Radiated noise and vibration from underground structures using a 2.5D BEM-FEM approach

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Abstract
This paper presents a numerical method based on a two-and-a-half dimensional (2.5D) boundary element-finite element (BEM-FEM) coupled formulation to study noise and vibration from underground structures. The proposed model properly represents the soil-structure interaction problem and the radiated noise. The soil is modelled with the boundary element method, and the Green's function for a fluid-solid formation is taken as the fundamental solution to represent a solid half-space flattened by a fluid medium, which represents the soil and the air above the ground surface. The finite element method is used to represent structures and enclosed air volumes. The problem representation is limited to a soil-structure interface and the ground surface does not need to be discretised. Radiated noise and vibration are determined after the soil-structure interaction problem has been solved. We verify the proposed method by comparing the solution with an analytical solution for the wave propagation in a fluid-solid medium. Three examples are given to illustrate the noise and vibration radiated by tunnels. The results show that the soil-structure interaction influences the sound pressure field above the ground surface.

Keywords: 2.5D BEM-FEM, noise and vibration, tunnels, soil-structure interaction, fluid-structure interaction

PACS no. 43, 46

1 Introduction

In their efforts to achieve sustainable growth many countries have implemented an efficient transportation model to separate economic growth from the use of resources, with lower use of fuel and carbon based systems. Several areas have therefore been modernised, including connected urban and interurban train, metro, and tram systems. However, noise and vibration are among the commonest environmental impacts of mass transit solutions, which stem from different sources [1]. Transportation noise can indeed cause annoyance by disrupting sleep, interfering with communication, adversely affecting health and even adversely affecting academic performance. Some studies on general annoyance and activity disturbances show that train noise is more of a nuisance when there is simultaneous exposure to vibration. This is because it is difficult to distinguish between noise and vibration and this exacerbates the annoyance from noise [2,3]. Because transport noise pollution affects large numbers of people, railway infrastructure managers require an assessment of the disturbances caused by transport operation and their mitigation.

Ground-borne vibration and radiated noise from underground traffic is another major environmental concern in urban areas. The vibration propagates through the underground structure and the surrounding soil and it is perceived directly and sensed indirectly as radiated noise. Technically-supported decisions should be backed up by the accurate numerical modelling of acoustic and elastic waves.

For this, several numerical models based on two-and-a-half dimensional (2.5D) formulations have been proposed to account for the longitudinally invariant geometry of structures such as tunnels. These formulations compute the three-dimensional (3D) wave field from two-dimensional (2D) problems with different wavenumbers [4] to avoid the computationally expensive disadvantage of 3D formulations. Forrest and Hunt [5] are among the authors who have proposed a semi-analytical solution for the time-harmonic displacements of a tunnel modelled as an infinitely long, thin cylindrical shell, where the soil was represented as a homogeneous full-space. The coupled problem was solved in the frequency domain by Fourier decomposition into ring modes circumferentially and a Fourier transform into the wavenumber domain longitudinally. François et al. [7] presented a 2.5D coupled BEM-FEM methodology to compute the dynamic interaction between a layered soil and structures with longitudinally invariant geometry. This formulation uses a 2.5D Green's function for a layered half-space, thus there is no need to discretise the free surface and the layer interfaces. A regularised boundary integral equation is derived to avoid the evaluation of singular traction integrals. Later, Galvín et al. [8] used that formulation to predict railway induced vibrations in a tunnel embedded in a layered half-space. Moreover, Gupta et al. [6] proposed a coupled periodic BEM-FEM approach, where a boundary element method is used for the soil and a finite element method for the tunnel. The tunnel periodicity is handled by the Floquet transformation to formulate the tunnel-soil interaction problem in the frequency-wavenumber domain, and to compute the wave propagation field in the soil.

