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Enhanced seismic response prediction of critical structures via 3D regional scale physics-based earthquake simulation

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ABSTRACT

Realistic physics-based 3D earthquake simulation for source-to-structure wave propagation consists of a powerful numerical tool for seismic response prediction of critical structures submitted to high safety standards. Structural response considering soil-structure interaction (SSI) is usually estimated by Finite Element Method (FEM) approach, as it is considered as the most flexible numerical approach for non-linear structural dynamics. However, current engineering practice considers seismic input motion as vertically incident plane waves, despite the fact that this assumption excludes wave passage effects for large infrastructures and surface waves appearing from possible local basin effects. In this framework, a realistic input excitation needs to be defined as an input excitation of the FEM model, accounting for : i) a realistic dynamic excitation, ii) wave propagation path in the regional scale, and iii) local site-effects.

The Domain Reduction Method (DRM), which allows for the imposition of a 3D complex incident wave field as an input to the SSI model is adapted and examined here in a Spectral Element Method (SEM) - FEM weak coupling approach. The weak coupling is verified at first for a canonical case-study and for an increasing complexity of the dynamic excitation: i) double-couple point-source, and ii) extended fault. An optimization approach, based on the decimation of SEM output signal, is then examined in order to decrease the computational burden by maintaining the same accuracy of the final solution.

The SEM-FEM weak coupling is then used to study the SSI problem, where the impact of the reduced domain size on structural response is examined at first. The current study shows that a reduced domain of dimension greater than $4 \times \lambda_s$, where λ_s the maximum wavelength, is sufficient for a proper representation of structural response. For a fixed size model, structural and soil response are then examined for a hypothetical case-study.

KEYWORDS

domain reduction method; SEM-FEM coupling; dynamic soil-structure interaction; seismic structural analysis; paraxial elements; re-sampling/decimation;

1. Introduction

Seismic safety of lifelines and (infra-)structures such as nuclear power plants, dams, roads, railways, and bridges are of crucial importance from an economic and social point of view. The complex interaction of these structures with the subsurface soil layers during an earthquake event represents an important phenomenon that needs to be taken into consideration so as to assess their performance. State of the art recommendations, based on recent research works, state that the seismic motion has to be controlled at the “reference bedrock” in depth, or at least at the outcropping bedrock, in order to reduce the consequences of geological conformation and site-specific parameters uncertainties, instead of the free-field motion. In such a way, the site effects can be easier analyzed separately from the analysis of the seismic hazard (1). To this end, the development of physics-based 3D models for the simulation of earthquake ground motion has been largely increased with the exponential increase of the computational power. In this context, important aspects of the seismic wave propagation problem can be explicitly taken into consideration, such as i) the earthquake source, ii) the propagation path, iii) the local site effects as well as iv) the non linear behavior of the soil, all gathered in a high-fidelity predictive numerical model (2). The latter brings an indubitable benefit to the prediction of complex scenarios, especially for the case of a near-source field (e.g. the San Francisco bay area (3)) and in regions of moderate seismicity where earthquake catalogs for strong ground motions are poorly populated (4, 5)). As a matter of fact, current outstanding computer power endows the scientific community with the power of solving a multi-scale Soil-Structure Interaction (SSI) problem, ranging from strong ground motion prediction at a regional scale (\sim several kilometers) to the prediction of the structural response at site/structure scale (\sim several hundreds of meters) including details that most conventional approaches have so far neglected (source directivity, spatial variability etc, see for instance (6)). Several examples in the literature showcased successful end-to-end (fault-to-structure) earthquake simulations (7–11). However, these improvements come with a price. From a computational standpoint, the most challenging aspect is represented by the semi-infinite nature of the Earth’s subsurface, which implies i) the choice of non-reflecting boundary conditions adopted at the virtual domain boundaries (12–14) and ii) a meshing scheme assuring *suitable* interpolation of the heterogeneous mechanical properties with their high local spatial gradients, so to grant *sufficient* numerical accuracy for the desired minimum wavelength to be rendered. Moreover, the geo-statistical uncertainty (15) requires, for a specific seismic scenario, a *sufficient* knowledge of the seismic source, the geological layout, and the geotechnical properties of soft sediments as those of bedrock in depth (16). The curse of dimensionality is easily encountered indeed: the finer the numerical modeling and the discretization, the more detailed the geotechnical, geological and seismological information required. The nonlinear material rheology of both structural components and soil deposits implies an even finer mesh to be correctly described (2, 14, 17). At the same time, a higher investment should be considered in the verification and validation (V&V) process, to increase confidence in the predictions of the simulations, for such critical decision making. (18)

