A-weighted sound level
K_{rad} = adjustment to account for conversion from vibration to sound pressure level including accounting for the amount of acoustical absorption inside the room.
the decibel reference value for L_v is 1 micro in/sec
K_{A-wt} = A-weighting adjustment at the 1/3-octave band center frequency

Figure 2 : Equations from the FTA manual [4] for calculating structure-borne noise and vibrations

The vibration spectra on the receptor floor are then compared to the vibration criteria.
The A-weighted ground-borne noise level inside the receptor room is calculated from the vibration spectrum and is compared to the criteria.

2.2 Train-track model using VibraFer

VibraFer, developed at CSTB [2], is a 2D source model (Figure 4 in the frequency domain and based on the wave approach, where (i) the rail is an infinite beam on a continuous multi-layered support representing rail pads, sleepers, under sleeper pads, and tunnel invert ; (ii) the tunnel + ground is represented for each frequency by its line mobility calculated in the wave number domain using MEFISSTO, and (iii) the train is represented by its unsprung mass as well as primary and secondary suspensions and masses (bogie and car body).

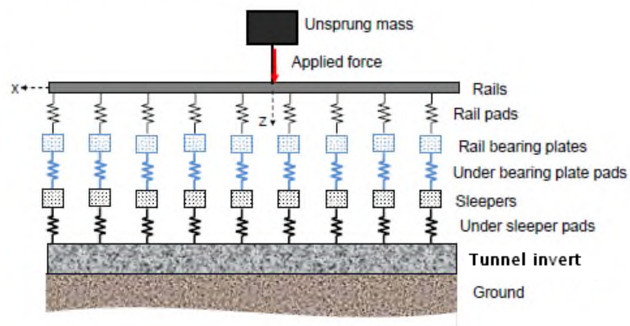

Figure 3 : Representation of 2D source model using VibraFer to calculate excitation forces in tunnel

Knowing the train and track parameters as well as the mobility of the ground, a given rail/wheel unevenness leads to the determination of the force density spectrum applied to the tunnel invert (FDL output data), expressed as a line uncorrelated forces of equal amplitudes and random phases.

2.3 Finite elements and boundary elements model of tunnel-soil using Mefissto

MEFISSTO, also developed at CSTB [3], is a 2.5D FEM BEM ground vibration numerical model used first to calculate the tunnel invert line mobility in the wavenumber domain (input data for VibraFer), and the line-source ground surface mobility (LSTM) at various distances from the tunnel axis. Once the excitation forces in tunnel have been calculated by VibraFer, it is possible to calculate ground surface vibration levels at various distances from the track (blue arrows on Figure 4).

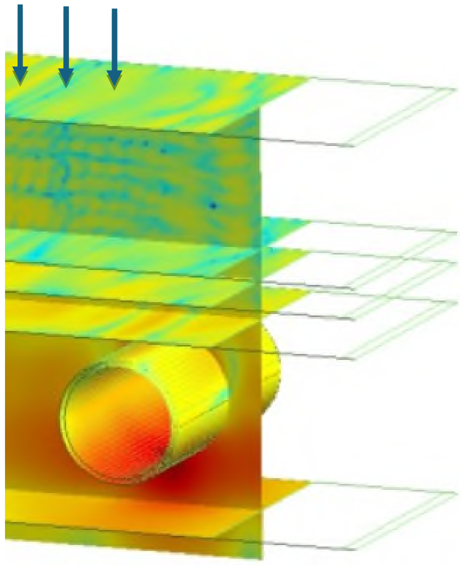

Figure 4 : Example of MEFISSTO 2,5D calculation of ground surface velocity response to excitation forces in tunnel

2.4 Statistical model of building response

After obtaining the resulting vibration level at the ground surface and at the desired distance, it is necessary to apply adjustment factors to estimate the building response to the ground-borne vibration and to estimate the A-weighted sound level inside buildings.
For this purpose, soil-foundation and foundation-floor transfer functions, as well as radiation factors, can be chosen based on knowledge of building characteristics, the main ones being the depth and type of foundations, the type of material used for walls and floors, and the dimensions of the receptor room.
A set of transfer functions associated with the receiver floor is selected from the transfer functions available in the literature (cf. RIVAS Del 1.6 [3]). In some poorly documented building configurations, it may be necessary to carry out field measurement campaigns to establish soil-foundation or foundation-floor transfer functions (cf. [5]).