Many works suggest radiated noise should be computed assuming that the sound receiver has no effect on the vibration generation mechanism. Therefore, this simplification allows the decoupling of the incident wave field and the radiated noise. Following this procedure, Nagy et al. [9] proposed a Rayleigh integral-based method combined with the FEM to predict radiated noise in buildings from underground railway traffic. This model was experimentally validated in a building close to a railway line in Paris and maximum sound pressure level was found to be $75\,dB$. Fiala et al. [10] also suggested a numerical model to study vibrations and radiated noise caused by underground railways. This model solves the soil-structure interaction problem with a BEM-FEM coupled formulation using the Green's function for the layered half-space. The acoustic radiation problem is then computed assuming weak coupling between structural and acoustic waves. An acoustic spectral finite element method is used to predict the radiated noise. Tadeu et al. [11] subsequently modelled the acoustic attenuation provided by a barrier in an underground train station using a comprehensive coupled formulation based on the BEM and the method of fundamental solutions (MFS). In this case, the proposed method can compute the noise without the former simplifications. Recent publications have produced computationally feasible numerical models which can represent the ground-borne vibration at specific sites. Romero et al. [12] presented a 2.5D BEM-FEM model to study noise and vibration within a tunnel embedded in an unbounded solid due to a moving load. They used the BEM for the full-space fundamental solution in elastodynamic and the FEM in fluid-acoustics and elastodynamics. The results showed that the tunnel displacement and the air pressure inside the tunnel increase with the load speed according to the regime defined by the wave propagation velocity in each medium. The same behaviour was observed in the unbounded solid. However, to the best of our knowledge the radiated noise and vibration at the soil surface from underground structures has been not studied using a coupled formulation.

This work describes a novel numerical model that can handle the above mentioned problem. The model takes a domain decomposition approach to study fluid acoustics and solid scattering waves in a half-space medium with an innovative BEM technique. The BEM formulation consider, as fundamental solution, a problem where a formation composed of an elastic solid medium bounded by an acoustic fluid medium that can be the soil as well the air above the ground surface. Therefore, the discretisation of the fluid-solid interface is not needed and only soil-structure interfaces are modelled. The proposed methodology is used to study the acoustic and elastic scattered wave field inside underground structures, within the soil, and above the ground surface.

2 Numerical model

The numerical model is based on a coupled BEM-FEM formulation (Figure 1). The underground structure, composed by solid (Ω_s) and fluid (Ω_f) enclosures, is represented by the FEM. The interface between both enclosures is denoted as Γ_q . The soil domain ($\Omega_{s\infty}$) and the air above the ground surface ($\Omega_{f\infty}$) are described by the BEM. The Green's function for a fluid-solid formation presented by Tadeu and António [13] is used as fundamental solution in the BEM. Therefore, the boundary element discretisation is limited to the limiting interface between the soil and the structure (Γ_o). The coupled BEM-FEM formulation is addressed by imposing proper conditions at both interfaces, the fluid-structure (Γ_q) and the soil-structure (Γ_o) interfaces. The radiated wave field is computed once the displacement and traction solutions at Γ_o are known.

The 2.5D formulation computes the 3D solution in the frequency domain, assuming that the problem is invariant in the longitudinal direction z, as the superposition of 2D problems with a different longitudinal wavenumber (k_z) in the z direction. An inverse Fourier transform is used to compute the 3D solution at a point **x**(x,y,z).

3 Radiated noise and vibration generated by a tunnel

This example analyses the noise and vibration field radiated from a tunnel embedded in a homogeneous half-space (Figure 8). Soil displacements and the sound pressure level inside the tunnel and above the ground surface due to a harmonic load $P=2\pi N$ are studied for a maximum frequency range of $f_{max}=250\,Hz$. The soil response of this problem has previously been studied by Gupta et al. [22]. This reference has been given to verify the conclusions obtained with the proposed methodology.

The tunnel is at depth $d=20\,m$, has radius $r=3.0\,m$ and wall thickness $t=0.3\,m$. The lining has concrete properties with Young's modulus $E=35\times10^9\,N/m^2$, Poisson's ratio $\nu=0.25$, and density $\rho=2500\,kg/m^3$. The soil has a P-wave propagation velocity $c_p=500\,m/s$, an S-wave propagation velocity $c_s=250\,m/s$, and a density $\rho_s=1750\,kg/m^3$. The sound propagation velocity is $c_f=340\,m/s$, and the air density takes a value of $\rho_f=1.22\,kg/m^3$. The analysis was carried out in the frequency-wavenumber domain for frequencies ranging from $2\,Hz$ to $250\,Hz$, with a frequency step of $2\,Hz$.