In engineering practice, the domain at stake is represented by a small soil chunk around the structural components, usually discretized via the Finite Element Method (FEM) and solved either in the time or in the frequency domain. As far as the incident wave-field is concerned, according to Eurocode 8 (19) the so-called Free Field Boundary Condition (FFBC) (20–22) is adopted, by first defining the free-field seismic response on the outcropping bedrock (recorded or simulated) and by deconvoluting it

50 at the base of a horizontal soil stratification as a plane-wave motion. The deconvo-
51 luted incident wave-field is propagated through the layered soil domain up until the
52 soil foundation (23).

53 With a similar approach, the free-field signal can be used in a Boundary Element
54 Method - Finite Element Method (BEM-FEM) coupling framework for instance, where
55 Green's functions for a layered visco-elastic half space are used to define the impedance
56 matrices and the equivalent seismic forces in the BEM-FEM interface, usually placed
57 in the vicinity of the structure (24). These seismic forces are then applied in a finite
58 element (FE) framework as an excitation so as to estimate the structural response.
59 An alternative solution in the frequency domain consists of formulating the BEM
60 solution via the Laplace transform and evaluating the impedance operator in the time
61 domain by a convolution integral (25, 26). In this context, and in the special case
62 where 3D physics-based simulations are used in order to define the outcropping free-
63 field input motion, (27) proposed to enrich the frequency content of the seismic
64 input motion using artificial neural networks (ANN) before calculating the dynamic
65 impedance matrices with BEM.

66 All the aforementioned methodologies hardly adapt to complex site conditions (e.g.
67 complex basin and topography effects) and seismic scenarios (near-source field direc-
68 tivity of a 3D incident wave field) (14, 20, 28, 29). This drawback can be mitigated
69 by adopting a sub-structuring approach, where the 3D excitation is obtained through
70 wave propagation in a regional scale domain, applied as an input excitation of a smaller
71 model on the scale of the site/structure of interest. The coupling strategy can be
72 achieved in two alternative ways: a less intrusive *weak coupling* approach or a *strong*
73 *simultaneous coupling*. The first strategy is well embodied by the so called Domain
74 Reduction Method (DRM) (30), a two-step procedure where free-field ground shaking
75 is computed via an auxiliary simulation and then injected as equivalent nodal force
76 distribution at the bounding interface of the small-scale domain. The DRM has the
77 advantage of an easier off-line implementation and it can take advantage of different
78 High-Performance Computing software, tailored for seismological and structural simu-
79 lations respectively, coupling Finite Difference Method (FDM) and FEM as in (28, 31),
80 FEM and FEM (32) and others (33–38). This is why this approach has been adopted
81 here.

82 The strong coupling approach (39–41, among others) instead aims at simultane-
83 ously solving the two problems exchanging the incident and diffracted wave energy
84 at each time step. A well known algorithm for dynamic coupling was introduced
85 by (42, 43). In this framework, (39–41) successfully coupled the Spectral Element
86 Method (SEM) and the FEM, via the standard mortar approach (44), and for the
87 dynamic soil-structure interaction (SSI) problem, an implementation however that
88 adopts a sequential solution of the source-to-site wave propagation. In a similar con-
89 text, (45) proposed FDM-FEM coupling. The core idea of the strong coupling to
90 enforce the continuity of the solution at the interface, producing a real time exchange
91 of information between the coupled models, leads to a definition of the 3D input ex-
92 citation on the boundary of the finite element domain used in order to perform the
93 dynamic SSI analysis that is the exact solution of the problem. This is the main differ-
94 ence with weak coupling techniques that only account for the complex incident motion
95 without accounting for the diffracted waves (30, 46). In addition, in the strong cou-
96 pling and given that each problem is solved simultaneously on the interface in general
97 no need for absorbing boundary is necessary. In this framework, the size of the FEM
98 domain can in principle be reduced at the soil-structure interface and only depends on
99 the computational capacity of each methodology and as a result on the discretization

100 of each domain. On the contrary, in a weak coupling approach the accuracy of the re-
101 sponse is related to the size of the finite element domain as a result of the position of
102 the absorbing boundary condition. Nevertheless, two major drawbacks of these strong
103 coupling techniques are: i) the difficulty of the implementation in existing codes due
104 to their intrusive character, and ii) the performance of the implemented solution on
105 a High Performance Computing (HPC) framework, which are the main reasons why
106 these types of solutions are not examined in this work.

