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Dynamic Analysis and Modeling Movement Transmission of Soil Construction Interaction

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ABSTRACT

This paper defines the dynamic analysis and geometric demonstration of movement transmission and the dynamic soil-structure interaction using two different approaches: the finite component process and the limit component approach (EM). This mathematical process is an influential geometric approach right for dynamic tasks. In this item, we used very advanced and effective computer geometric converter approaches to study multifaceted difficulties. The fractional difference equation leading the motion is outcoming and resolved by EM. The influence of 3 dimensions on the movement transmission imitation (1D and 2D) has a conversed captivating effect, dependent on the different finite components kinds (triangles, rectangles, tall degree components). Geometric modeling of stifling is too discussed (Rayleigh checking). The finite component technique then treats a model of movement transmission owing to the vibration of a foundation. The limit component technique's capacities are remembered, and outcomes found through 2D and 3D mockups are planned. Numerous cases of dynamic soil-structure interaction (building, tunnel) are formerly pickled. The outcomes of these properties are discussed here.

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1. Introduction

The study of movement transmission is present in different subfields of civil engineering, such as earthquake engineering and vibration isolation. Movement transmission complications are characterized by means of different phenomena [1, 2]: distribution, curving, checking, movement category adaptations, etc. Altogether, these physical characteristics are seldom available directly by involvement. It is generally essential to practice typical research (model materials, small-scale tests [3, 4], etc.) or to use geometric computation and or inverse approaches [5, 6] to determine the parameters characterizing the material and the movements which propagate there. The validation of the movement transmission calculations can be carried out by comparing the geometric outcomes with experimental outcomes. However, the joint determination of the parameters of material behavior and the physical characteristics of the movement transmission is a more complex task. The authentication of geometric movement transmission models permitting investigative resolutions is also possible in the case of simple geometry and behavioral media. Several geometric approaches are available to simulate the phenomena of movement transmission: finite differences [7, 8], finite components [9, 10], border components [11, 12], and spectral components [13, 14]. These geometric approaches have their advantages and limitations, as mentioned ahead. The finite component approach is very powerful due to its capability to handle different geometries and behaviors. However, it also has two main drawbacks related to movement transmission: the reflection of spurious movements on the boundaries of the mesh domain and the digital distribution of the movements. The digital distribution causes a synthetic variation of the movement transmission speed according to the characteristics of the finite component model. These two aspects of digital finite component modeling of movement transmission will be discussed in the outcomes.

The limit part technique has the improvement of permitting easy modeling of the transmission of movements in a countless or semi-countless medium. The radiation settings at boundless movements are directly involved in the design. Furthermore, the margin component technique solves the complications at the boundaries between media of similar characteristics: it is consequently limited to somewhat heterogeneous media. However, it permits a significant gain for modeling the level transmission (1-dimensional boundaries) or 3-dimensional (surface boundaries).

The request for this process for the transmission of seismic movements in alluvial formations will be discussed in this work. In command to advantage from the rewards of these two approaches, it possibly will be interesting to associate them (coupling of finite components to integral equations [12].

2. Movement Transmission Modeling by Finite Components

In a linear viscoelastic medium, the 1-dimensional movement equation can be expressed in the frequency domain as follows:

$$\frac{\delta^2 u(x,\omega)}{\delta x^2} + \frac{\rho\omega^2}{E^*(\omega)} u(x,\omega) = 0 \quad (1)$$

Where u is the displacement, x the distance, ω the pulsation, ρ the density, and E*(ω) the complex module [1, 15]. The resolution to the complication can then take the following form (10):

$$u(x,\omega) = u(0,\omega).\exp(ik^*(\omega)x) \quad (2)$$

where k* (ω) is the complex movement number such that:

$$k^*(\omega) = \frac{\omega}{c(\omega)} + ia(\omega) \quad (3)$$

Besides the shift period of the first classical phase, this composite movement quantity includes another imagined checking period. These two relations, i.e., phase shift and checking, are contingent *a priori* on the frequency. The necessity between the phase speed c (ω) and the rate reflects the material distribution within the medium [1,10]. From the geometric point of view, these two properties have their equivalents, often called digital distribution and digital checking. The digital distribution makes the movement transmission speed dependent on the model characteristics (time incorporation system, dimension, and category of the basics). Geometric stifling corresponds to the same category of dependence with regard to the largeness of the movement [16].

2.1. Digital Distribution

In the field of structural dynamics, two kinds of mathematical mistakes can be studied [16]: on the one hand, the relative period mistake related to the assessment of the vibration period of the construction and, on the other hand, the algorithmic checking corresponding to a synthetic discount in largeness owing to chastely digital checking. It is likely to study and calculate these mathematical mistakes. The relative period mistake can differ depending on the time addition scheme considered [16]. For movement transmission complications, the relative period mistake looks through the assessment of the transmission speed and is called geometric dispersal. The transmission of a movement in an assumed digital system is contingent, for illustration, on the dimension of the components, the integration system, the category of component, etc. This phenomenon is named geometric distribution in reference to the physical distribution, which makes transmission speed dependent on the frequency [9-10]. The transmission phenomena can be difficult to typical, depending on the finite variances or finite components since the geometric mistake tends to increase through the transmission of the movement.

The geometric outcome of equation (1) can be written in a form similar to that of the theoretic resolution (2):

$$u_h(x,\omega) = u(0,\omega).exp(ik_h(\omega)x) \quad (4)$$

Where u_h and k_h are the displacement and the number of movements approached geometrically, respectively. Several theoretical works relate to the analysis of the mistake made in the geometric estimate of k_h compared to the theoretical movement number k [17, 18]. Ihlenburg and Babuška [18] suggest, in the case of finite components with linear interpolation, the following relation:

$$cosk_h h = \frac{1 - K^2/3}{1 + K^2/6} \quad (5)$$

Where K is the normalized frequency depending on the theoretical movement number k in the form: K = k X h = ω_h / c.

Expression (5) demonstrates that the geometric resolution of equation (1) links to a transmission phenomenon only for the normalized frequencies lower than the cutoff frequency K_0 [18]. On the other hand, intended for these frequency values, the geometric movement propagates earlier or slower than the theoretic resolution. Consequently, it is required to investigate the digital distribution of the movements and quantify the outcome of digital mistakes.

2.2. Digital Distribution Assessment: 1D and 2D Cases

On the way to study the geometric mistake in movement transmission complications, we first consider a 1-dimensional case where the average is similar, flexible, linear, and isotropic (no physical distribution). Table **1** displays the number of components of the 1-dimensional model in each case and the equivalent component dimension Δh. In the previous column, the ratio Δh / π characterizes the regularized component dimension associated with the movement length π.

Table 1: The fineness of the mesh and dimension/movement length ratio for the different cases calculated.

Number of Components	50	100	200	250	500	800
Item size Δh	2 m	1 m	0.5 m	0.33 m	0.25 m	0.125 m
Report Δh/λ	2/5	1/5	1/10	1/15	1/20	1/40

Figure **1** gives the shape of the movement at different periods through the transmission in each case obtainable in Table **1**. These curves evidently show that the components' dimension considerably influences the geometric mistake. The coarse meshes are responsible for mathematical consequences that undervalue the size while also misjudging the speeds (of cluster and period). This is the functional importance of digital distribution, which may be minimised by choosing a component dimension that is more suited to the complicationatic movement length. The dimension of the components is conservatively occupied to be tenth or twentieth of the movement length. Though, as displayed in Figure **1**, in cases 3 (200 components, Δh / π = 1/10) and 5 (400 components, Δh / π = 1/20), the geometric mistake becomes important again beyond a transmission distance of approximately 5 π to 10 π. On the other hand, the geometric mistake is practically zero for case 6 (800 components, Δh / π = 1/40).

The appreciation of the phenomena of geometric distribution is simple in the 1-dimensional case. In 2 dimensions, these phenomena are more delicate to evaluate. As Bamberger *et al*. [17] specify, in addition to the mechanical characteristics of the transmission medium, it is required to take into account the movement category, the angle of incidence, and the mesh geometry (triangles, quadrilaterals). Distribution relations are suggested by Bamberger *et al*. [17] and Ihlenburg and Babuška [18] for different categories of discretization. The investigative expressions of digital movement's phase and group velocities are assumed for numerous categories of movements [17]. Using these distribution relations, we generated the curves shown in Figure **2**, which give the dimensionless phase velocities of the P movements and the S movements in a 2-dimensional mesh. The dimensionless phase speed is the ratio between the speed of digital movements and the theoretical phase speed. Figure **2** resembles quadrangular components with a linear exclamation. After the qualitative example of the earlier paragraph, these outcomes agree with the geometric mistake to be quantified as a purpose of the ratio of mesh dimension to movement length for different values of angle of occurrence.