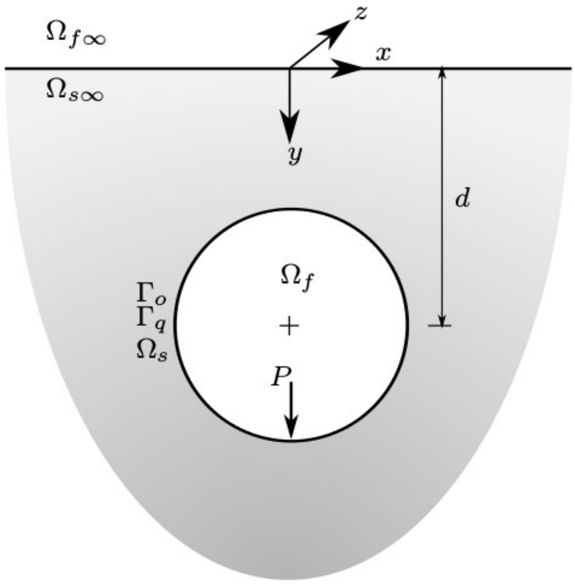

Figure 8: Definition of tunnel and subdomains.

The tunnel lining is represented with 216 shell finite elements (Ω_s), and the discretisation matches with the boundary element mesh used for the soil-structure interface (Γ_o), as well as the fluid-structure interface (Γ_q). The air volume inside the tunnel (Ω_f) is represented with 9562 fluid finite elements [12], allowing the representation of wavelengths with at least 6 elements.

Figure 9 shows vertical displacements and sound pressure levels at three observation points on the ground surface ($y=0\,m$), at different distances from the tunnel axis: $x=0\,m$, $x=4\,m$, and $x=16\,m$. The frequency content has an undulating behaviour because different waves are propagating through the fluid-solid formation, and the frequency step between subsequent undulations becomes lower as the distance of the observation point increases, but remains uniform in the frequency range. The Green's function for the fluid-solid formation is also represented in this figure to show that differences between the field radiated by the tunnel and the fluid-solid formation behaviour are due to the waves scattered by the structure. The mismatch becomes more significant as fluid-solid wavelengths are smaller than the tunnel size. These results are consistent with those reported in Reference [22] for the soil response.

Vertical soil displacement and sound pressure level distribution, both inside the tunnel and above the ground surface, are represented in Figure ref{tunnel4} for frequencies of $10\,Hz$ and $80\,Hz$. Results were computed at a grid of 7141 receivers equally spaced, and the 3D solution was computed afterwards. Maximum displacements were found around the tunnel invert according to the soil wavelength. A shadowed part is observed above the tunnel where the response is lower. Moreover, the sound pressure distribution is defined by the fluid-momentum relation, which links fluid pressure with soil displacement. Therefore, radiated waves at the free field show a maximum above the tunnel, and the maximum inside the tunnel is found around the lining. Fluid wavelengths are longer than those in the solid, according to the wave propagation velocity in each medium.