107 Regardless the coupling scheme, the choice of the two numerical methods to be
108 coupled depends on the scale of the problem (regional or site/structure) and on the
109 rheology of the soil media (linear, nonlinear). In this regard, the FEM is traditionally
110 well suited for structural elements and nonlinear behavior to be taken into account
111 for the soil-structure interaction (SSI) problem (2). More recently, the FEM has been
112 used in a large-scale domain earthquake simulation, due to its flexibility (47–50).
113 Another advantageous solution to solve regional scale numerical wave propagation is
114 the SEM (2, 5, 51, 52), belonging to the FEM family, with higher order polynomials as
115 basis functions. The SEM displays a lower numerical dispersion (53, 54), compared to
116 the FDM (traditionally employed in seismology), as quoted by many authors for many
117 decades, e.g. (55). (56) proposed in the SEM context the use of Lagrange polynomials
118 in conjunction with the Gauss-Lobatto-Legendre (GLL) quadrature, which leads to
119 a diagonal mass matrix of the problem, allowing a faster solution of the system of
120 equations. This diagonal matrix, in conjunction with the higher order shape functions
121 allowing the choice of larger elements for the discretization of the physical domain in
122 comparison to the FEM methodology.

123 The aim of this work is to apply the DRM method by employing a SEM kernel
124 to solve the auxiliary wave propagation problem and a FEM kernel for the reduced
125 domain problem. Compared to other implementations of the DRM strategy ((29, 57–
126 59) among others), the aim of the present work is two-fold and it resides in: i) the
127 optimization of the transferred field between SEM-FEM in order to accelerate the
128 source-to-structure wave propagation computation, and ii) the use of the *paraxial*
129 *boundary conditions* (60, 61) to both absorb outgoing waves impinging the fictive
130 boundary and to apply the dynamic excitation (formulation proposed by (62)) on the
131 reduced scale domain.

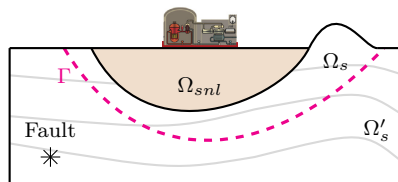
132 This paper is organised as follows: Section 2 focuses on a brief description of the
133 DRM theory and of the paraxial element formulation used to reconstruct the dynamic
134 excitation on the boundary of the reduced domain. Paraxial elements consist of a
135 surface boundary condition and allow a simple and robust implementation while their
136 consideration on the DRM framework lies in the fact that they provide a smaller
137 computational domain comparing to other DRM applications where absorbing layers
138 are taken into account ((29, 57–59, 63) among others). Sub-section 2.3 focuses on the
139 description of the adopted SEM/FEM weak coupling approach and discusses spatial
140 and temporal discretisation hypothesis used to optimize the weak coupling. Finally,
141 the numerical verification of the coupling approach will be presented on section 3, and
142 for a canonical case-study proposed in the literature. Applications on the SSI problem
143 will be discussed in section 4 in order to identify the importance of a realistic input
144 excitation definition.

145 2. SEM-FEM Numerical modeling

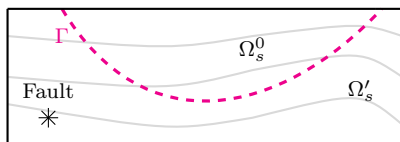
146 The key concept of the DRM approach lies in the use of a complex incident wave
 147 field to be imposed as an input excitation to the SSI model (14, 64). In this context,
 148 the objective of the DRM is to transfer the dynamic excitation of the seismic source
 149 closer to the boundaries of a reduced (smaller) domain of interest, at the scale of the
 150 site/structure.

151 The initial domain of interest Ω , is divided in two sub-domains by a virtual boundary
 152 surface Γ : i) the interior domain Ω_s , and ii) the exterior domain Ω'_s (Fig 1a). The wave
 153 propagation problem is then solved in two separate steps:

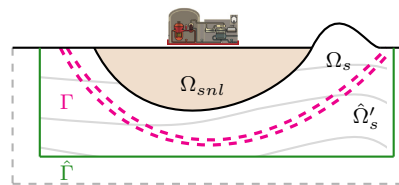
- 154 (1) **Auxiliary domain problem** \mathcal{P}_0 : it consists of a source-to-site simulation on
 155 a background soil configuration Ω_s^0 , where local features (eg. geological aspects,
 156 structures, etc) of interest in Ω_s are replaced with a simpler soil domain modeling
 157 as the one adopted for the soil in depth, see (Fig. 1b). Coarser discretization
 158 can be chosen, based on a higher wave velocity of the soil media (soil in depth
 159 assimilated to rock) and the whole calculation is performed only once for the
 160 specified earthquake source and regional scale properties, so as to define the
 161 corresponding ground motion at the boundary of the interior domain;
- 162 (2) **Reduced domain problem** \mathcal{P}_r : The second step considers the interior domain
 163 where the local features of interest are accurately modeled (see Fig. 1c). The
 164 input excitation expressed in terms of equivalent nodal forces obtained directly
 165 from \mathcal{P}_0 and applied on the boundary Γ in a region that is slightly bigger than
 166 the local interior domain. The soil outside the boundary Γ is only used for
 167 absorbing the diffracted waves traveling out of the domain and incompatible
 168 with \mathcal{P}_0 solution. In this case, for any change of system parameters inside the
 169 localized region of interest (interior and exterior domains), only this step has to
 170 be repeated so as to determine the variation of the wave propagation inside the
 171 interior domain.



(a) Problem of reference.



(b) Auxiliary domain problem.



(c) Reduced domain problem.

Figure 1.: Schematic representation of the domain reduction method (adopted from (30)).

172 Finally, it is important to remind here that in the DRM approach proposed by
 173 (30), two key points must be treated: i) an external region with a suitable absorbing

174 boundary condition around the reduced domain, and ii) the definition of the equivalent
175 nodal forces on a region in the reduced domain boundary.

176 Concerning the former point, alternative approaches for suitable absorbing bound-
177 ary conditions with the DRM methodology have been proposed in the literature: sim-
178 ple dash-pot approach (e.g. 34, 36, 65, 66), buffer zones or damping layers (e.g.
179 8, 9, 30, 38, 46, 67), PML (57, 68, among others). In the following (subsection 2.1),
180 the adopted solution in this work for the boundary condition (*i.e.* paraxial approxi-
181 mation) will be briefly presented.

182 As far as the latter point is concerned, a DRM layer needs to be defined for the
183 computation of the equivalent nodal forces. The way that these equivalent nodal forces
184 are computed and implemented in the current weak SEM-FEM coupling is presented
185 in subsection 2.3.

186 2.1. Paraxial Boundary Conditions

187 The seismic excitation from the auxiliary domain problem is then transferred (in terms
188 of equivalent nodal forces (12, 30, 69)) as an input excitation on the reduced domain
189 problem on the scale of the site/structure to be studied with the FEM (70) open-
190 source software. The weak coupling SEM3D-Code_Aster is ensured by the *paraxial*
191 *elements*, capable to impose the dynamic excitation (62, 70) as well as to absorb the
192 outgoing waves arriving on the boundary. The formulation of the paraxial elements was
193 initially introduced by (61) and (60) while the implemented version in Code_Aster
194 is based on a modification initially discussed by (62) allowing to take into account
195 the dynamic excitation. Starting from the general expression of the elastic equation
196 of motion, the derivation of the spectral impedance on the boundary of the reduced
197 domain Γ requires the projection of the equation of motion on a local tangent plane
198 ($\mathbf{e}_1, \mathbf{e}_2$), with outward normal \mathbf{e}_3 . The solution of this projected equation, expressed
199 in the Fourier wave number-frequency domain, $\hat{\mathbf{u}}'$ and $\hat{\mathbf{u}}_3$, leads to the derivation of
200 the spectral impedance on the interface Γ , provided schematically with Eq. 2.1 .

$$\hat{\mathbf{t}}(\boldsymbol{\xi}, \mathbf{x}_3 = 0, \omega) = a_0 \mathbf{e}_3 + b_0 \boldsymbol{\xi} + c_0 \boldsymbol{\xi} \times \mathbf{e}_3 \quad (2.1)$$

201 where a_0, b_0 , and c_0 are functions of the wave number vector $\boldsymbol{\xi}$ associated with the
202 local plane coordinate \mathbf{x}' and the pulsation ω . In order to obtain the expression of
203 Eq. 2.1 in the physical domain, an inverse Fourier transform has to be applied.