Agreeing to the curves of Figure **2**, it is possible to find some simple conclusions for the grids with quadrilateral components:

- The geometric distribution (and therefore the geometric mistake) is more important as the mesh size is large (compared to the movement length).
- The mistake is maximum for zero incidences (up to 40% in P movement and 50% in S movement) and minimum for incidence at 45 degrees (for this particular digital diagram).
- Intended for low mesh dimension values, the P movements are more sensitive to the angle of incidence than the S movements.

The usual of these outcomes is assumed for a Poisson ratio ν = 0.25 and for a given value of the ratio Δ = Δt/Dt* = 1 with $\Delta t^* = \Delta h / \sqrt{v_P^2 + v_S^2}$ (Δt is the time step used for computation; V_P and V_S are correspondingly the celebrities of the movements P and S).

Designed for a mesh of triangular components (right triangles), the effect of the occurrence depends on whether the angle is positive or negative (there is no regularity). In the example of P movements, there is no numeral distribution for an incidence Ѳ = 45 degrees (constant phase velocity).

The angles of incidence giving the lowest geometric distribution are diverse for P movements and S movements [10,17].

3. The Efficiency of High Precision Finite Components

The mathematical distribution is similarly influenced by the degree of polynomial interpolation of the finite components measured. Finite components per a high degree of interpolation are identified for their excellent accuracy in elastoplastic calculations. In movement transmission, some theoretic mechanisms suggest investigative expressions for the geometric mistake expressed in relations of distribution [9, 17, 18]. Through an advanced degree of interpolation, finite components have mostly principal to a lower geometric distribution [20].

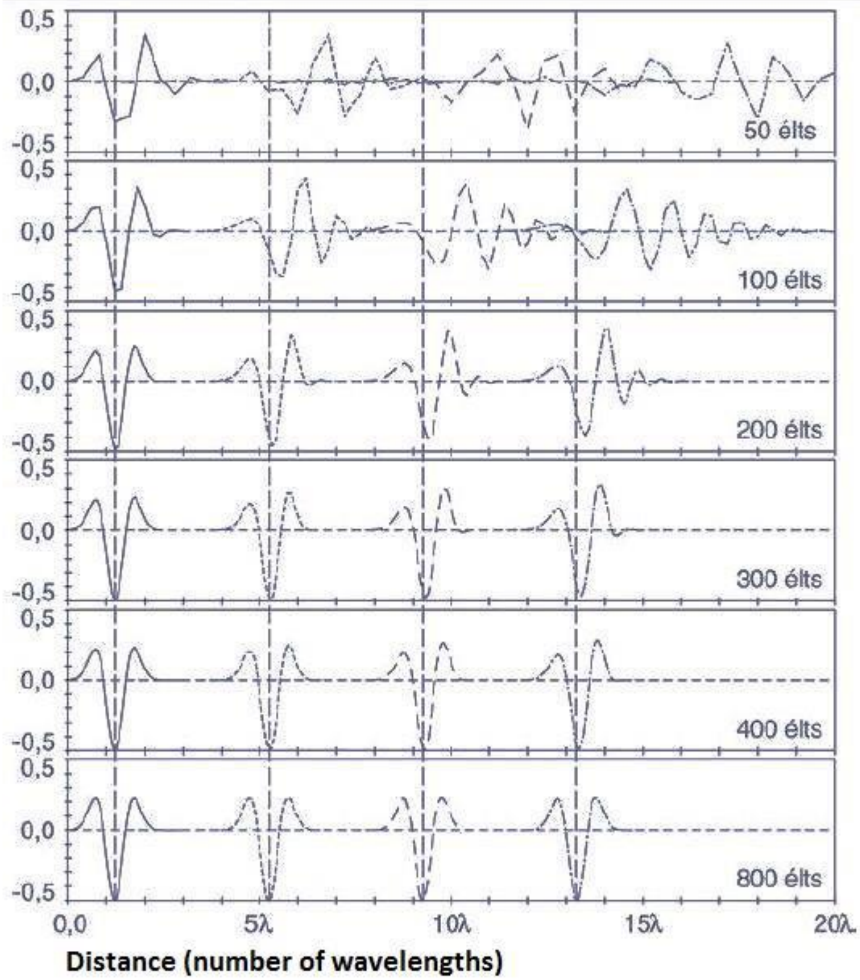

Figure 1: 1-dimensional digital distribution analysis for movement transmission complications (profile at different times).

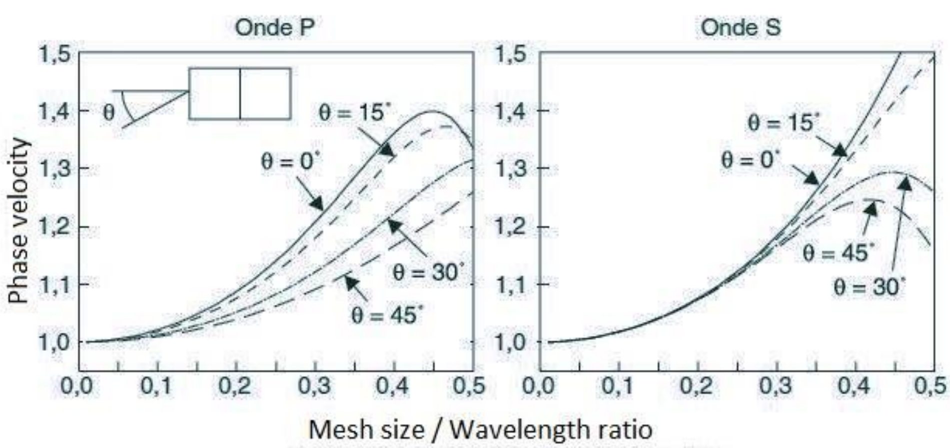

Figure 2: Geometric distribution of P and S movements (2D quadrilateral mesh), according to Bamberger *et al*. [17].

In order to compare the efficiency of finite components of different degrees of interpolation, an example of 1-dimensional movement transmission is calculated in detail in Semblat and Brioist [19]. Three different sorts of (triangular) components are measured: linear components with three bulges, quadratic components with six bulges, and components with fifteen bulges with a degree of interpolation equal to four [16]. For the evaluation to be illustrative, the number of components of all of the matching finite component meshes is selected so that the whole number of bulges in the direction of transmission is similar for the three categories of components [19]. It turns out that the proportionality of the number of components corresponds to the ratio between the degrees of interpolation of the three categories of components. The three meshes are made up of 80 linear components for the first (degree of interpolation: 1), 40 components for the second (degree of interpolation: 2), and 20 components for the third (degree of interpolation: 4). Thus, a mesh made up of components of a degree of interpolation twice higher will comprise half as many components for a total number of bulges in the identical direction of transmission. The outcomes obtained by Semblat and Brioist [19] display that the geometric distribution is very robust for the linear components (T3). The consequences are considerable for the quadratic components (T6), but the cumulative mistake becomes important beyond a certain distance. In the case of components with a high degree of interpolation (T15), the digital distribution is almost zero. With the number of matching bulges in the direction of transmission, the imitation using these components thus gives precise good outcomes. The efficiency of finite components with a great degree of interpolation with respect to digital distribution phenomena consequently looks brilliant.

4. Validation of Calculations in a Checking Environment

The study of transmission phenomena in a checking average requires implementing a suitable checking model. One of the checking models widely used in dynamics is the Rayleigh model, which contains constructing a checking matrix like the linear grouping of the mass and stiffness matrices [16, 21]. The main interest of this formulation is to lead to a diagonal checking matrix at the base of the real eigenmodes [22]. In movement transmission, this Rayleigh checking typically corresponds to a widespread Maxwell rheological model [23]. This equivalence makes it possible to validate the calculations of movement transmissions by finite components using logical or semi-investigative outcomes found with this rheological model. However, this endorsement is lone for low to moderate checking standards [23]. Similar investigative proofs can be done when the checking characteristics match those of a known rheological model. The curves in Figure **3** deliver a contrast of the investigative outcomes found from a widespread Maxwell model with the outcomes from finite component calculations counting Rayleigh checking. The coincidence between the two approaches is good when the checking factor does not exceed 20%. This rheological clarification of Rayleigh checking likewise lets informal determination of the two factors used in the formulation from behavioral parameters determined experimentally [23].

In the case of checking media, the movement distribution is both physical (due to checking) and digital (due to discretization). The authentication of movement transmission calculations has to consider these two aspects. Movement checking can mask the mistake due to digital distribution [10].

