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Determination of effective properties of concrete by Finite Element simulations for ultrasonic NDT

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ABSTRACT The ultrasonic testing of concretes is strongly affected by their inhomogeneous structure, which determines wave propagation velocities and causes attenuation. The work presented here aims at determining the effective properties of a concrete using time-domain Finite Element simulations. Numerical samples of concrete, represented as a mortar matrix containing aggregates, are randomly generated. The propagation of plane waves through these samples is simulated using Finite Elements for space discretization, and an explicit time scheme for time integration. The obtained ultrasonic field is processed to extract effective velocities and attenuations. The whole procedure has been implemented as new simulation modules in a development version of the CIVA platform. A module performing high-order Finite Element calculations in two dimensions had been the subject of a joint study between CEA and EDF. This communication introduces another tool, based on low-order computations on regular grids. It can perform two or three-dimensional calculations. These tools aim at providing input data for propagation calculations, and at validating analytical models. Cross-validation results obtained with the two approaches for two-dimensional configurations are presented. Results obtained with the low-order code in three dimensions are also shown. Theoretical results obtained with the Waterman and Truell model are included for comparison.

Mots-clefs Simulation, ultrasons, éléments finis

Key-words Simulation, ultrasound, finite elements

I. INTRODUCTION

Ultrasonic inspections of concrete can be significantly impacted by the inherent inhomogeneity of the material, leading to variations in wave speeds and attenuations. Modelling can help in better understanding these phenomena, in order to develop robust inspection methods or characterization processes. In a simplified representation, concrete can be treated as a cement matrix containing a distribution of aggregates [Chaix et al., 2012]. Assuming that the aggregates are spherical, it becomes possible to use analytical models to evaluate the effective wave velocities and attenuations, while taking into account multiple scattering phenomena. Several models have been developed over the years with various degrees of refinements [Waterman and Truell, 1961; Luppé et al., 2022]. Another approach, based on the same material description, relies on Finite Elements (FE) simulations of ultrasonic field propagation through random aggregate distributions. It has been applied to two-dimensional configurations [Chekroun et al., 2012; Yu et al., 2019]. The work presented here aims at applying the same approach to three-dimensional configurations.

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New FE simulation modules were recently added in a development version of the CIVA simulation platform. The first approach performs two-dimensional computations and relies on high-order FE and triangular meshes. The second approach, introduced in this communication, performs two or three-dimensional computations. It relies on low-order FE and regular grids over which material properties are projected, rather than a mesh. Comparisons between the two approaches in two-dimensional (2D) cases are presented, in order to validate the capabilities of the low-order approach. Some three-dimensional (3D) results are then shown. Results obtained with an approached analytical model [Waterman and Truell, 1961] are included for comparison.

II. METHODS

We simulate the propagation of plane waves through aggregate distributions using two different FE codes, referred to as high-order and low-order FE codes. We then apply the same post-processing method to their results in order to estimate the effective velocities and attenuations of the coherent waves.

A. High-order Finite Elements on triangular mesh

The code used in this computation is based on the CIVA FEM Computation Core, initially developed for other ultrasonic testing applications, such as scattering by complex flaws [Imperiale et al., 2019]. A version adapted to 2D simulations for concrete applications was recently implemented [Dorval et al., 2022]. In the work presented here, the concrete version of the code simulates the propagation of a plane wave through a matrix containing a random distribution of circular aggregates. For this particular problem, a plane wave is made to propagate through a rectangular sample surrounded by Perfectly Matched Layers [Joly, 2012] that prevent reflections at boundaries. A triangular mesh is generated using GMSH [Geuzaine and Remacle, 2009]. The FE computation itself relies on high order elements and mass lumping techniques [Cohen et al., 2001].

B. Low-order Finite Elements on regular grid

The low-order simulation module is based on a generic code dedicated to the simulation of the propagation of ultrasonic waves through heterogeneous microstructures. One of its applications is polycrystalline metallic microstructures [Dorval et al., 2023]. It is suited to strongly varying and discontinuous material properties. Unlike the code presented above, it projects the microstructure over a regular grid of low-order elements. This projection alters the microstructure description, which might make results less accurate. This method still has several advantages: it avoids meshing the geometries, is computationally efficient, and can readily be applied to 3D configurations. For the applications presented here, this code was used in 2D and 3D configurations. The computation domains were either rectangles containing circular aggregates, or bricks containing spherical aggregates. In both cases, plane waves were generated by setting a uniform load on the top surface and periodic boundary conditions on the side surfaces. The aggregate distribution is also made periodic to make the problem statistically invariant.