$$\hat{\mathbf{t}}(\mathbf{x}', \mathbf{x}_3 = 0, t) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \hat{\mathbf{t}}(\boldsymbol{\xi}, \mathbf{x}_3 = 0, \omega) e^{-i(\omega t + \boldsymbol{\xi} \cdot \mathbf{x}')} d\omega d\boldsymbol{\xi} \quad (2.2)$$

204 Eq. 2.2 is not local in time and space. In addition, the computation of the double
205 integral in Eq. 2.2 cannot be conveniently obtained for the general case of a complex
206 geological domain and 3D excitation. In order to simplify the computation of the
207 impedance, (60, 61) proposed to develop the wave numbers for the transverse ξ_s and
208 longitudinal wave ξ_P as a function of the ratio κ .

$$\begin{aligned} \xi_P &= \frac{\omega}{C_P} \sqrt{1 - C_P^2 \kappa^2} \\ \xi_S &= \frac{\omega}{C_S} \sqrt{1 - C_S^2 \kappa^2} \end{aligned} \quad \text{where } \kappa = \frac{|\boldsymbol{\xi}|}{\omega} \quad (2.3)$$

209 where, C_S , and C_P are the shear and longitudinal wave velocity respectively, under
 210 the assumption of linear isotropic elasticity. The wave vectors ξ_S and ξ_P , can now be
 211 approximated through a Taylor expansion in the form of :

$$\xi_a = \frac{\omega}{C_a} \sqrt{1 - C_a^2 \kappa^2} \approx \frac{\omega}{C_a} \left[1 - \frac{1}{2} C_a^2 \kappa^2 + \dots \right] \quad a = S, P \quad (2.4)$$

212 The paraxial approximation of the impedance consists in assuming that the ratio κ
 213 is sufficiently small ($\kappa \ll 1$), and thus the lower orders of the Taylor expansion are
 214 enough for the approximation of the values of ξ_S and ξ_P .

215 It is important to state here that this assumption of $\kappa \ll 1$, is valid for large frequencies
 216 ω , or small ξ (propagation in the direction close to \mathbf{e}_3). More precisely, based on Eq. 2.3,
 217 the wave vectors ξ_S and ξ_P take imaginary values (evanescent waves) for $|C_S \kappa| > 1$,
 218 and thus stability problems appear in the solution. An easy modification that allows
 219 to eliminate the evanescent component of the solution is based on the restriction of
 220 the range of solutions to those waves that propagate within a cone of the \mathbf{e}_3 vector
 221 (paraxial waves).

222 Here, the zero-order paraxial approximation is used in Code_Aster (70). Conse-
 223 quently, the expression of the spectral impedance (Eq. 2.1) can be rewritten in the
 224 schematic form of Eq. 2.5, that can be assimilated to a distribution of linear viscous
 225 dash-pots:

$$\mathbf{t}(\mathbf{x}', x_3 = 0, t) = A_0(\partial_t \mathbf{u}) \quad (2.5)$$

226 where, A_0 is a function of C_S , and C_P representing the shear and longitudinal wave
 227 velocity.

228 Finally, it is well-known that the accuracy of the paraxial approximation could
 229 diminish significantly due to soil material heterogeneity, the increased wave-field com-
 230 plexity, and the angle of incidence of the arriving scattered wave field among others.
 231 Consequently, it is clear that when a more complex diffracted wave field with an an-
 232 gles of incidence far from the vertical one (*e.g.* surface waves, wave scattering) arrives
 233 on the boundary, the zero-order approximation present low absorbing performance
 234 (60, 61). This phenomenon that might impact the size of the finite domain to be
 235 numerically modeled for the SSI problem is discussed in subsection 4.1. In order to
 236 amend for this inconvenience, (60, 61) proposed higher-order approximations in order
 237 to increase the performance of the boundary for higher incidence angles. In a similar
 238 way, higher-order approximations were used by (71) in order to account for material
 239 heterogeneity. These solutions however, increase the complexity of the numerical im-
 240 plementation (involvement of higher-order derivatives of the traction vector on the
 241 boundary) and might cause stability problems.