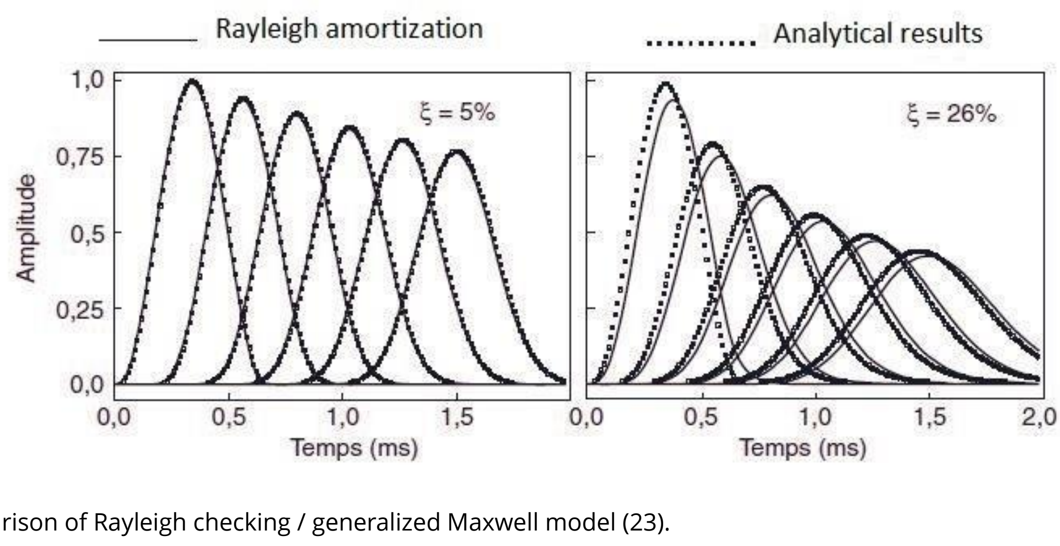

Figure 3: Comparison of Rayleigh checking / generalized Maxwell model (23).

5. Processing of Reflections at the Edges of the Model

Modeling the transmission of movements by finite components also needs to account for the limited circumstances of the complication. In fact, the transmission of seismic movements occurs in media of almost unlimited postponement (compared to the scale of analysis of the complication). Hence, it is fundamental to consider the conditions of radiation of the movements that outcome from it. In a finite component model, it is then needed to implement unusual behaviors within the bounds of the model (absorbing borders, unlimited components) in order to reduce the reflections of parasitic movements on the borders of the discretized domain [22, 24, 25].

5.1. Example: Transmission of Movements Due to the Vibration of a Foundation

Figure **4** presents the outcomes of a finite component modeling of the movement transmission due to the vibration of a foundation (DYNI module of CESAR-LCPC [26]). The finite component model is axisymmetric, includes 2,600 quadrilateral components, and the re-resolution is made by direct addition over the period.

In Figure **4**, the outcomes obtained at two different periods are characterized by two arrangements: movement diagrams (middle) and movement fields in the form of vectors (right). In period T2, the diagrams display the compression movements, which propagate faster, and the shear movements at a lower speed. In Figure **4**, the outcomes in the movement field (right) specify that, in an area near the surface, the movement describes an ellipse. This category of movement reflects the existence of Rayleigh movements, whose largeness declines fast with the depth [27].

A case of finite component modeling of the 3-dimensional movement transmission is proposed in Guéguen, *et al*. [28]; nevertheless, the components need to be minor to limit the geometric distribution, this category of imitation proves to be enormously expensive in calculation volume.

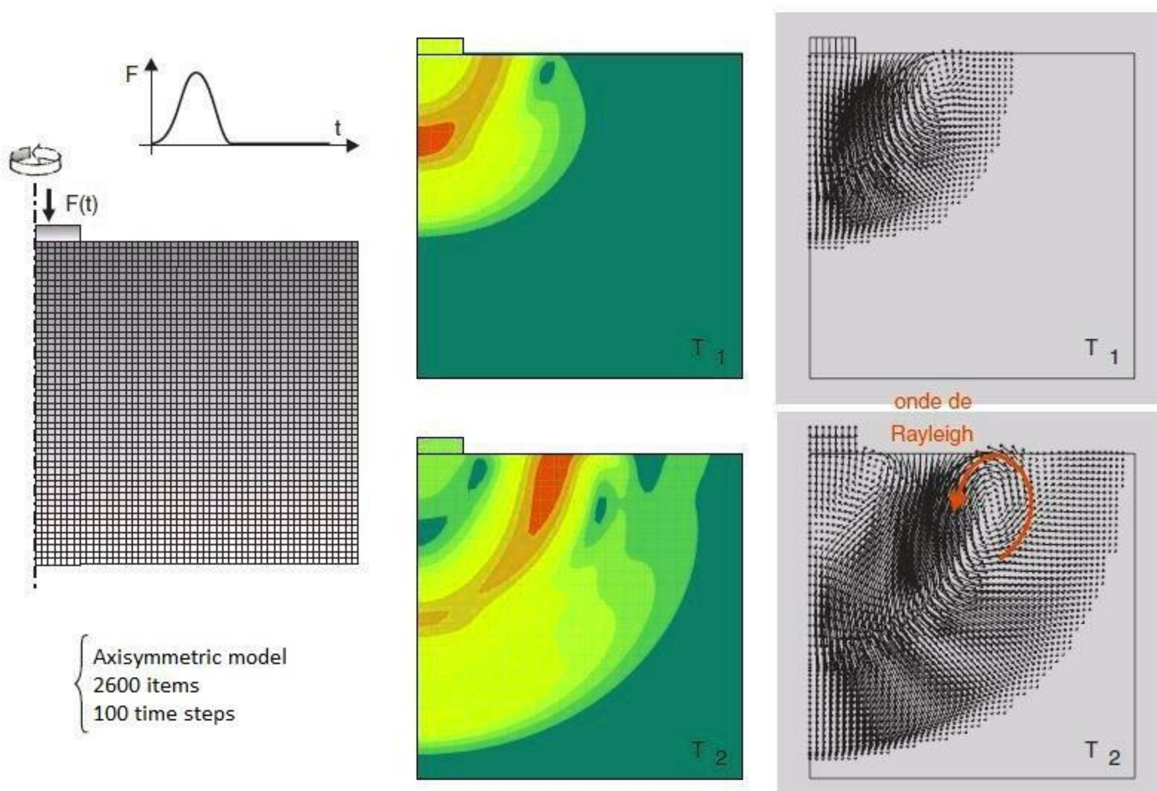

Figure 4: Finite component modeling of the movement transmission due to the vibration of a foundation (model (left), displacement s (center), and displacement field (right).

5.2. Digital Modeling of Movement Transmission by Integral Border Equations

In addition to the finite component approach, the limit component approach is mainly interesting for modeling the complications of movement transmission [11, 29, 30]. This approach is based on understanding componentry resolutions of elastodynamic equations in unlimited domains (resolutions known as Green's purposes). It makes it possible to overcome, completely or partly, parasitic reflection phenomena on the limits of the discretized domain. On the other hand, it needs the application of approaches to regularizing singular integrals [11, 31] and is improved in environments with a linear behavior. For applied applications, this approach permits, for example, complete modeling of seismic movement transmission in soil or even at the scale of an alluvial basin.

These approaches have been established in CESAR-LCPC for more than a few years now and make it possible to explain complications that are difficult to deal with a direct application of the finite component approach. Generally, the finite component approach and the essential border equation approach have very complementary specificities. Thus, it is possible to combine them to take advantage of their particular capabilities [12].

6. Authentication Built on an Investigative Resolution

The diffraction of a flat movement by a cylindrical cavity can, for example, be entirely categorized as investigative. In the case of a flat, SH movement propagating from left to right, Figure **5** gives (dotted lines), and the displacement calculated investigative [2] in several directions around the cavity. As for the geometric resolution of the complication (symbols) is carried out by the approach of border components in the frequency domain using the DYNF module of CESAR-LCPC [26]. As the limit component approach permits rigorously modeling the media of unlimited postponement, the investigative and geometric outcomes coincide perfectly.

Such a comparison would be more difficult to envisage with the finite component approach because it would require implementing particular techniques such as absorbing boundaries [22, 25, 32]. Validation in more general cases (complex geometry, heterogeneous environments, stress characteristics, etc.) can be extremely difficult. Validations for movement transmission complications in a heterogeneous medium [6], for the finite component approach, or in three dimensions [11], for the border component approach are available. A realistic analysis of the transmission of seismic movements is also proposed below.