The following figure shows an example of transfer functions that can be used for predictions. They are taken from statistical laws presented in [3] obtained for surface railways, not tunnels. In the case of tunnel railways, depending on the configuration studied, it is necessary to take into account the specific propagation between the tunnel and the building foundations.

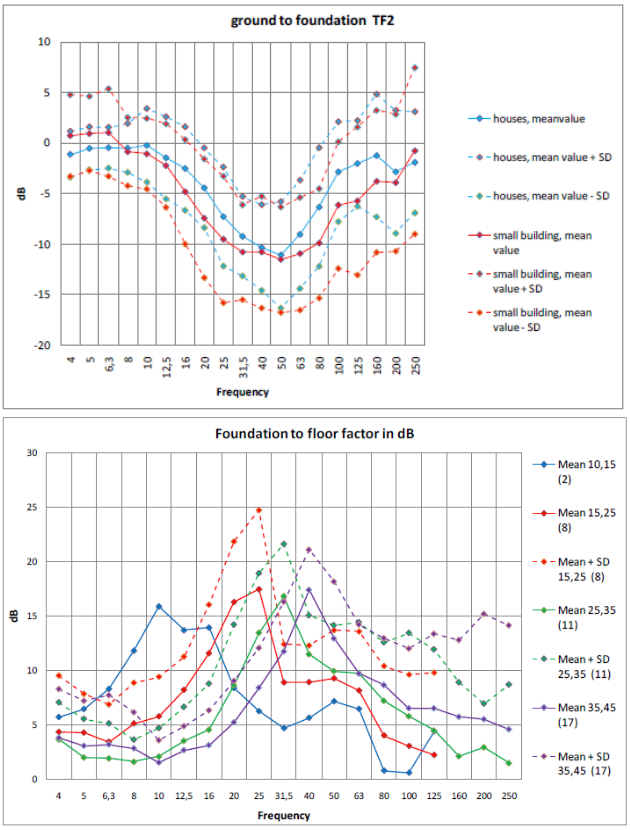

Figure 5 : (Top) Ground to foundation and (Bottom) Foundation to floor vibration statistical transfer function in dB for concrete floors, from [3]

3. TUNNEL-SOIL-BUILDINGS DATABASE USING QGIS

ACOUSTB has selected the QGIS geographic information system (GIS) software to analyze and edit spatial information. The use of QGIS in the calculation method is to provide geographic information on the study area.

We use QGIS to input the field investigation data needed to identify each building in the study area, as well as the building mechanical characteristics relevant to vibration propagation. The characteristics taken into account in VibraSig are: type of walls, type of floors, type of foundations (shallow or deep), number of underground floors, and geometry. The geometric characteristics of the calculation receiver are defined by the distance from the tunnel axis, the tunnel depth and the type of soil used for the calculation. Each calculation receiver is positioned on the second floor and in the center of the floor of a room. For a given building, one or more calculation receivers are defined, enabling to evaluate the variation of vibration levels with distance in the case of a building measuring several tens of meters. The following figure shows an example of data layout in QGIS and a presentation map of field data.