242 2.2. Variational formulation of the coupling

243 The variational formulation of the coupling is derived here in order to provide the
 244 expression of the external dynamic excitation. On the boundary surface of the reduced
 245 domain Γ , a continuity of the displacement and traction vector needs to be considered
 246 in order to ensure the equilibrium on the interface (Eq. 2.6).

$$\begin{aligned} \mathbf{u}_s - \mathbf{u}'_s &= 0 \\ \mathbf{t}_s + \mathbf{t}'_s(\mathbf{u}'_s) &= 0 \end{aligned} \quad (2.6)$$

247 Based on the *Sommerfeld* radiation condition, the incident wave field \mathbf{u}'_i has to be
 248 equal to the total wave field \mathbf{u}'_s in infinity. Consequently, the diffracted wave field \mathbf{u}'_r
 249 can be expressed following Eq. 2.7.

$$\begin{aligned} \mathbf{u}'_s &= \mathbf{u}'_i + \mathbf{u}'_r \\ \lim_{r \rightarrow \infty} \|\mathbf{u}'_r\| &= 0 \end{aligned} \quad (2.7)$$

250 The diffracted field \mathbf{u}'_r , can now be completely described via the zero-order paraxial
 251 approximation and as a result the traction vector takes the following form.

$$\begin{aligned} \mathbf{t}_s &= -\mathbf{t}'_s(\mathbf{u}'_s) = -\mathbf{t}'_s(\mathbf{u}'_i) - \mathbf{t}'_s(\mathbf{u}'_r) \approx -\mathbf{t}'_s(\mathbf{u}'_i) - A_0(\partial_t \mathbf{u}'_r) \Rightarrow \\ \mathbf{t}_s &\approx -\mathbf{t}'_s(\mathbf{u}'_i) - A_0(\partial_t \mathbf{u}'_s) + A_0(\partial_t \mathbf{u}'_i) \end{aligned} \quad (2.8)$$

252 Finally, the variational formulation of the system can be expressed based on the
 253 expression of the traction vector.

$$\int_{\Omega_s} \rho \partial_{tt} \mathbf{u}'_s \cdot \mathbf{w} d\Omega + \int_{\Omega_s} \boldsymbol{\sigma}'_s : \boldsymbol{\epsilon}(\mathbf{w}) d\Omega + \int_{\Gamma} A_0(\partial_t \mathbf{u}'_s) \cdot \mathbf{w} d\Gamma = \int_{\Gamma} (-\mathbf{t}'_s(\mathbf{u}'_i) + A_0(\partial_t \mathbf{u}'_i)) \cdot \mathbf{w} d\Gamma \quad (2.9)$$

254 External forces representing the dynamic excitation are described from the right-
 255 hand side of Eq. 2.9 from where it is clear that in order to “transfer” the excitation of
 256 the fault close to the domain of interest, only the traction vector $\mathbf{t}'_s(\mathbf{u}'_i)$, and the viscous
 257 stress vector field from the incoming velocity $A_0(\partial_t \mathbf{u}'_i)$ are required. This conclusion is
 258 of crucial importance as it demonstrates which are the necessary fields to be transferred
 259 from SEM to FEM in order to ensure the coupling.

260 2.3. Coupling procedure and comparison methodology

261 The traction vector $\mathbf{t}'_s(\mathbf{u}'_i)$ and the incident wave velocity field $\dot{\mathbf{u}}'_i$, are the necessary
 262 fields needed in order to correctly construct the transient dynamic impedance with the
 263 paraxial elements on the boundary Γ of the reduced domain. Nevertheless, special care
 264 needs to be taken in the definition of this traction vector for each one of the numerical
 265 solutions.

266 Kinematic fields such as displacement and velocity, are discrete fields directly ob-
 267 tained as the solution of the numerical time integration scheme in each one of the
 268 two computational software. On the contrary, the traction vector, is obtained after a
 269 post-processing procedure, which is fundamentally different between SEM and FEM,
 270 due to their differences in terms of formulation (shape functions, quadrature rules and
 271 degrees of freedom-dofs). In consequence, the approximation introduced from a direct
 272 transfer of a traction vector on the boundary of the reduced domain might lead to
 273 important errors in the definition of the dynamic excitation.

274 A remedy to this approximation, consists in reconstructing the traction vector on
 275 a FEM framework, based on the more accurate expression of the displacement fields
 276 directly obtained as the solution of the wave propagation problem in SEM3D.

277 Consequently, the necessary kinematic fields to be “transferred” between the two
 278 software are : i) the displacement field \mathbf{u} , exported in an auxiliary layer neighboring
 279 to the reduced domain boundary so as to reconstruct the traction vector in a FEM

280 framework, and ii) the velocity field $\dot{\mathbf{u}}$ exported on the reduced domain boundary (Fig.
281 2).