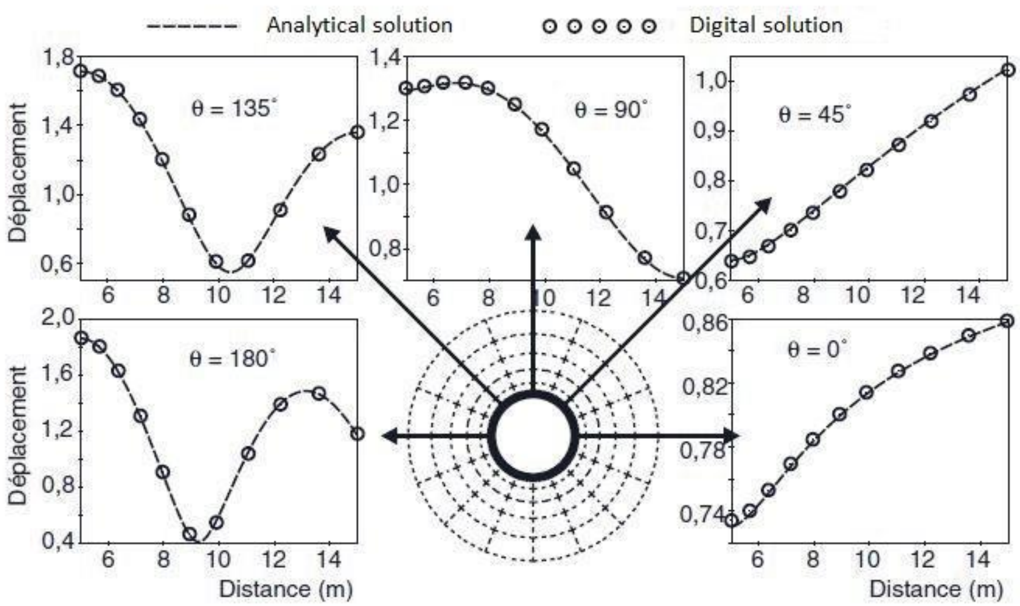

Figure 5: Diffraction of a flat movement SH by a cylindrical cavity: investigative/digital comparison (displacement values are related to the largeness of the incident movement and therefore dimensionless).

7. Transmission of Seismic Movements in a 2D Alluvial Basin

Through the limit component approach, the intensification of seismic movements (or "site effects") can be studied mathematically, taking into account the unlimited postponement of the transmission average. For these kinds of complications, it is crucial to resort to such approaches. The relevance of the digital outcomes can then be investigated from seismic recordings made in situ. The effects of seismic locations lead to a significant local intensification of the seismic movement [33, 34]. This intensification of the movement happens mainly in alluvial filling zones whose characteristics (geometry, mechanical properties) govern the extent of the phenomenon [35, 36].

In our case study, Figure **6** gives the s of the intensification factor in the filling and the substratum for different frequency values by considering an SH movement with vertical occurrence (weak movements). The intensification appears clearly on the surface of the filling, and it takes a maximum value of 15.0 for a frequency of 1.6 Hz. In the thickest part of the filling, the intensification is stronger. However, for the maximum frequency (f = 2.0 Hz), the intensification factor in the thinnest fill area increases meaningfully (shorter movement lengths at higher frequencies).

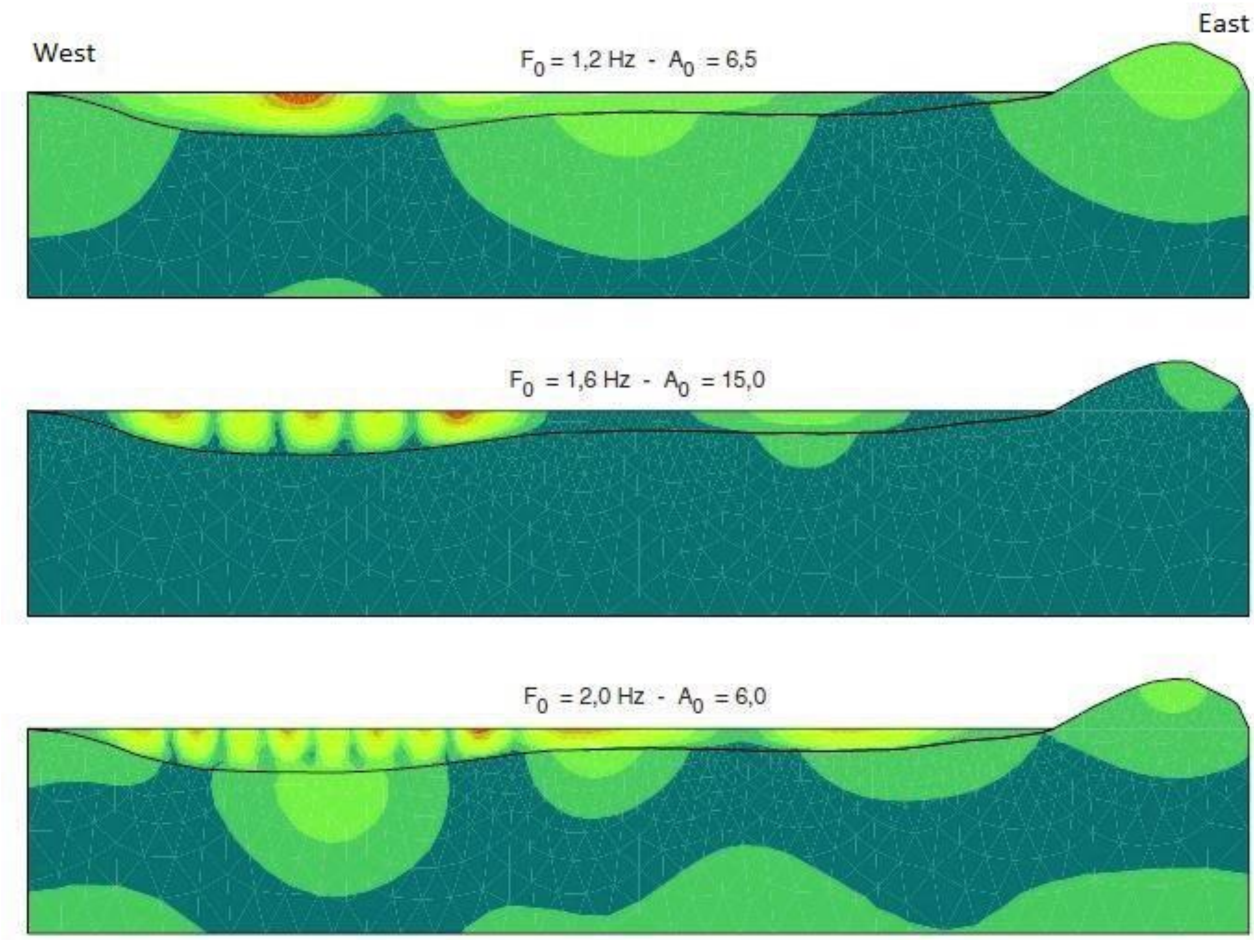

Figure 6: Modeling by border components of the intensification of seismic movements: intensification factor A0 at different frequencies F0 (from Semblat, *et al*. [37]).

The intensification-frequency curves measured on our study site are presented in Figure **7** (time zone of experimental measurements in gray, average value in thin line). For a homogeneous filling, the geometric outcomes obtained by the limit component approach using a 2-dimensional model [37] resemble three different shear modulus values (μ1, μ2, and μ3) of the surface layer. Geometric imitations accurately reproduce the intensification-frequency relationship, and the maximum intensification level is well estimated for the weakest shear modulus (μ3). From this 2-dimensional model, it is even possible, by considering different categories of seismic movement, to investigate the transmission of seismic movements in three directions in space: two planar movements and one anti-flat movement. The outcomes obtained in the case of our study area are very interesting from this point of view [37].