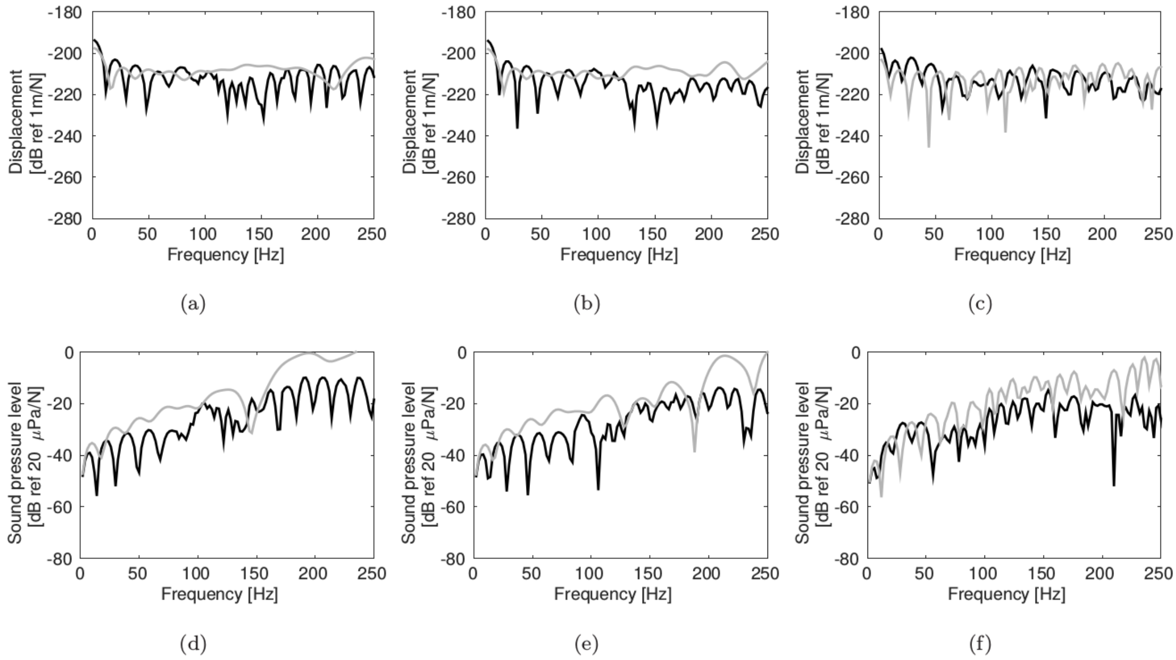

Figure 9: (a-c) Vertical displacement (black line), and (d-f) sound pressure level (black line), at points on the ground surface with (a,d) $x = 0\,\mathrm{m}$, (b,e) $x = 4\,\mathrm{m}$, and (c,f) $x = 16\,\mathrm{m}$ due to a load acting at the tunnel invert. The analytical solution for a homogeneous fluid-solid formation [13] is also represented (grey line).

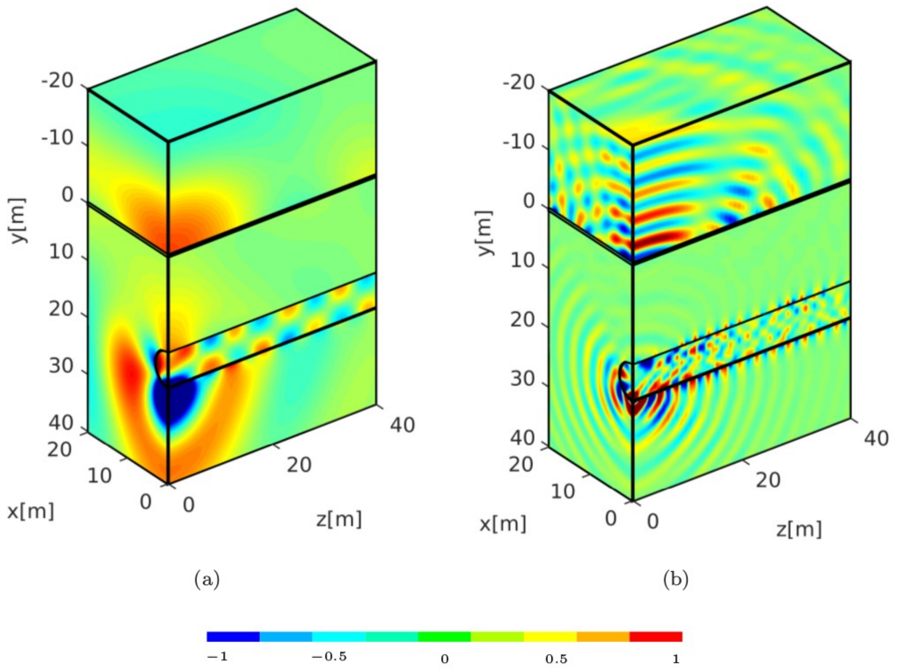

Figure 10: Real part of tunnel and soil vertical displacements ($\times 10^7$ m), and sound pressure inside the tunnel ($\times 10^2$ Pa at 10 Hz and $\times 10^1$ Pa at 80 Hz) and above ground surface ($\times 10^3$ Pa), produced by a point load of (a) 10 Hz and (b) 80 Hz acting on the tunnel invert.