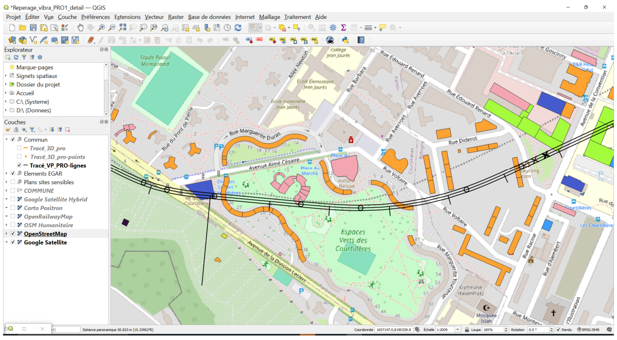

Figure 6 : Data layout in QGIS

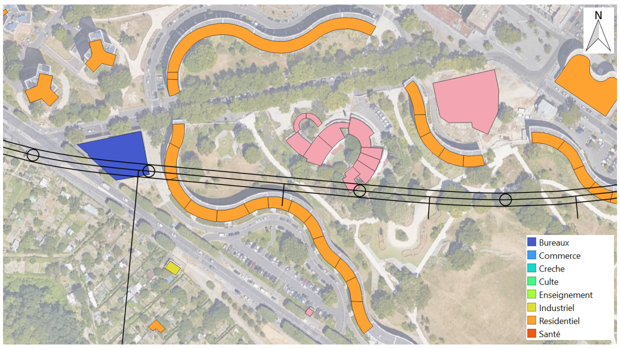

Figure 7 : Example of field data visualization

4. EVALUATION STANDARDS

The standards applicable to the project vary according to the applicable regulations and the specific requirements of each network operator. However, it is commonly observed that the limit values proposed by the FTA [4] for ground-borne noise and vibrations are respected, with variations of the order of 5 dB for ground-borne noise limit.

These limit values are presented in the following table for reference.

Table 6-3 Indoor Ground-Borne Vibration (GBV) and Ground-Borne Noise (GBN) Impact Criteria for General Vibration Assessment

Land Use Category	GBV Impact Levels (VdB re 1 micro-inch /sec)			GBN Impact Levels (dBA re 20 micro Pascals)		
	Frequent Events	Occasional Events	Infrequent Events	Frequent Events	Occasional Events	Infrequent Events
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB*	65 VdB*	65 VdB*	N/A**	N/A**	N/A**
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB	35 dBA	38 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB	40 dBA	43 dBA	48 dBA

* This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. For equipment that is more sensitive, a Detailed Vibration Analysis must be performed.
** Vibration-sensitive equipment is generally not sensitive to ground-borne noise; however, the manufacturer's specifications should be reviewed for acoustic and vibration sensitivity.

Figure 8 : Impact criteria for General Vibration Assessment, from Transit Noise and Vibration Impact Assessment Manual [4]

5. EXAMPLE OF PREDICTION RESULTS

Calculation results are obtained for a set of receptors located along the project route, for the chosen ground-borne noise and vibration indicators. The indicators $L_{v,S,max}$ and $L_{p,A,S,max}$ are used to estimate the conformity of calculated values with project requirements.
An example of results map is shown in the following figure. The figure shows the maximum Lv level per third octave for each receiver.

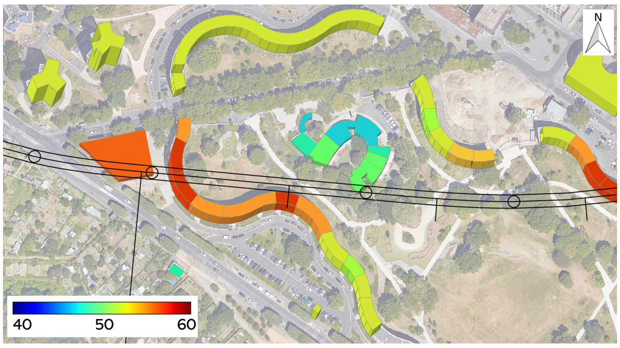

Figure 9 : Example of calculation results, Maximum $L_{v,S,max}$ level per third octave for each receiver

6. CONCLUSIONS

A three-step prediction method for calculation of ground-borne noise and building vibration induced by train pass-by has been proposed in this work. In the first step, the equivalent dynamic force applied to the tunnel invert has been computed using Vibrafer (CSTB) train-track model. In the second step the equivalent force is applied to a model of a tunnel-soil coupling system to obtain the soil surface vibration. In the third step, a statistical model based on transfer function for ground-foundation-floor vibrations is used to estimate ground-borne noise and vibrations at the second floor inside a building. Lastly this model is extended to the entire study area, which can include several thousand buildings for a 20 km metro line project.

The noise and vibration levels thus estimated on a large scale can be used to assess the impact of the project on neighboring buildings, and to check compliance with noise and vibration targets imposed by regulations or by the project owner's commitments.
When limit values are exceeded under operating conditions, vibration control measures can be defined and iteratively integrated into the model to define the appropriate control systems.
Exceedances of limit values in buildings close to the tunnel are commonly observed for tunnel configurations with less than 20 m rail depth, justifying the need for a reliable prediction tool with a high level of detail for underground rail projects. However, while this simplified tool can be used to identify areas where vibration is a major concern, it needs to be supplemented by detailed calculations in the case of foundations very close to the tunnel (less than 10 m).

7. REFERENCES

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