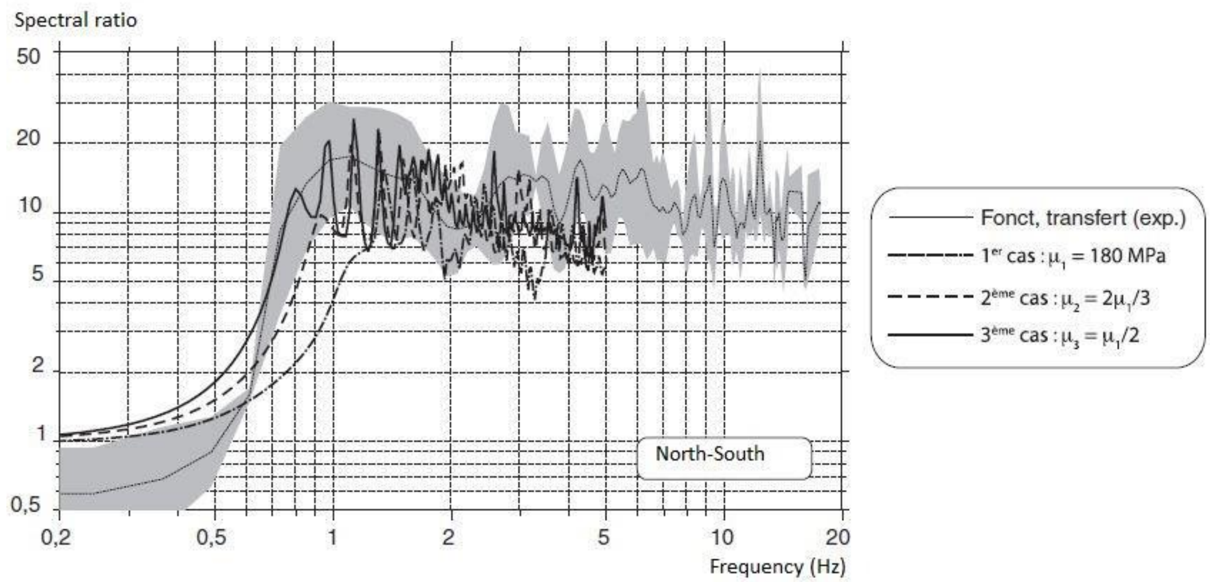

Figure 7: Local intensification of seismic movements: comparison between measurements and modeling by limit components (from Semblat, *et al*. [37]).

8. Modeling of 3-Dimensional Movement Transmission

By means of the limit component approach, it is also possible to simulate the transmission of seismic movements in three dimensions [11, 31, 37]. The case in Figure **8** resembles the case of a semicircular alluvial basin resting on bedrock that is more rigid. Limit components are surface components arranged at the boundaries between the different 3dimensional media. In the case of a flat P movement with vertical incidence, the outcomes obtained at different frequencies are displayed in Figure **9**.

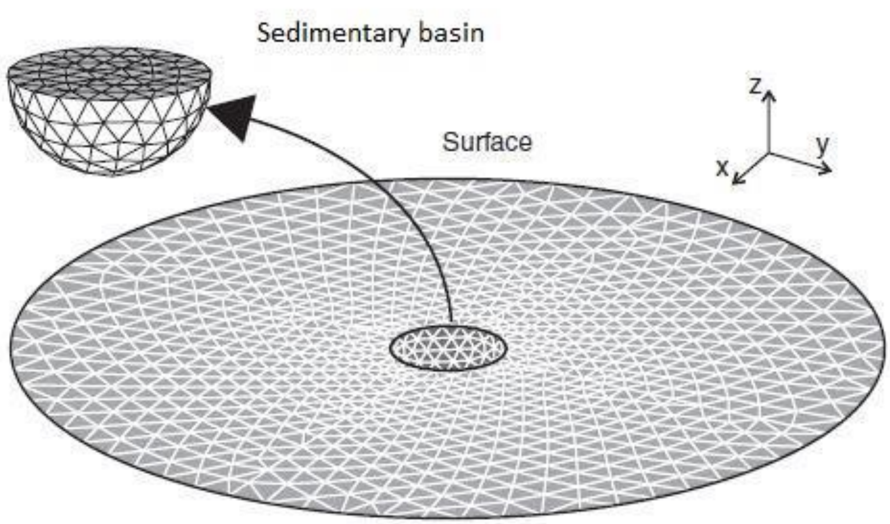

Figure 8: Limit component modeling of the transmission of 3dimensional seismic movements: semicircular alluvial basin model (from Dangla, *et al*. [38]).

It can be realized that the largeness of the seismic movements is greater inside the alluvial basin. This is due to the difference in mechanical characteristics between the basin and the bedrock, which leads to the intensification of the movements at the surface of the basin. In addition, the geometry of the basin also influences the largeness of the movements on the surface. Subsequently, it can cause the movements to be focused on the basin [33, 39, 40].

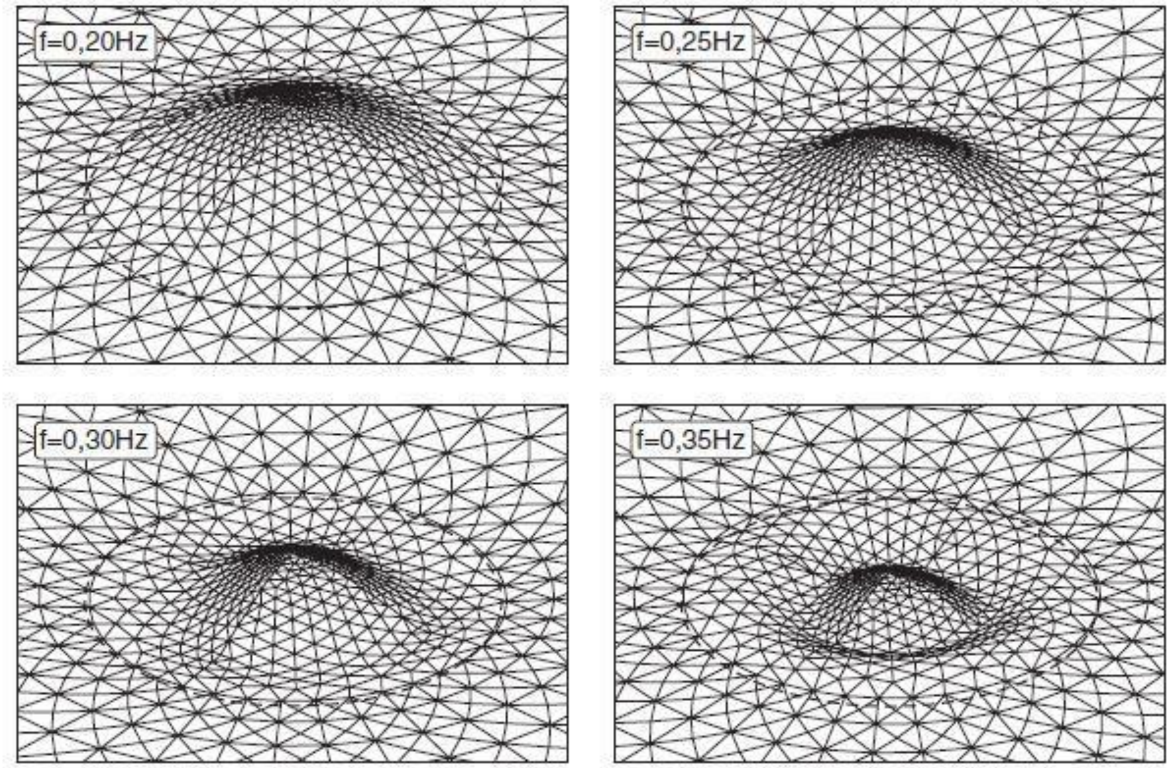

Figure 9: Limit component modeling of the transmission of 3dimensional seismic movements: deformation of the alluvial basin at different frequencies (see validation of this outcome in Dangla, *et al*. [38]).

8.1. Soil-Construction Interaction

The dynamic soil-structure interaction is also addressed beyond the transmission of seismic movements in alluvial formations. The complications of soil-structure interaction are present in calculating structures in earthquakes and all the complications of transmission of vibrations by soils. Considering the soil structures, interaction is very important for calculating the response of constructions to earthquakes [28, 41-43]. The mechanical coupling between the structure and the soil that supports it has, in fact, a negative impact on the latter. When the construction vibrates under the effect of an earthquake, the movement at its base depends on the characteristics of the supporting soil, namely: modifying the stiffness at the flat of the foundation and the energy radiation in the soil. In accumulation, the structure produces movements, which can thus disturb the movement that the ground would have in free field (that is to say, without the construction). In the frequency range of earthquakes, this disturbance can be neglected for light constructions but not for massive constructions.

To compute the response of massive constructions to earthquakes, it is consequently needed to model the soil-structure set. Soil being semi-unlimited, the finite component approach is not adapted to this calculation category. Specific approaches make it possible to attenuate the movements on the mesh boundaries for interpretation for geometric checking. Nevertheless, we know very rarely (except for particular geometries) the careful effect of these approaches on the mistake committed. It is often better to practice the approach of integral border equations (DYNF module of CESAR-LCPC).