4 Noise radiated from an underground train station with acoustic insulation

The last application examines the noise radiated by an underground railway station (Figure 14) that has an acoustic barrier that separates the two railway tracks. An acoustic point pressure load, located at $S_0(-2,14)$ simulates the noise of a passing train. This example was proposed by Tadeu et al. [11] for an unbounded domain to study the sound wave propagation inside the station in 2D cases. We have extended the problem to evaluate the influence of an acoustic barrier on the free-field radiated noise.

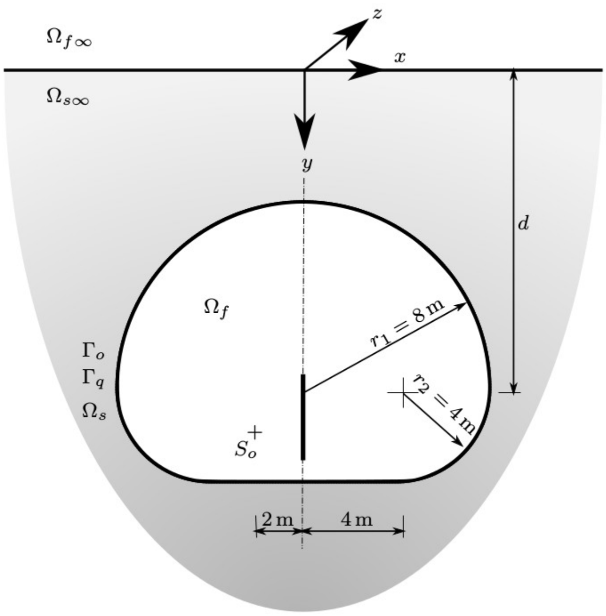

Figure 14: Diagram of underground station and definition of subdomains

The station is at a depth $d=12\,m$ and the geometry can be found in Figure 14. The structure has a concrete wall of thickness $t=0.3\,m$, Young's modulus $E=50\times10^9\,N/m^2$, Poisson's ratio $\nu=0.3$, and density $\rho=2500\,kg/m^3$. The soil has a P-wave propagation velocity $c_p=500\,m/s$, an S-wave propagation velocity $c_s=250\,m/s$, and a density $\rho_s=1750\,kg/m^3$. The air takes sound propagation velocity $c_f=340\,m/s$, and density $\rho_f=1.22\,kg/m^3$. The acoustic barrier was assumed to be rigid, and $3.5\,m$ long, and it was modelled as a discontinuity for the air volume Ω_f. There is a gap of $1\,m$ exists between the station invert and the barrier.

The vibration and radiated noise produced by a moving pressure load $P=2\pi\,Pa$ acting at point S_o are analysed next. This load reproduces a harmonic moving source travelling in the z direction at speed $c_f=\omega/k_z$. The solution was computed for a frequency range from $2\,Hz$ to $512\,Hz$, with a frequency step of $2\,Hz$. Each frequency step was solved for a wavenumber defined by the load speed. The characteristic element size enabled the minimum wavelength to be suitably represented with at least six elements.

Figure ref{estacion1} compares the sound pressure distribution inside the station with and without the insulation barrier at the cross section defined by the coordinate plane $y=12\,m$. The pressure distribution was represented for the time when the load passes at $z=0\,m$. Time solutions were obtained by applying an inverse Fourier transform to the frequency response, when the source is assumed to be represented as a Ricker wavelet with a characteristic frequency of $145\,Hz$ [11]. The sound pressure fields exhibit a typical Mach cone and many differences between the two cases were found, due to the presence of the barrier. The acoustic screen induced several wave reflections at the station wall and at the barrier.