282 A schematic representation of the coupling between SEM and FEM is presented in
283 Fig. 2 and the procedure of field transfer is executed as follows:

- 284 (1) Define the surface boundary of the DRM interface and the neighboring auxiliary
285 layer in SEM domain (Fig. 2a).
- 286 (2) Export displacement and velocity fields $(\mathbf{u}, \dot{\mathbf{u}})$ on predefined sensor points on
287 GLL points lying on the DRM boundary and auxiliary layer. These points are
288 the nodes of the FEM mesh and the kinematic fields are obtained using the high
289 order basis functions of SEM. No spatial interpolation is therefore needed at
290 this interface, since a matching correspondence between SEM and FEM dofs is
291 enforced.
- 292 (3) On the auxiliary layer (Fig. 2b), impose nodal displacement field \mathbf{u} and compute
293 the traction vector solving the static problem with FEM. The traction vector
294 defined on nodes is simply the nodal forces.
- 295 (4) In the reduced domain (Fig. 2c), reconstruct the dynamic excitation from using
296 the velocity field $\dot{\mathbf{u}}$ directly exported from SEM, and the nodal forces F_{node}
297 computed in FEM from the auxiliary layer model.

298 All field transfer between the SEM and FEM codes was performed using MEDCou-
299 pling, an open-source SALOME¹ tool used for mesh/field handling (72).

300 It is important to state here that the proposed methodology for the computation of
301 the traction vector is based on the assumption of hexahedral 8-node linear elements
302 within the FEM. One of the main advantages of the finite element method lies in the
303 fact that quadratic elements as 10-node tetrahedral ones can be used in the numerical
304 model so as to represent any more complex geometries as well as decrease the number of
305 points per wavelength for a correct wave propagation. In this framework, the proposed
306 methodology for the traction vector calculation has to be adapted to a reduced domain
307 discretized with quadratic tetrahedral elements between step 3 and 4 of the coupling
308 procedure.

309 As already discussed in the introduction, the difference of the proposed methodology,
310 comparing to the one proposed by several authors in the literature ((29, 57–59, 63)
311 among others) lies in the fact that the dynamic excitation is imposed directly on
312 the boundary of the reduced domain. This provides an important advantage deriving
313 from the use of the paraxial elements. In this context no extra absorbing soil layers
314 are needed so as to absorb outgoing waves and as a result the size of the FEM domain
315 to model is less important.

316 2.4. Strategy for the spatial and temporal discretization of the problem

317 The main hypothesis for the spatial and time discretization of the finite element model
318 are presented hereafter. The presented assumptions are to be considered later in the
319 numerical verification of the SEM-FEM coupling approach as well as in the numerical
320 applications on the SSI problem.