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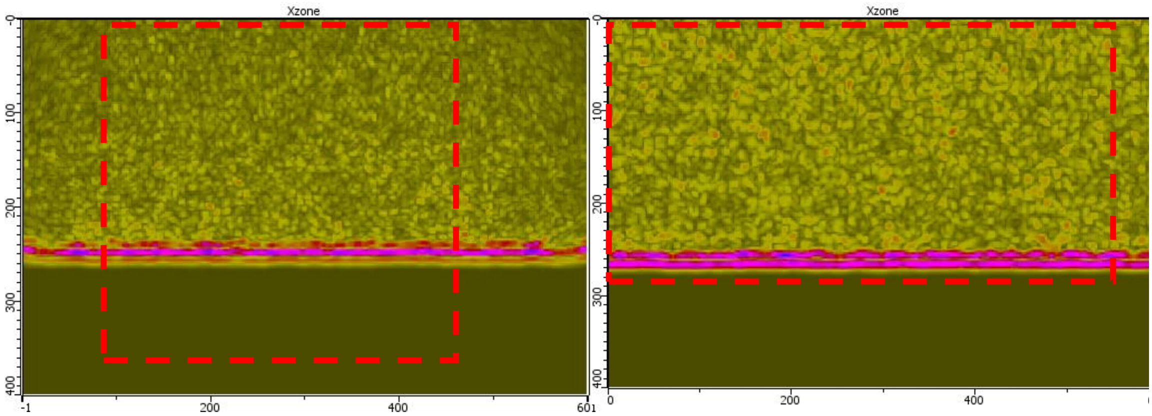
C. Estimation of effective velocities and attenuation

The coherent ultrasonic field is defined as an average over all possible realizations of the microstructure. For an incident plane wave propagating through an infinite medium, the coherent field only depends on the distance travelled and is equivalent to the average of the wave perpendicularly to its propagation direction. We approximate it by averaging plane waves that propagates in limited domains. In the case of our high-order code, the behaviour near the side boundaries can not be considered equivalent to the one in an infinite medium (as no aggregate are introduced in the PML). We therefore restrict the analysis to an area away from these boundaries. In the case of the low-order code, periodic boundary conditions on the sides allow the entire cross-section of the sample to be taken into account in the computation. However, since this code allows reflections at the bottom of the sample, we include a buffer zone to stop the computation before the reflected waves come back to the area of interest. These processing areas are illustrated (red dashed line) over computed fields in Figure 1. In the case of the high-order code, the alteration of the plane wave outside of the zone is slightly visible as a curvature of the wave front. For both codes, the average is done for a series of travelled distances. The averaged fields are then processed in the frequency domain, using the decrease of the complex amplitude and the variation of the phase to estimate respectively the attenuation and the velocity [Yu et al., 2019]. Results are obtained for a range of frequencies around the characteristic frequency of the pulse.



High-order FE simulation **Low-order FE simulation**

FIGURE 1. Example of computed plane waves and processing areas

III. RESULTS

These methods were used to estimate velocities in 2D and 3D configurations using the same parameters. 2D configurations were treated with the two FE codes, while 3D configurations can only be treated with the low-order code. Results from an approximated analytical model [Waterman and Truell, 1961] are included for comparisons.

A. Parameters

The properties for mortar and aggregates are given in Table 1. They are the same as those used by [Yu et al., 2019], in order to allow for direct comparisons with some of their results.

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TABLE 1. Material properties used in the simulations

Medium	Density (kg/m³)	Compressional wave velocity (m/s)	Shear wave velocity (m/s)
Mortar	2050	3950	2250
Aggregate	2610	4300	2475

