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Experimental and numerical study of the ground transmission of structure-borne sound generated by trams

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The increase of railway traffic in urban areas leads to developments in modeling and understanding the propagation of structure borne sound through soil, foundation and structure. Vibration propagation through the ground is still not well known. The present paper focuses on the propagation of trams vibrations (20-250Hz) in the ground and the energy transmission to the structure. In the first part, calculations performed using a 2D code based on a FEM/BEM approach are compared to measurements performed on a test site. The railway excitation is produced with a vibrator in order to recreate a line of uncorrelated forces. Soil properties are evaluated by an analysis of surface waves. Both bending and in-plane waves are measured on the structure. The ratio of the soil velocity over the structure velocity is computed in order to evaluate the accuracy of the computation. A 2.5D computation is also performed in order to evaluate the effect of a point source on the velocity fields on the soil and on the structure. In the second part, a parametric study using the 2D code is performed on typical cases in order to evaluate the modification of vibration transmission from the ground to the foundation.

1 Introduction

For the last 30 years, lots of numerical methods have been developed in order to compute the ground borne noise generated by railways in buildings [1]. The problem of energy transmission between soil and structure (which is one part of the propagation path) has been evaluated by Boundary Element Method (BEM) [2], Finite Element Method (FEM) [3,4], Semi-analytical methods [5], mixed approaches (BEM/FEM) [6,7] or Finite Difference Time Domain [8]. For vibration propagation in urban areas, numerical methods are needed because of complex foundation geometries and buried structures (T-shaped foundation, pipes, cables, etc…). These codes have been used in particular configurations and gives poor results compared to measurements at mid-frequencies (50-250Hz). What's more, those codes are used in global approaches (from train to room), and can't be easily generalized to large areas because of the size of numerical problems. At last, a perfect soil-foundation contact is supposed on most of those codes, witch is not the case for real configurations. The aim of the work presented in this paper is to show the difference between a computation and measurement on a simplified track/foundation problem. A second goal of this work is to use a code to evaluate the importance of soil type and of configuration on the soil velocity in front of a building. In order to solve the first problem, a confrontation between measurement and computation, on a test site has been made. The second problem is treated by a parametric study on a 2D BEM/FEM code.

2 Measurements and modelization of the test site

2.1 Test Site

The test site was located at CSTB in Grenoble (France). It consisted of a concrete shoebox buried in soil. The upper wall of the structure was 1m high while the foundation wall was 2.5m high (see Fig. 1). It was 10m length and 5m wide. The thickness of the walls and the floor was 0.2m and foundations were T-shaped. The concrete blocs in front of the structure were at 4m away from it. The test site was away from any source of vibrations, and background noise was low (around 30dB (ref. $5x10^{-8}$ m/s)) enough to prevent any perturbation during measurements. Two measurement phases have been performed. The first one was focused on mean velocities and the second one was focused on the shape of the structure. During the first one, a small vibrator was used while during the second one it was a more powerful device (characteristics are given in Table 1).

Name	Force [daN]	Rotation [rpm]	Voltage [V]	Amperage [A]
Vibrator 1	183.4	3000	220-230 380-400	0.6/0.35
Vibrator 2	785.0	3000	220-230 380-400	1.5/0.85

Table 1 Vibrators configuration (manufacturer data).

During the first experiment, the vertical velocity of soil surface was evaluated by accelerometers placed on T-section steel beams (length 70cm). These beams were placed on three "measurement lines" in front of the structure (3m between lines). Three accelerometers were placed on each measurement line (see Fig. 1). Three other lines were plotted inside the structure. Again, three accelerometers were placed on each line. Here vertical and horizontal components were measured using aluminum cubes (dimension: 5cm; stiff but no mass). The first cube was glued on the top of the upper wall, the second 0.2m below the surface and the third 1.46m below the surface. During the second experiment, the soil velocity has been evaluated with only one accelerometer situated in the middle of the AB segment (see Fig. 1). Then, the structure velocity has been evaluated at 5 points placed on DF segment (one accelerometer every 60cm). Velocities were recorded for 2 minutes for each source position. Measurements were performed for constants source regimes.