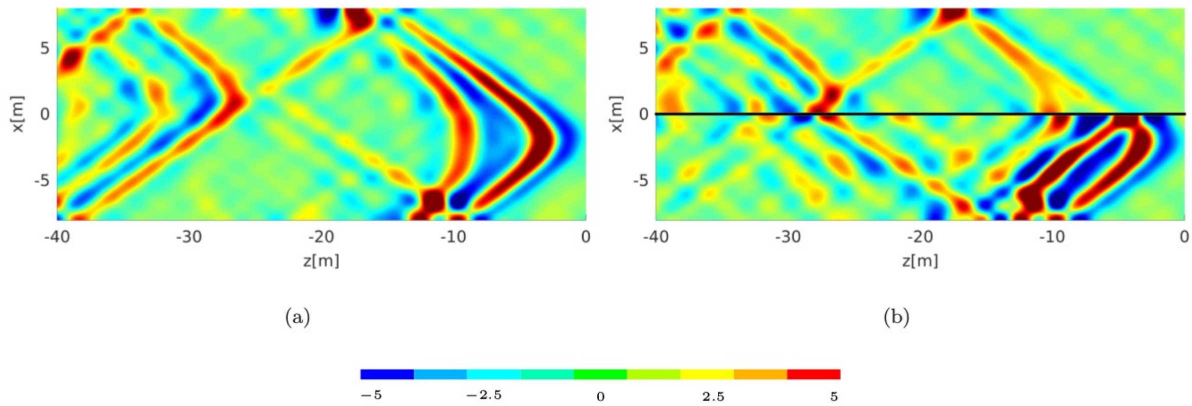

Figure 15: Radiated noise inside the station at a plane defined by the coordinate $y = 12\,\mathrm{m}$, due to a moving load travelling at $v = c_f$, (a) without acoustic barrier, and (b) with acoustic barrier (black line).

The free-field radiated noise is due to ground-borne vibration defined by the stated boundary conditions at soil surface. The sound pressure changes after the insertion of the acoustic barrier, as can be seen in Figure 16, and so does the soil displacement (Figure 17). The barrier redistributes displacements and tractions at the soil-structure interface and this modifies the wave field at the ground surface. The arrival time of S waves gives a spatial delay of $18\,m$ in the displacements and sound pressure field.

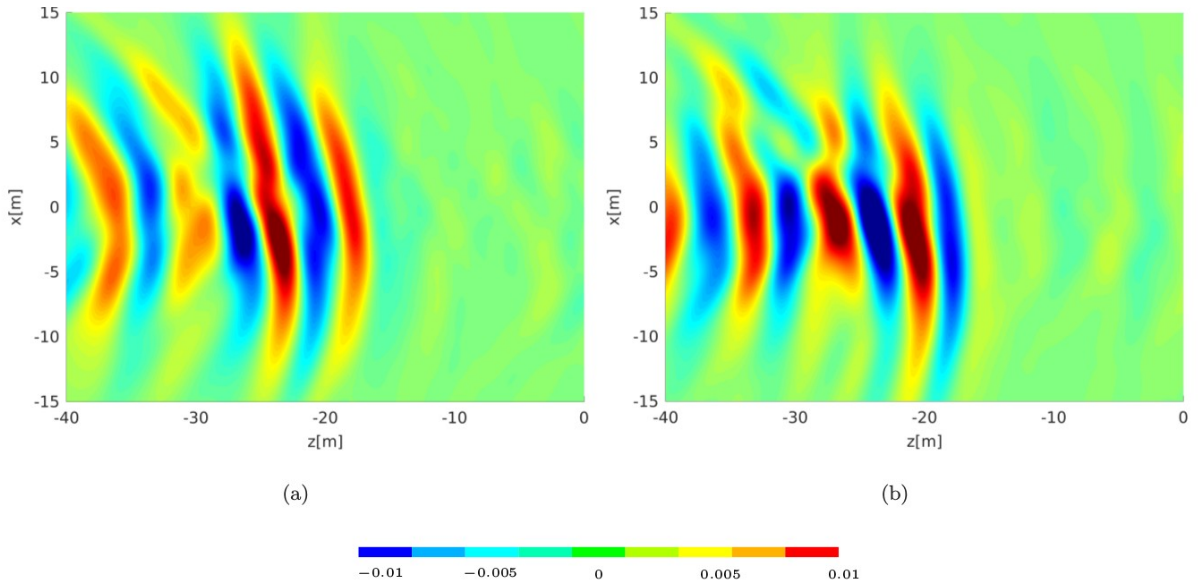

Figure 16: Radiated noise at the soil surface due to a moving load travelling at $v = c_f$ (a) without acoustic barrier, and (b) with acoustic barrier.