The aggregate radius was assumed to be constant and set to 6 mm. A minimal distance of 0.1 mm between grains was set: this prevents very small elements from appearing between grains in the triangular mesh. Such elements could make computations significantly slower, since the time step is determined by the smallest element. Two aggregate densities were tested : 4% and 24%. The positions of the aggregates are generated sequentially in a random manner. Each new aggregate position is randomly drawn from a uniform distribution, and kept if it is not too close to previously generated aggregates. This simple algorithm is limited to relatively low aggregate densities (less than approximately 45% in 2D and 33% in 3D), after which it is unable to find free spaces for new aggregates. The plane wave pulse is a Ricker wavelet with a 200 kHz characteristic frequency. The characteristic element size of the triangular mesh was set to 1.88 mm, using a rule of thumb of 1/6 of the shear wave wavelength at 200 kHz (the wavelength in the mortar at 200 KHz are approximately 19.8 mm for longitudinal waves, and 11.3 mm for shear waves). After some convergence tests, the step of the regular grid was set to 0.14 mm in the propagation direction and 0.56 mm in the others. The grid is smaller in the propagation direction because the post-processed velocities exhibited significant numerical dispersion at high frequency for larger steps. The grid step in the other directions does not appear to have the same effect. The height of the samples (along the propagation direction) is 400 mm. The lateral dimensions of the samples are the only parameters that differ between the 2D and 3D computations: they are 600 mm in the 2D case, and 150 mm*150 mm in the 3D case.

B. Two-dimensional configurations

The main purpose of the 2D comparisons presented here is to validate the capability of the low-order FE method to compute velocities and attenuation, before applying it to a 3D problem more representative of actual concrete.

Figure 2 shows examples of a 2D simulation and of circular aggregates as seen by the two codes. The side from which the plane wave is emitted is indicated by the yellow line.

The simulations were run on a computed with two 3.40 GHz processors and a 32 Go RAM. The high-order code required approximately 5 minutes to perform a single computation for the 4% aggregate density case, and 15 minutes for the 24% case. The discrepancy is explained by the mesh differences. The low-order code, which uses a fixed regular grid instead of a mesh, required around 5 minutes per computation regardless of the aggregate density. The low-order code proves to be more efficient for this specific application. However, the high-order code has different strengths, particularly its capability to handle implicit fine layers, making it more suited in other contexts.

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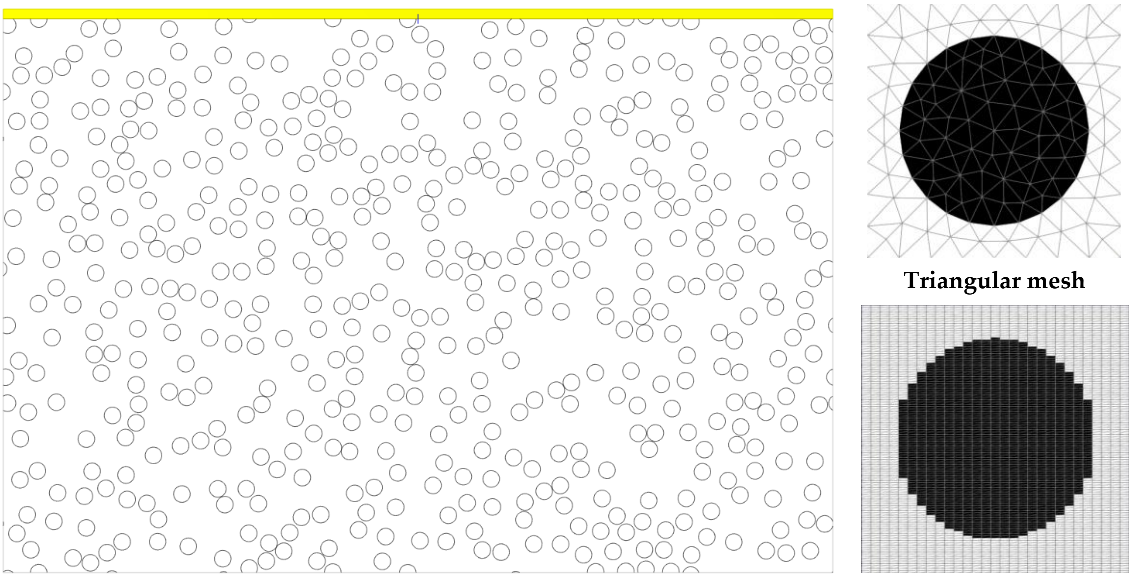