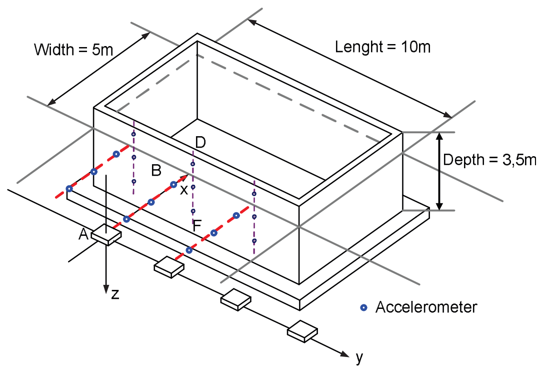

Fig.1 Schematic view of the test site.

2.2 Source

Previous works has been already performed on the test site. It was designed to evaluate the efficiency of a PSE layer between the soil and the structure to decrease the groundborne vibrations generated by railways. The source used in this study was a dropped mass (used in our study to perform SASW tests). The confrontation between computations, and measurements performed with this source was poor [9]. One of the reasons was supposed to be the impulsive nature of this source. Indeed, even if all the frequencies are supposed to be excited, the maximum excitation is located at 25-30Hz (third octave bands) and higher frequencies are not sufficiently excited to give reliable results. This problem can be solved by using a time-constant excitation. The solution chosen here is to use an industrial vibrator (electric motor coupled with an unbalanced mass) to generate vibration in the soil. This excitation is powerful enough to excite the structure even if the source is away from the structure. The main problem of this source is the impossibility to change its frequency. The vibrators generate 50Hz vibrations which is approximately the frequency where the trams generate the most of their power. They were faster to concrete blocs (see Fig. 1). Due to the vibrator technology, the power injected to the soil depends of the rotation velocity, so, the excitation at different frequencies would give rise to different power (the higher the frequency, the higher the power). What's more a higher velocity could induce larger forces and moments on the axis and the ball bearings, while slower velocity could damage coils.

2.3 Soil properties

Soil properties have been investigated by a Spectral Analysis of Surface Waves. This method is based on three properties of Raleigh waves: 1 – Energy propagation concentrated on one wavelength depth; 2 – Dispersive wave in layered soils; 3 – High frequencies waves have interactions with higher layers while low frequencies have interactions with deep layers too. The method is based on the determination of an experimental dispersion curve. This curve is obtained by signal processing the soil surface velocities obtained by impact excitations. Excitation is performed here by a dropped mass [9]. The procedure has been described by Foti, and Degrade and Clouteau [10, 11] and can be sketched in five steps: 1 - Computation of autospectrum and cross-spectrum; 2 - Computation of coherence function; 3 - Computation of phase cross power spectrum; 4 - Computation of delay between accelerometers; 5 - Computation of phase velocity between accelerometers. This procedure has been applied on our measurements and an experimental dispersion curve has been plotted (see Fig. 2). In order to find soil properties, an inversion operation has to be performed. This operation consists in adjusting properties and thicknesses of layers in a 2D semi-analytical code of vibration propagation, in order to find the experimental dispersion curve. Some automated inversion operation has been proposed [11] but in this study this operation has been performed manually.

The map plotted in Fig. 3 shows the computed velocity at the top of the multilayered soil. It had a 1m thick layer, lying on a half-space of one stiffer material. By plotting the velocities at fixed frequencies and analysing the maximum amplitude, the velocities of the Rayleigh wave can be adjusted. The results of the fit gives a layer of one meter (properties: $E = 32.85 \times 10^6$ Pa; $\rho = 1850$ kg/m^3; $\nu = 0.15$; $\eta = 0.06$) on a half space (properties: $E = 240 \times 10^6$ Pa; $\rho = 1900$ kg/m3; $\nu = 0.49$; $\eta = 0.05$). The computed velocities at 30, 40, 50, and 60Hz are respectively $c_{30} = 125$m/s; $c_{40} = 94$m/s; $c_{50} = 84$m/s; $c_{60} = 81$m/s. These velocities fit the experimental velocities (see Fig. 3) and will be used as soil properties for the 2D FEM/BEM code.