8.2. Seismic Response of Constructions

The first illustration proposed for soil-construction interaction complication demonstration is displayed in Figure **10**. Construction with 50 m high and 30 m wide rests on the ground surface. The ground and the construction are exposed to an incident harmonic movement SH (that is to say, polarized in the direction perpendicular to the flat of the figure). The construction and the ground should be elastic, homogeneous, and isotropic. Figure **10** characterizes the displacement of the base and the top of the construction considered as a purpose of the frequency for an SH movement of vertical incidence and unitary largeness. For very low frequencies (long movement lengths), the movements do not perceive the presence of the construction, and we, therefore, get the largeness of the free field (sum of the incident movement and the reflected movement), i.e., 2. We note characteristic frequencies for which the base displacement is canceled. They match the resonance frequencies of the construction with its recessed base. At these frequencies, the displacement of the base can only be zero because if it were not, the energy absorbed in the construction would be unlimited, which is unrealistic. This effect is characteristic of the phenomenon of soil-construction interaction, and it is essential to consider it approximately these resonance frequencies if we want to obtain relevant outcomes.

Captivating into account the soil-structure interaction makes it possible to accurately estimate the frequencies for which the movement of the construction is maximum. Figure **10** displays that these frequencies are not the resonance frequencies of the construction resting on the ground, the maximum largeness of the summit being obtained for 0.25 Hz. By modifying the mechanical characteristics of the ground, the outcomes would be different, which displays that there is indeed interaction between the soil and the construction.

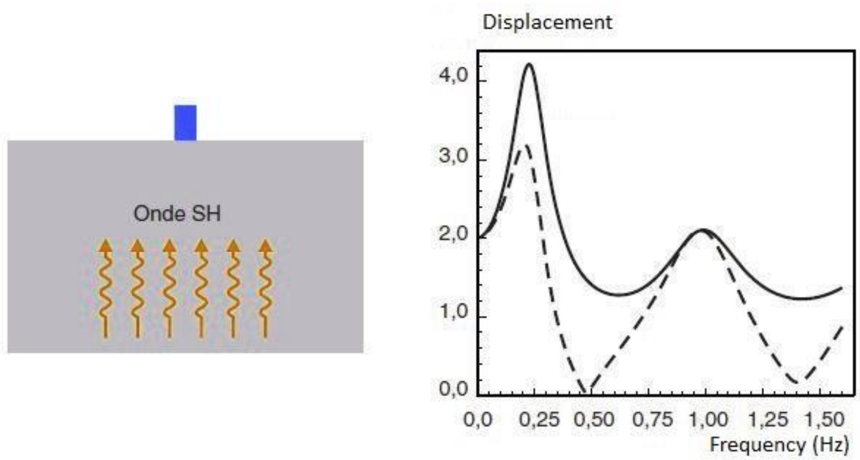

Figure 10: Soil-Construction interaction of the considered model (left); dimensionless displacements at the base and the top of the construction as a purpose of frequency (right).

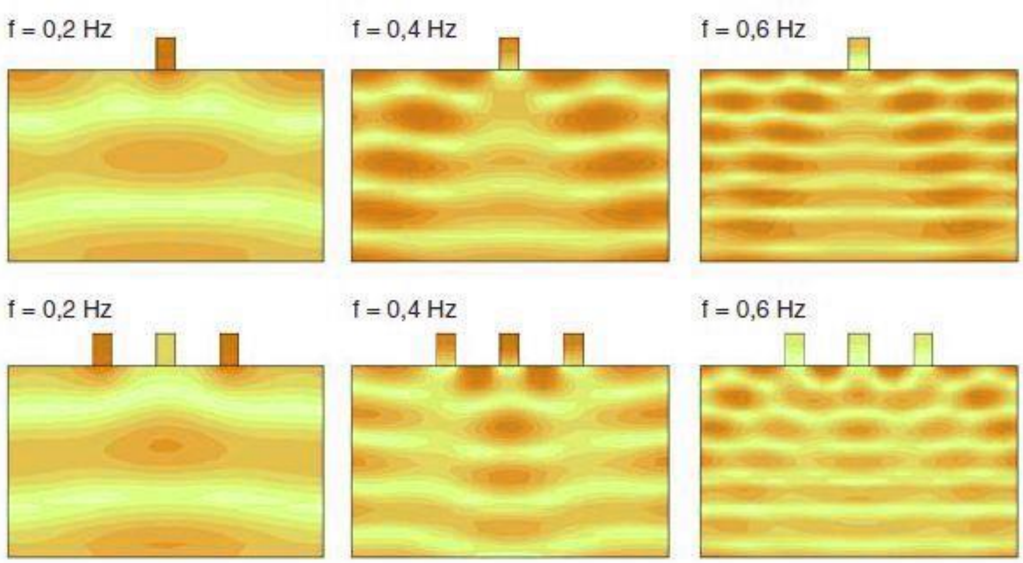

Figure 11: Movement of soil and constructions at different frequencies.

Figure **11** displays the zones of iso-displacement in the ground and kinds it possible to evaluate the zones of reinforcement of the movement by interference qualitatively. Due to the soil-structure interaction, we get areas of high or little largeness both in the soil and construction. In the same figure, the case of three constructions 100 m apart is also treated. We can thus visualize the constructions most requested, according to the frequency and the mutual interactions concerning constructions by the ground. Full outcomes in 2D and 3D are suggested in the references [28, 39, 41-45].

8.3. Vibrations of a Railway Tunnel

The additional model is related to a rail tunnel of 10 m in diameter under cover of 10 m (Figure **12**). The concrete covering has a thickness of 50 cm. The tunnel is first subjected to seismic stress in the SH movement (Figure **12**, left). Figure **13** displays the zones of iso-displacement for a vertical incidence and an incidence of 60 degrees compared to the horizontal and for three different frequencies.

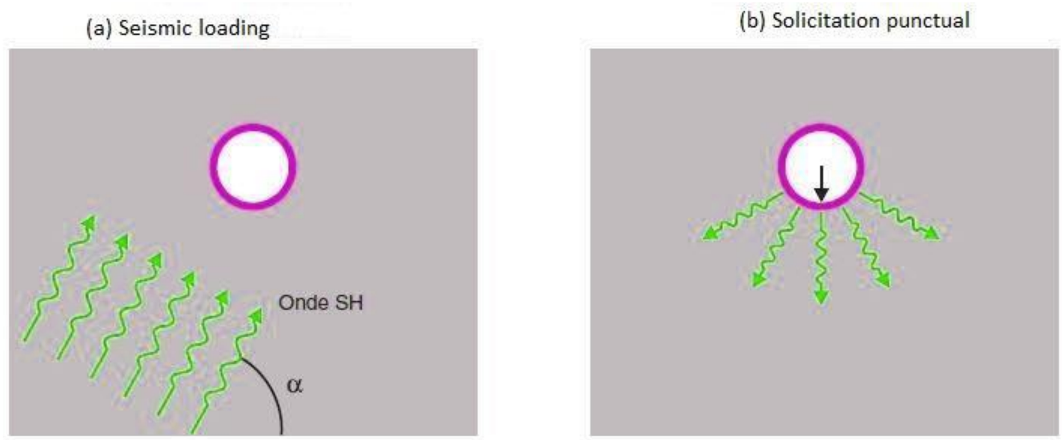

Figure 12: Tunnel under an SH seismic movement (a) or a point excitation (b).

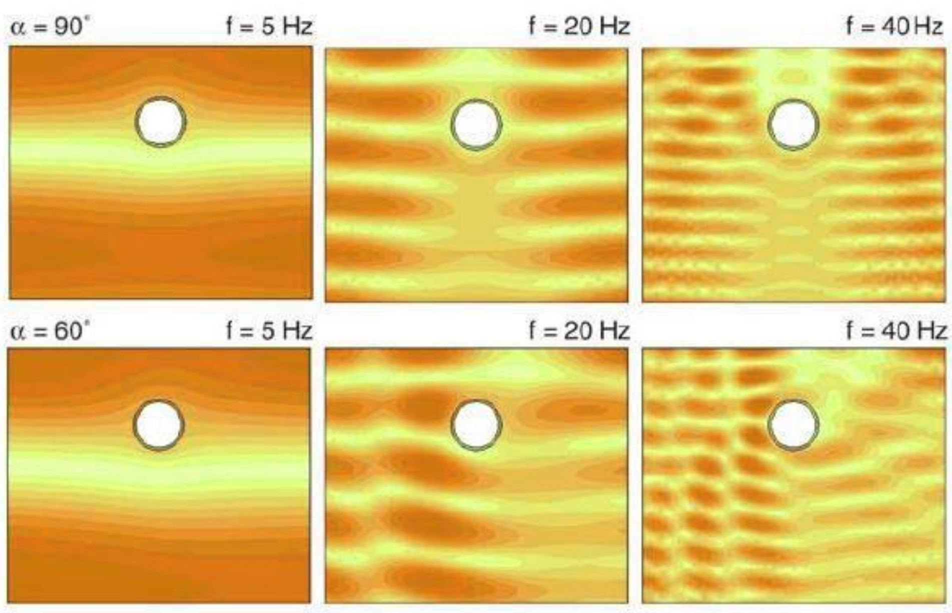

Figure 13: Iso-displacement zones for an SH movement of vertical and inclined incidence.