FIGURE 2. Configuration and aggregate descriptions for 2D simulations

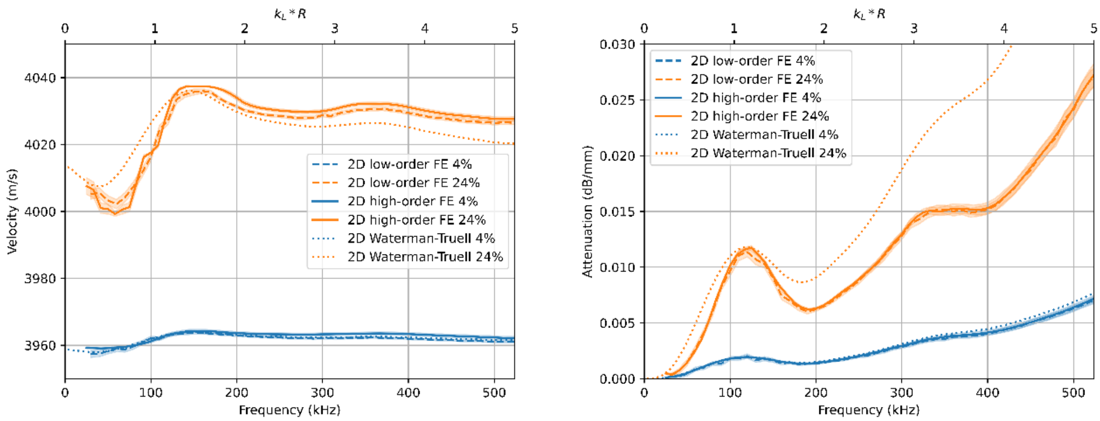
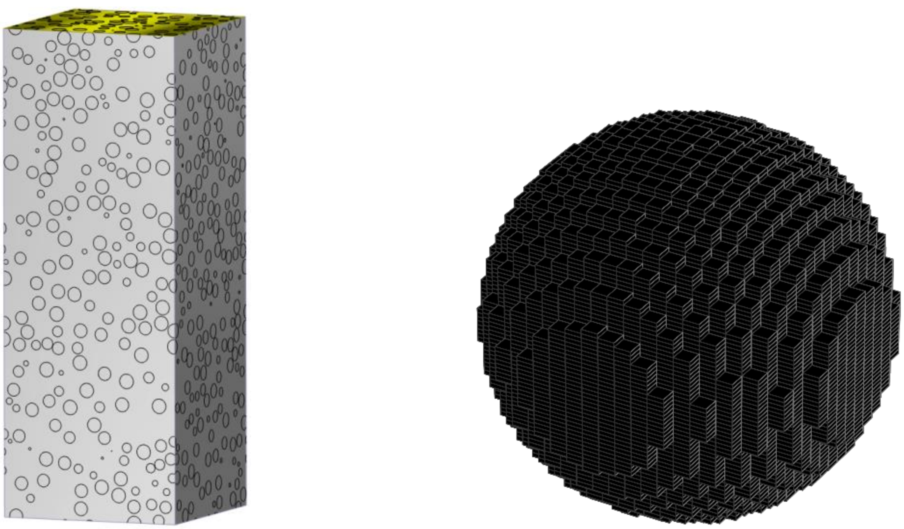


FIGURE 3. Velocities and attenuations obtained for longitudinal waves in 2D configurations over 50 realizations, with 95% confidence intervals

Figure 3 shows results obtained by the two FE codes and by the Waterman and Truell model. The two FE codes are in overall good agreement. Their confidence intervals overlap almost everywhere, except for a difference of up to 2 m/s for the velocities with 24% aggregate. This might be an effect of the approximation introduced by the regular grid in the low order code. The FE results agree with the Waterman and Truell model at 4% but not at 24%, which is expected as this model tends to be inaccurate at higher aggregate densities [Layman et al., 2006]. The FE results at 24% agree with results that were previously obtained with similar methods for the same parameters [Yu et al., 2019].

C. Three-dimensional configurations

The 3D configurations were simulated using a low order FE code, which has a simple 3D implementation and does not require dedicated meshing tools, unlike the high order code. Figure 4 shows an example of a configuration and of the representation of an aggregate. A single 3D simulation took approximately 7 hours, i.e. 84 times longer than a 2D simulation on the same computer (though 3D and 2D simulations are not strictly comparable, the 3D samples contain approximately 4.6 times more spherical aggregates than the 2D samples contain circular aggregates). These computations could be made significantly shorter by reducing the dimension of the sample in the propagation direction, for two reasons: the regular grid is more refined in that direction, and if the wave has less distance to travel the simulation is stopped earlier. However, this would yield shorter signals and reduce the frequency resolution of the results. Due to the high computation times, only two realizations of the microstructure for each aggregate density were considered. Velocities and attenuations results are shown in Figure 5.