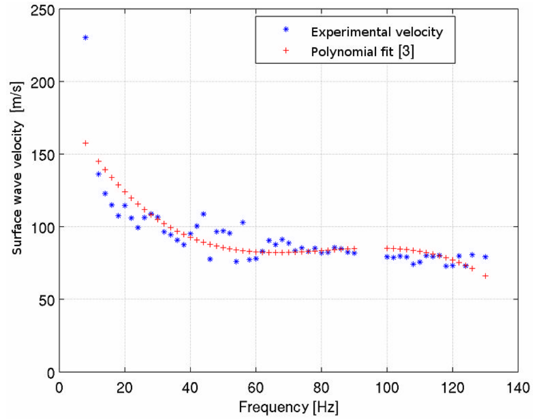

Fig. 2 Experimental dispersion curve and polynomial adjustment.

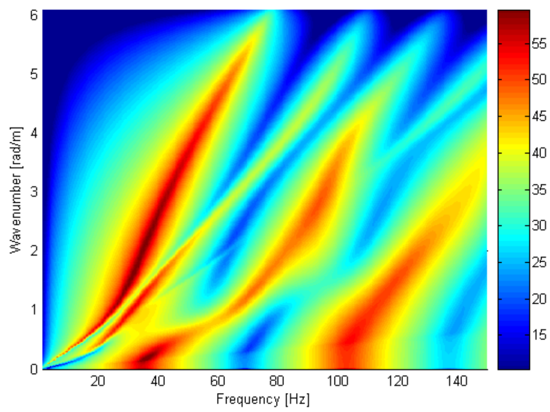

Fig. 3 Map wavelength/frequency (colour scale: vertical velocity [dB – ref. 5.10^{-8} m/s]).

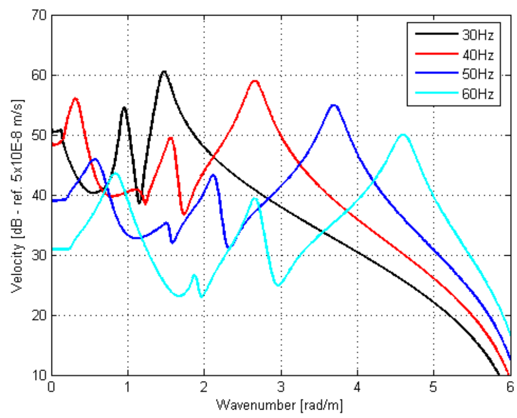

Fig. 4 Velocities in k_x domain at 30, 40, 50 and 60Hz.

2.4 Site modeling

The test site was modelled with a 2D code based on FEM/BEM formulation. As usual, the finite parts (concrete blocs, and structure) were modelled by the FEM formalism while soil layers of infinite extend was modelled by the BEM formalism (see Fig. 5). The BEM model extends to 10m before and after the domain presented in Fig. 4. The concrete bloc is excited by a point force applied at the boundary between the FEM and BEM domains (centre of

AB segment). The FEM and BEM domains are supposed to be perfectly bounded; more details on the formulation are given in [6, 7]. The meshing used for computations is given in Table 2.

Segment	AA'	AB	BC	DD'	DC	CE	EF	FG
2D	8	16	160	8	15	20	40	160
2.5D	8	33	40	8	30	40	40	160

Table 2 Meshing of the domain for two geometries: 2D, and 2.5D.

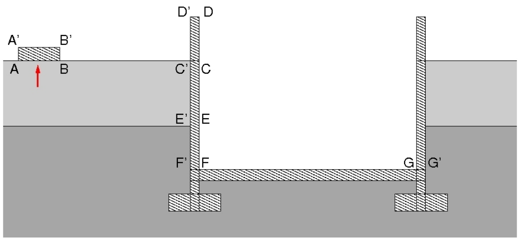

Fig. 5 Test site modelling.