Due to the diffraction of the movement through the tunnel, interference figures make it likely to find the robust actions of the ground and specifically those of the surface. In addition, areas of low largeness (shaded areas) can be observed downstream of the tunnel (relative to the transmission direction). The interactions between the seismic movement and the tunnel depend on the tunnel's dimensions, its depth, the movement length of the stress, etc. A full examination of the impact of these dissimilar factors has been projected using geometric approaches [39,46, 47] or an investigative approach [48].

The tunnel is too exposed to vibratory stress due to the passage of a train (cf. Figure **12**, right). Figure **14** displays the iso-displacement zones obtained. In addition, the wall stress values are also influenced by the characteristics of the complication [39, 48]. This calculation category was compared with the outcomes of a full-scale vibration experiment on a tunnel on the Constantine-Skikda line [12]. Ground movements were recorded on the surface and vertical of the tunnel.

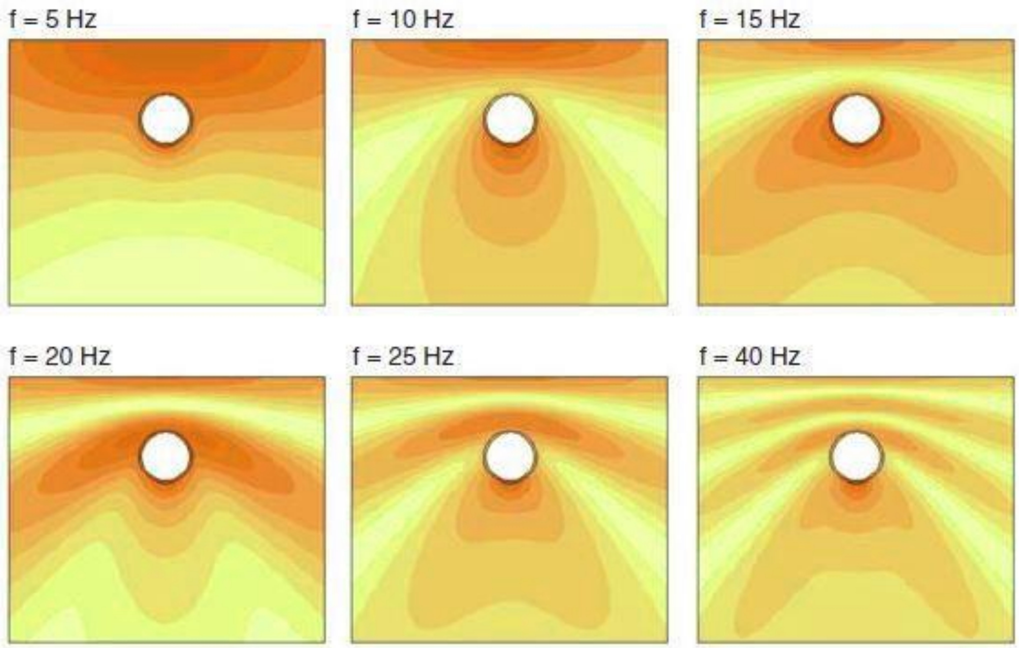

Figure 14: Iso-displacement zones for a point excitation.

Figure **15** compares the outcomes of the calculation experiment. Model 2 differs from Model 1 by taking into account the heterogeneity of the soil thanks to a modeling coupling the finite component approach and that of the integral border equations. The 2-dimensional calculations have been modified by a theoretic aspect captivating into account the out-of-flat geometry of the tunnel, making it possible to include the three-dimensional effect roughly. These outcomes are entirely acceptable, and the largeness obtained is comparable. We must still observe a frequency shift, around 5 Hz, between the calculated curves and the experimental outcomes.

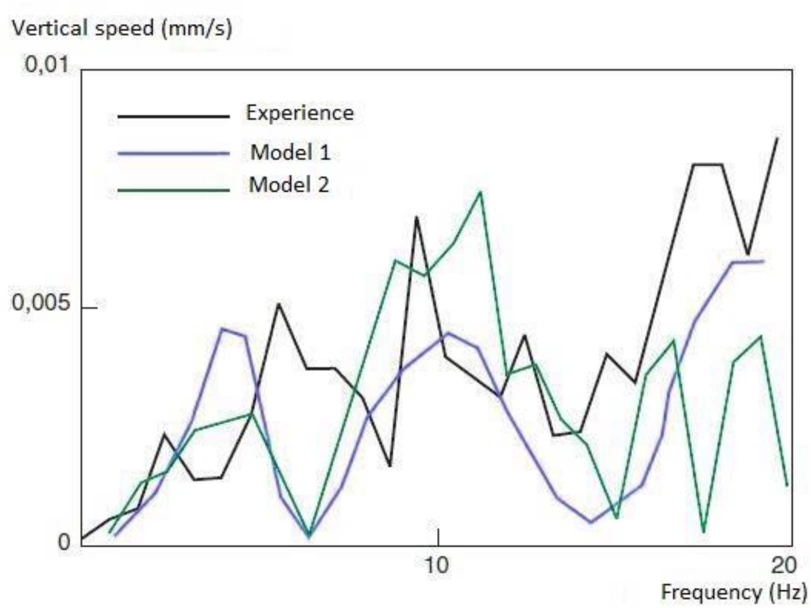

Figure 15: Comparison between calculation and experience on a real tunnel.

9. Conclusion

Geometric finite component modeling of movement transmission complications can be quite tricky. It is indeed essential to switch specific characteristics of the transmission phenomena: distribution, etc. In the linear item, the validation of the outcomes can be carried out using investigative or experimental outcomes. Intended for multifaceted behaviors, the investigative outcomes of movement transmission are few, and experiments of this category are particularly delicate. In the linear case, digital finite component modeling of movement transmission complications must take into account the main sources of digital mistakes: digital distribution, digital checking, and parasitic movement reflections. Several aspects prejudice geometric distribution, which translates the mathematical mistake on the movement transmission speed: the dimension of the components, degree of interpolation, and integration scheme over time, frequency, etc.

An additional important specificity of finite component movement transmission models concerns the parasitic reflections of movements on the boundaries of the discretized domain. Certain geometric approaches (absorbing borders, unlimited components) make it possible to eliminate this complication, but that makes it challenging to validate geometric outcomes in the most complex cases. Checking modeling is particularly important for transmission complications. However, it is necessary to have models that are simple to interpret and relate to the values of the parameters determined experimentally.

The main advantages of the finite component approach are to permit the transmission modeling in environments with complex geometry and behavior, which present high heterogeneities. On the other hand, it is necessary to finely discretize the model to limit the geometric mistake (geometric distribution). This requires huge computation resources, particularly in 3dimensions.

The border component approach is very efficient for modeling the complications of movement transmission in an unbounded domain. However, it is not suitable for modeling very heterogeneous environments or complex behavior. The validation of calculations carried out with this approach can be based on investigative transmission resolutions in unlimited mediums that are easily accessible. It is a good technique for studying seismic phenomena such as site effects or soil-structure interaction.

The cases presented (foundation, intensification of seismic movements, soil-structure interaction) display the variety of movement transmission complications that can be modeled geometrically. Such approaches do not have the same benefits and disadvantages. It could be essential to combine them to familiarize the optimal approach to the many mechanisms of the complication (near field, far field, category of behavior, heterogeneities, frequency range, etc.)).

Declarations

Ethics approval. All data and outcomes belong to the authors.

Consent to participate. Not applicable.

Consent for publication. Not applicable.

Conflicts of interest. The authors declare no competing interests.

References

[1] Eringen AC, Şuhubi ES. Elastodynamics, 2nd ed. Academic press: New York 1975.

[2] Bourbié T, Coussy O, Zinsner B. Acoustique des milieux poreux, Technip-IFP ed: France 1986.

[3] Chazelas JL, Guéguen P, Bard PY, Semblat JF. Modeling of the site-city effect in a centrifugal reduced model. Validation of experimental techniques, 6th National Symposium on Earthquake Engineering, École Polytechnique, Palaiseau 2003; pp. 245-252.