Configuration for 3D computation with 24% aggregates **Aggregate description over the regular grid**

FIGURE 4. Configuration and aggregate description for 3D simulations

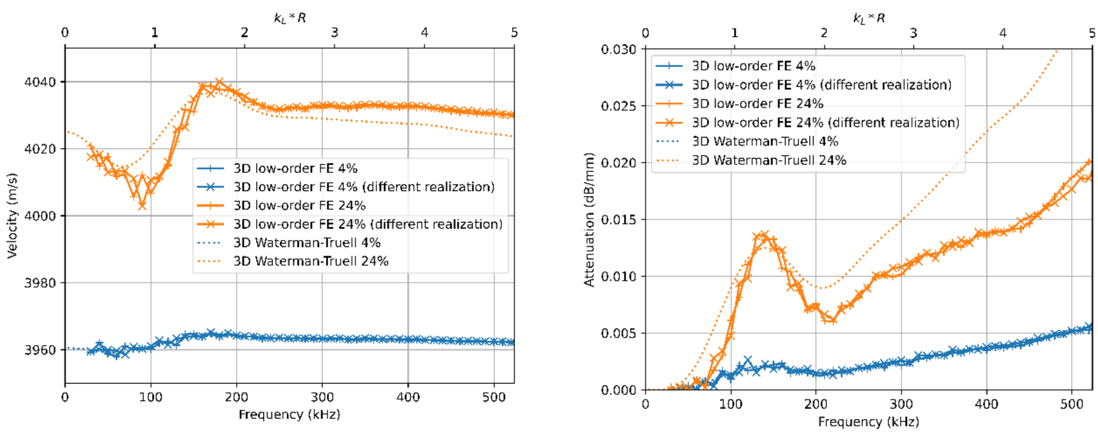


FIGURE 5. Velocities and attenuations obtained for longitudinal waves in 3D configurations

The FE results do not vary significantly between the two realizations, which indicates that the volume considered is sufficiently large to produce robust and representative outcomes. These results are in agreement with the Waterman and Truell model for a 4% aggregate density but not for 24%. This was once again expected. Interestingly, 2D and 3D behaviours are similar. This is consistent with comparisons for longitudinal waves made between 2D and 3D models [Chekroun, 2008].

IV. CONCLUSION AND PERSPECTIVES

Modeling the scattering of waves by granular distributions, such as those found in concrete, has been a long-standing research topic. Numerical simulations can help address the subject. Two FE tools are being developed in the CIVA simulation platform: one based on a high-order FE code for triangular mesh, and one based on a low order FE code for regular grids. They have different strengths and weaknesses, but can both be used for characterisation of 2D granular media. They yield very similar results for the application tested here. The low-order code also has the capability of simulating 3D cases. In both cases, the velocities and attenuations obtained are in good agreement with the Waterman-Truell model at low aggregate density. This approach has the potential of being used for the validation of more recent and elaborate analytical models [Luppé et al., 2022]. The results presented here focused on longitudinal waves: they have similar behaviours in 2D and 3D, which helps in validating 3D results. The same computations could be performed for shear waves. Higher aggregate densities could also be tackled, using a more robust random aggregate generation algorithm. It would then be useful to verify if the grid of the low-order code is able to handle small gaps between aggregate at very high densities. This could be achieved by further cross-validations between the two codes.

Real concrete is more complex than a distribution of homogeneous spheres in a homogeneous matrix. Aggregates are not spherical: polygonal shapes can be taken into account in numerical simulations, even though they do not seem to have a significant effect [Yu et al., 2019]. Interfacial Transition Zones (ITZ) exist between mortar and aggregates, and are suspected to strongly impact the propagation of ultrasonic waves [Ramaniraka et al., 2019]. Additionally, damping effects in the mortar can increase attenuation. The high-order code used here can take into account ITZs using an implicit numerical scheme [Dorval et al., 2022] and can also include damping. Those functionalities have yet to be implemented in the low-order code, in order to build towards a more realistic 3D model of concrete.

The inclusion of these simulation tools in a future commercial version of CIVA is being considered.

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