A second modelling of the test site has been performed with a 2.5D BEM code. This approach supposes a 2D structure while the source is evaluated along y axis. It has the great advantage of suppressing source coherence of the 2D formulation with no excessive computation time. Details of the 2.5D formulation can be found in [9, 12]. This time, the entire domain was modelled by BEM. This formulation naturally induces some numerical difficulties since the solution depends of an inverse function of the relative distance between the source and the receiver. The relatively dense meshing used for 2D formulation has been reused. Some elements used to mesh structure floor have been used this time to mesh segments DF and AB. Intensive convergence tests have been done on the 2D model (FEM/BEM) and also on the 2.5D model (for $k_z = 0$). With this meshing, the same solution has been found for the two formulations (at 50Hz). The source meshing along the z axis has been performed according to remarks of [9]. So, the Δk_z has been chosen to 0.01 rad/m, so the maximal distance in real domain will be 314m. What's more the k_z domain extends to 5rad/m, so the spatial resolution will be 3m. Due to the important computation time, a single frequency of 50Hz (real source frequency) has been computed. The values computed at this frequency will be compared to third octave values (2D computation and measured).

3 Confrontation between computations and measurements

As first evaluation of the results, the computed and measured velocities have been compared. The measurements of the four concrete blocs have been summed in order to produce a line of uncorrelated sources:

$$L^{acc}_{vallblocs} = 10 \times \log_{10}\left(10^{\frac{L^{acc}_{vbloc1}}{10}} + 10^{\frac{L^{acc}_{vbloc2}}{10}} + 10^{\frac{L^{acc}_{vbloc3}}{10}} + 10^{\frac{L^{acc}_{vbloc4}}{10}}\right)$$

where : $L^{acc}_{vblocs} = 10 \times \log_{10}\left(\frac{< v^2_{acc} >}{v_0^2}\right)$ and $v_0 = 5 \times 10^{-8}\, m/s$.

The first comparison between measurements and computation has been made for a 2D modelization. Different material properties have been tested and are presented in Table 3. After a validation of the soil losses and the coherence of results in front of the structure, the mean velocities (computed and measured) on the segment BC' have been computed. The ratio of structure velocity (horizontal and vertical) on the soil vertical velocity has been evaluated. This ratio is then added to the measured averaged soil velocity and compared to velocity measurements on the structure. Figures 6 and 7, show 2D computations of horizontal (Fig. 6) and vertical (Fig. 7) velocity components for one layered soil (thickness 1m). Two measurements phases have been performed, the first one (Phase 1) is focused on the global behaviour of the structure, and the second one (Phase2) is focused on the determination of its shape. The difference at 1.5m for the two phases can be explained by the use of different vibrator (Vib. 1 for Phase 1 and Vib. 2 for Phase 2; see Table 1).

Material	E [Pa]	η	ρ [kg/m^3]	υ
Concrete	28 x 10^9	0.06	2400	0.15
Soil 1	32.85 x 10^6	0.06	1850	0.25
Soil 2	100 x 10^6	0.06	1500	0.15
Soil 3	240 x 10^6	0.06	1850	0.10
Soil 4	32.85 x 10^6	0.06	1850	0.25
	80 x 10^6	0.06	1850	0.15
Soil 5	32.85 x 10^6	0.06	1850	0.25
	100 x 10^6	0.06	1500	0.15
Soil 6	32.85 x 10^6	0.06	1850	0.25
	240 x 10^6	0.06	1850	0.10

Table 3 Material properties used in the FEM/BEM code.

This comparison (Fig. 6) shows quite big modal behaviours between measured and computed velocities. Nevertheless, the measured modal behaviour of the upper wall is computed and differences between the Phase 2 measurements and computations of soil 6 are less than 3dB for the buried structure. The agreement is better for vertical component is better (still considering soil 6), because the difference is now less than 2dB. One can see that different soil properties can induce large differences for vertical velocities. This behaviour has been investigated by the authors and one hypothesis to explain it is the presence of the strip footing foundation (see Fig. 5). Vibration of this element in the computation may involve important vertical velocity for specific soil properties; however, this explanation is not yet satisfying.

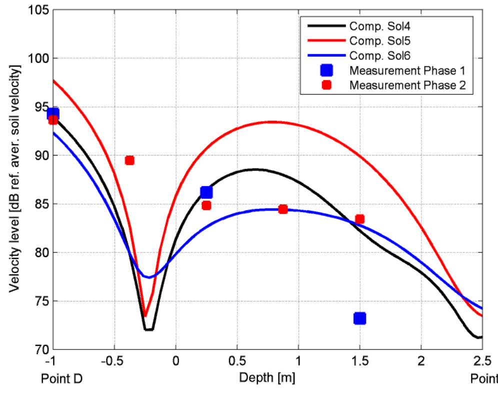

Fig. 6 Measured and computed velocities (2D horizontal) on the structure wall (one layered soil and half space modelization).