[4] Semblat JF, Luong MP. Movement transmission through soils in centrifuge experiments. J Earthq Eng 1998; 2 (1):147-171. https://doi.org/10.1142/S1363246998000071

[5] Bui HD. Introduction to inverse complications in materials mechanics, Eyrolles: Paris 1993.

[6] Chammas R, Abraham O, Côte P, Pedersen H, Semblat JF. Characterization of heterogeneous soils using surface movements: homogenization and geometric modeling. Int J Geomech (ASCE) 2003; 3(1):55-63. https://doi.org/10.1061/(ASCE)1532-3641(2003)3:1(55)

[7] Moczo P, Bard PY. Movement diffraction, intensification and differential motion near strong lateral dis- continuities. Bull Seismol Soc Am 1993; 83:85-106.

[8] Virieux J. P-SV Movement transmission in heterogeneous media: velocity-stress finite-difference Approache. Geophys 1986; 51:889-901. https://doi.org/10.1190/1.1442147

[9] Jol P. Digital Rayleigh movements. Res Rep INRIA 1982; 107.

[10] Semblat JF. Checking and scattering of movements: physical and digital points of view. Fr Civ Eng J 1998; 2 (1):91-111. https://doi.org/10.1142/S1363246998000071

[11] Bonnet M. Limit integral equation approaches for solids and fluids, Wiley: Chichester UK 1999.

[12] Dangla P. Coupling finite components-integral equations in dynamic elasto and soil-structure interaction, Doctoral thesis of ENPC 1989.

[13] Faccioli E, Maggio F, Paolucci R, Quarteroni A. 2D and 3D elastic movement transmission by a pseudo-spectral domain decomposition approache. J Seismol 1997; 1:237-251. https://doi.org/10.1023/A:1009758820546

[14] Komatitsch D, Vilotte JP, Vai R, Castillo-Covarrubias JM, Sanchez-Sesma FJ. The spectral component approache for elastic movement equations. Application to 2D and 3D seismic complications. Int J Geom Appr Eng 1999; 45:1139-1164. https://doi.org/10.1002/(SICI)1097-0207(19990730)45:9<1139::AID-NME617>3.0.CO;2-T

[15] Aki K, Richards PG. Quantitative seismology, Freeman éd: San Francisco 1980.

[16] Hughes TJR. Linear static and dynamic finite component analysis, Prentice Hall, Engle wood Cliffs N-J 1987.

[17] Bamberger A, Chavent G, Lailly P. Study of geometric diagrams for the equations of linear elastodynamics, Res Rep INRIA1980; 41.

[18] Ihlenburg F, Babuška I. Distribution analysis and mistake estimation of Galerkin finite component approaches for the Helmholtz equation. Int J Num Meth Eng 1995; 38:3745-3774. https://doi.org/10.1002/nme.1620382203

[19] Semblat JF, Brioist JJ. Efficiency of higher order finite components for the analysis of seismic movement transmission. J Sound Vib 2000; 231:460-467. https://doi.org/10.1006/jsvi.1999.2636

[20] Cohen G. High order finite components with mass condensation for the dimension 1 movement equation. Res Rep INRIA1994; 2323.

[21] Imbert JF. Analyse des structures par éléments finis, Cépadues: Toulouse 1979.

[22] Bisch PH, Langeoire A, Prat M, Semblat JF. Ouvrages en interaction (emploi des éléments finis en génie civil), Chap. 7: Modélisation des ouvrages en zone sismique transmission d'ondes, Hermès: Paris 1999; pp. 467-562.

[23] Semblat JF. Rheological interpretation of Rayleigh checking. J Sound Vib 1997; 206 (5):741-744. https://doi.org/10.1006/jsvi.1997.1067

[24] Chadwick E, Bettess P, Laghrouche O. Diffraction of short movements modelled using new mapped movement envelope finite and unlimited components. Int J Num Meth Eng 1999; 45:335-354. https://doi.org/10.1002/(SICI)1097-0207(19990530)45:3<335::AID-NME591>3.0.CO;2-A

[25] Modaressi H, Benzenati I. An absorbing limit component for dynamic analysis of two phase media, 10th World Conf. on Earthquake Engineering, Madrid 1992; pp. 1157-116.

[26] Humbert P, Fezans G, Dubouchet A, Remaud D. CESAR-LCPC, a software package dedicated to civil engineering. Bull Lab Ponts et Chaussées 2005; 256-257.

[27] Pecker A. Soil dynamics, Presses de ENPC 1984.

[28] Guéguen P, Bard PY, Semblat JF. Site-city interaction: a new aspect of seismic hazard. Bull Lab Ponts et Chaussées 2002; 236:17-36.

[29] Bonnet M. Integral equations and limit components, CNRS Editions/Editions Eyrolles, Engineering Sciences and Techniques Collection 1995.

[30] Dangla P. A flat strain soil-structure interaction model. Earthq Eng Struct Dyn 1988; 16:1115-1128. https://doi.org/10.1002/eqe.4290160803

[31] Xiao HH, Dangla P, Semblat JF, Kham M. Modelling seismic movement transmission in the frequency domain with investigatively regularized limit integral equations, 5th European Conf. on Geometric Approaches in Geotechnical Eng: Paris 2002.

[32] Collino F. High order absorbing limit conditions for the 3D movement equation. Research Report. INRIA 1996; 2932.

[33] Bard PY, Bouchon M. The two dimensional resonance of sediment filled valleys. Bull Seismol Soc Am 1985; 75:519-541. https://doi.org/10.1785/BSSA0750020519

[34] Pitilakis KD, Raptakis DG, Makra KA. Site effects: recent considerations and design provisions, 2nd Int. Conf. on Earthquake Geotechnical Engineering, Balkema ed: Lisbon 1999; pp. 901-912.

[35] Dobry R, Oweis I, Urzua A. Simplified procedures for estimating the fundamental period of a soil profile. Bull Seismol Soc Am 1976; 66:1293-1321.

[36] Semblat JF, Kham M, Parara E, Bard PY, Pitilakis K, Makra K et al. Seismic movement intensification: Basin geometry vs soil layering. Soil Dyn Earthq Eng 2005; 25:529-538. https://doi.org/10.1016/j.soildyn.2004.11.003

[37] Semblat JF, Duval AM, Dangla P. Geometric analysis of seismic movement intensification in Nice and comparisons with experiments. Soil Dyn Earthq Eng 2000; 19(5):347-362. https://doi.org/10.1016/S0267-7261(00)00016-6

[38] Dangla P, Semblat JF, Xiao HH, Delépine N. A simple and efficient regularization approache for 3D BEM: application to frequency domain elastodynamics. Bull Seismol Soc Am 2005; 95(5):1916-1927. https://doi.org/10.1785/0120050012

[39] Kham M. Transmission of seismic movements in alluvial basins: from site effects to site-city interaction, Doctoral thesis l'ENPC 2004.

[40] Lokmane N, Bonnet G, Semblat JF, Driad-Lebeau. Seismic stresses due to mining: intensification of movements and vibrations of surface structures, National Geotechnical and Geology Days: Lille 2004.

[41] Guéguen P, Bard PY, Chazelas JL, Semblat JF. Earthquakes in the city. For sci 2003; 310:56-61.

[42] Clouteau D, Aubry D. Modifications of the ground motion in dense urban areas. J Comput Acoust 2001; 9:1659-1675. https://doi.org/10.1142/S0218396X01001509

[43] Tsogka C, Wirgin A. Seismic response of a set of blocks partially embedded in soft soil. Mech Rev 2003; 331 (3):217-224. https://doi.org/10.1016/S1631-0721(03)00041-X

[44] Lombaert G, Clouteau D, Ishizawa O, Mezher N. The city-site effect: a fuzzy substructure approach and geometric imitations, 11th Int. Conf. on Soil Dynamics and Earthquake Engineering, University of California at Berkeley 2004, January 7-9, pp. 68-75.

[45] Semblat JF, Kham M, Bard PY. Could Site-City Interaction modify site effects in urban areas 13th World Conf. on Earthquake Engineering, Vancouver 2004.

[46] Luco JE, De barros FCP. Dynamic displacements and stresses in the vicinity of a cylindrical cavity embedded in a half-space. Earthq Eng Struct Dyn 1994; 23:321-340. https://doi.org/10.1002/eqe.4290230307

[47] Semblat JF, Kham M, Kurose A, Xiao HH, Dangla P. (2002). Movement/cavity interaction: investigative and BEM approaches, 12th European Conf. on Earthquake Engineering, London, 9-13 Septembre.

[48] Kurose A. Effects of earthquakes on underground structures, Doctoral thesis from the Polytechnique 2000.