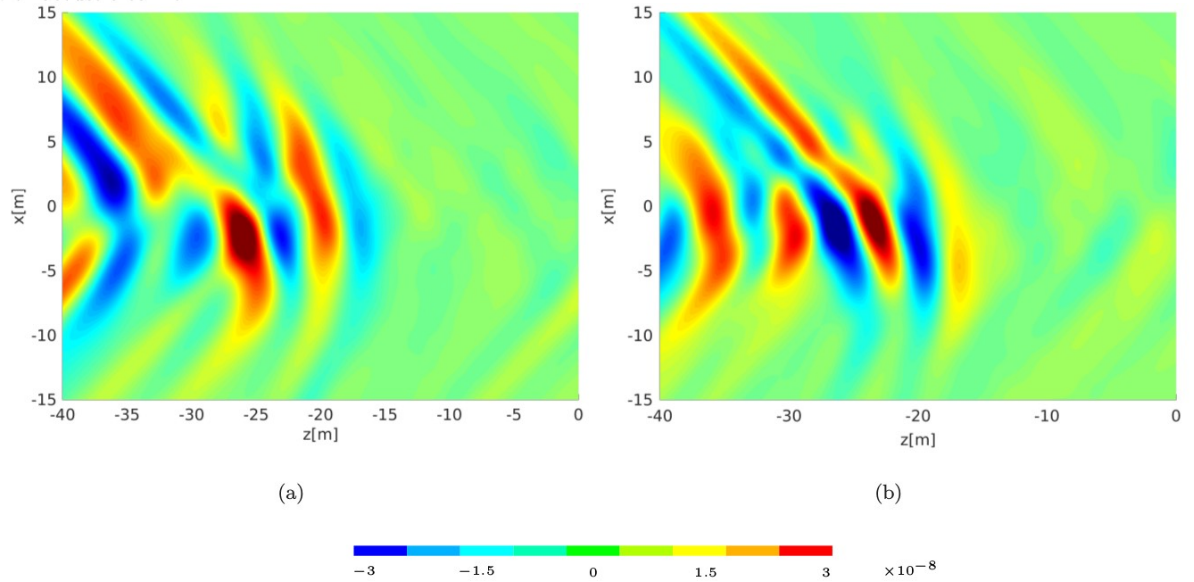

Figure 17: Vertical displacement at the soil surface, due to a moving load travelling at $v = c_f$, (a) without acoustic barrier, and (b) with acoustic barrier.

5 Conclusions

This work has proposed a BEM-FEM formulation to study fluid and solid wave scattering in half-space formations. The method was formulated in 2.5D but is suitable for 3D problems whose material and geometric properties are homogeneous in one direction. The proposed model has been developed to analyse the acoustic and elastic wave propagation from underground structures. The FEM modelling structures and enclosed fluid subdomains, while the BEM represents the soil-structure interface. The model was verified through a benchmark problem with a known analytical solution, and numerical results were in good agreement with the reference solution.

The main practical application of the method is the analysis of the noise and vibration radiated from tunnels, with a comprehensive formulation that predicts both sound pressure and soil displacement. Three examples were given that show the free-field radiated noise dependence on the scattered waves within the soil. The solution of the problem shows that:

a) When a single tunnel is studied, the radiated wave field shows wavelengths according to soil and sound wave propagation velocity. A shadowed cone zone is found above the tunnel where soil displacements are lower. The wave field scattered by the tunnel is more important for wavelengths shorter than the tunnel size.
b) Any modification of the pressure distribution inside structures involves a variation of both the pressure field at the ground surface and the soil displacements. This subject has been analysed in an underground station with an acoustic barrier, with the findings stated above.

These conclusions show that a fully coupled formulation is needed to accurately compute the noise and ground-borne vibration radiated from underground structures.

Acknowledgments

This work was framed within the POCI-01-0247-FEDER-003474 (coMMUTe) Project funded by Portugal 2020 through the Operational Programme for Competitiveness Factors (COMPETE 2020)”. This research was also funded by the Spanish Ministry of the Economy and Competitiveness (Ministerio de Econom'ia y Competitividad) through research project BIA2013-43085-P. Financial support is gratefully acknowledged. The authors also wish to acknowledge the support provided by the Andalusian Scientific Computing Centre (CICA).

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