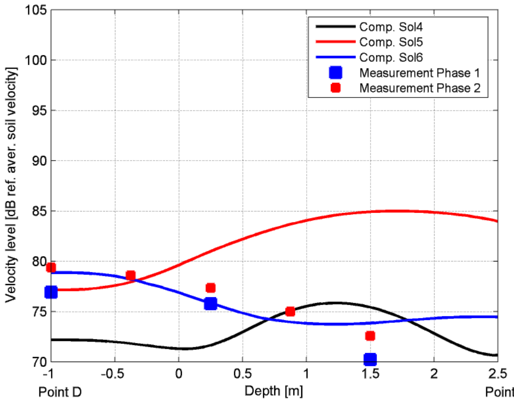

Fig. 7 Measured and computed velocities (2Dvertical) on the structure wall (one layered soil modelization).

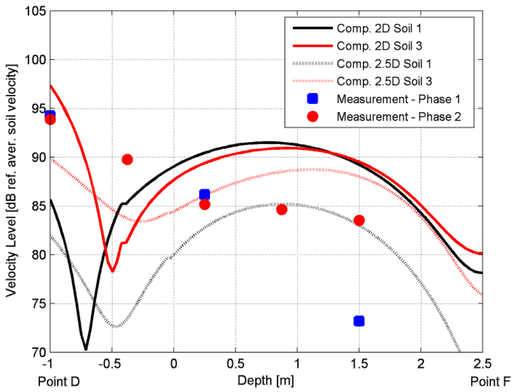

Fig. 8 Measured and computed velocities (2D and 2.5D horizontal) on the structure wall (half space modelization).

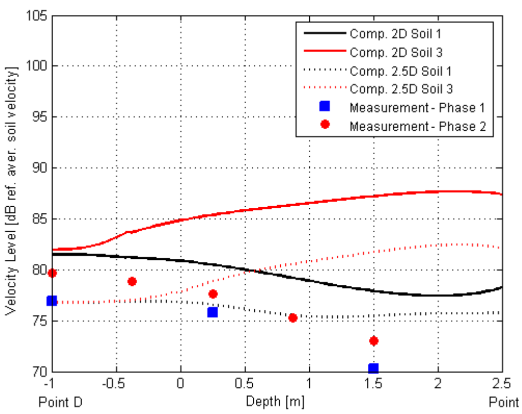

Fig. 9 Measured and computed velocities (2D and 2.5D vertical) on the structure wall (half space modelization).

The figures 8 and 9 show both computations in 2D and 2.5D for half space modelization. The 2.5D modelization reduces the modal behaviour of the structure (the source now, is not a line of coherent forces but a finite segment of forces). Despite of this, the agreement between 2D one layered soil computation and measurement is better than 2.5D half space computation and measurements, for both horizontal and vertical components.

4 Parametric study

4.1 Configurations

As shown in last section, the 2D code used to compute the velocity ratio between soil and structure gives results close to the reality. So, it has been used to evaluate the importance of soil properties (3 soils smooth to hard), foundation dimensions, on the soil and foundation velocities (see Fig. 10). The three soils are half space and their physical properties are: E_1 = 14.9x10^6 Pa, ρ_1 = 2000 kg/m^3; ν_1 = 0.49, η_1 = 0.06; E_2 = 108x10^6 Pa, ρ_2 = 1850 kg/m^3; ν_2 = 0.33; η_2 = 0.06; E_3 = 768x10^6 Pa, ρ_3 = 1800 kg/m^3; ν_3 = 0.33, η_3 = 0.06. The spread footing represents confined configurations found in real cases. The distance between the platform and the foundation is 3m and the foundations are 0.5 to 1.5m deep. This is typical for new residential buildings (see [13]). Three configurations A, B, C represent the three depths 0.5m, 1m, and 1.5m respectively. The results are given in dB ($L_v=20\times Log_{10}(v_{x,z}/v_o)$).

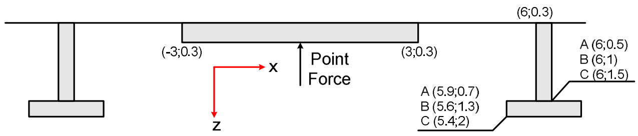

Fig. 10 Description of parametric study configurations.

4.2 Results

The comparison of vertical velocity of the soil between the track and the foundation is given on figure 11. It shows configuration A only (foundation depth 0.5m). The results are given for four third octave bands (31.5, 63, 100 and 200Hz). The results show a strong relation between soil properties and soil velocities. The standing wave between the track and the foundation (partially due to the 2D modelization) is more important for soft soil than hard soil. However, this modification of amplitude is certainly not measured in reality. The modification of this velocity for other foundation depths is given on figure 12. Again, it can be seen that the amplitude modification for others depths is very small.

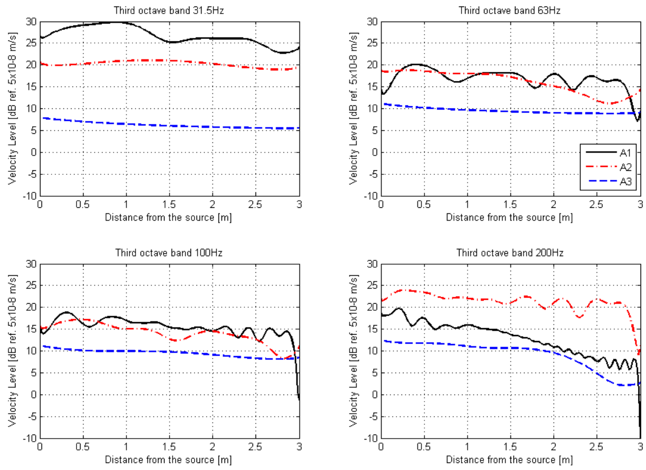

Fig. 11 Soil velocity (rms) of the soil between track and foundation.

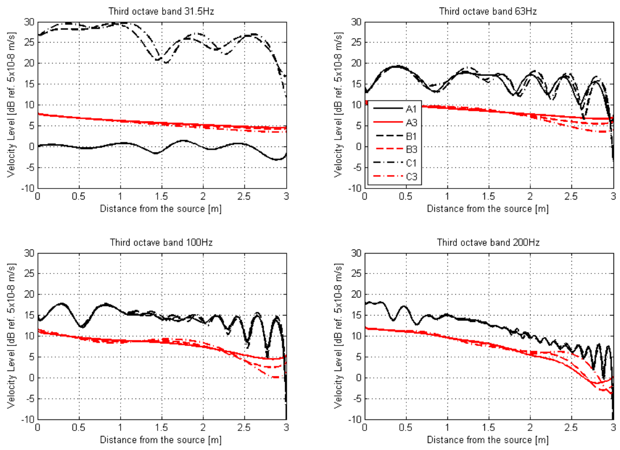

Fig 12 Soil velocity (rms) between track and foundation for 3 foundation depths and two soils (1 and 3).

The differences found for the hard soil are located near of the foundation, but are of the same order than the measurement precision seen before. So, the differences induced by deeper foundation are small compared to the measurement precision. Finally, other configurations (without left foundation, without footing strips, with upper wall) have been computed. The results (not presented) showed that these parameters have a slight influence on soil velocity, power flow injected to the foundation, and soil impedance.

5 Conclusion

A comparison between numerical simulation and measurements has been performed. This comparison was focused on the relation between soil and structure velocities. It has been showed that this relation computed by 2D FEM/BEM code gives large amplitudes witches are not present on our measurements. These amplitudes can be lowered using a 2.5D formulation (point source), but the results are strongly dependant of the soil parameter. Half space used in a 2.5D formulation and two-layered soil used in 2D formulation gives results of the same order. A parametric study performed with a 2D BEM/FEM code showed that the velocity level in front of the building is strongly dependent of soil type and that the deeper foundation does not influence the soil velocity in front of the foundation.

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