¹<https://www.salome-platform.org/>

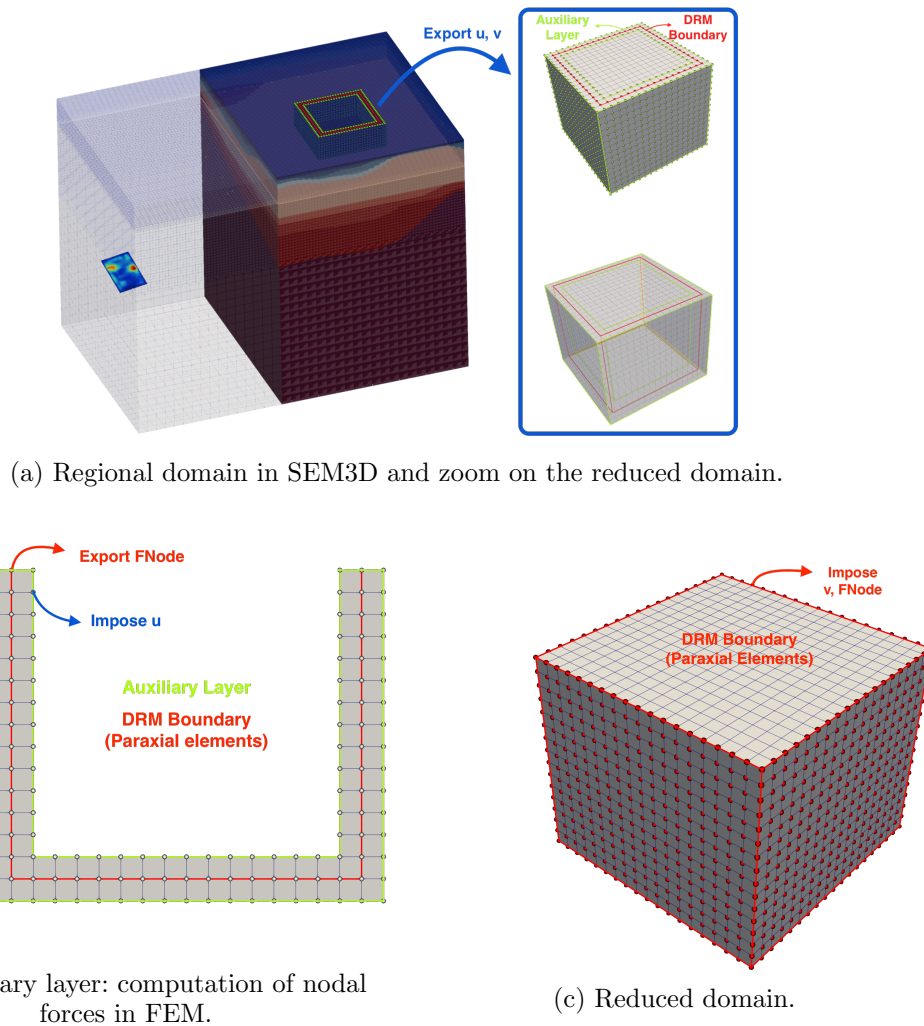


Figure 2.: Schematic representation of the coupling procedure between SEM3D and code_aster.

321 2.4.1. Spatial discretization

322 According to (5, 73, 74), seismic wave propagation with the SEM can be accurately
 323 modeled when a number of $N = 5$ points per wavelength (or equivalently a 4th order
 324 GLL approximation) is adopted for the spectral elements. Based on this assumption,
 325 the maximum size of the spectral elements on the basin, and the minimum shear wave
 326 velocity, the maximum frequency of the spectral element model can be estimated.

327 Element size for the FEM model is defined based on this maximum frequency of
 328 the SEM model. In a similar way as with the SEM, in FEM the empirical rule says
 329 that 10 points per wavelength are sufficient when linear elastic finite elements are used
 330 (75). As a result, the element size in FEM can be fixed at $\Delta x_{FEM} = \frac{V_s^{min}}{10 \times f_{max}}$. This
 331 size corresponds to the spacing between the sensor points introduced in SEM3D in
 332 order to export the necessary kinematic fields. As explained in the description of the
 333 coupling procedure, the kinematic fields are exported directly on the sensor points
 334 after an interpolation inside SEM taking into advantage the high order basis functions
 335 of the spectral element method.

336 In a similar SEM-FEM weak coupling approach, (76) stated that a ratio of 1/8
 337 between the FE (Δx_{FEM}) and the SE element size is sufficient for a 4th order GLL
 338 approximation. Nevertheless in this study we stick to a ratio of 1/10 in order to satisfy
 339 the assumption of 10 points per wavelength.

340 2.4.2. Time discretization

341 An explicit 2nd order (*leap-frog*) time-integration scheme (13) is used for the numerical
 342 time-integration in SEM3D, while an average constant acceleration implicit scheme
 343 is considered in the finite element context with (77). One of the major difficulties
 344 when coupling explicit and implicit time-integration schemes lies in the difference of
 345 the computational time-step. In the explicit scheme smaller time-steps are usually
 346 necessary so as to ensure the stability of the time-integration scheme. This is not the
 347 case for the average constant acceleration implicit scheme which is unconditionally
 348 stable and thus larger time-steps can be chosen (without excess, to avoid a too large
 349 period distortion).

350 In this framework, an optimization procedure is proposed here in order to increase
 351 the efficiency of the coupling procedure in terms of computational time and memory
 352 demand. This optimization consists of a re-sampling/decimation procedure to be ap-
 353 plied to the initial signal exported from SEM before introducing it to the finite element
 354 computation. As already explained, the main goal is to obtain a larger time-step in
 355 the implicit solver than the one of the explicit one.

356 In the decimation/downsampling procedure in digital signal processing (DSP) the
 357 Nyquist frequency, f_{NQ} , plays a crucial role in aliasing effect. More specifically, any
 358 frequency component above the Nyquist frequency will cause aliasing of the final signal.
 359 In order to avoid aliasing special anti-aliasing filters need to be applied before re-
 360 sampling the signal.

361 The re-sampling steps are summarized as following:

- 362 (1) **Define the maximum frequency f_{max} of the problem :**
 363 The f_{max} is the frequency that the spectral element code can propagate for a
 364 given order of GLL approximation and mesh discretisation (section 2.4.1).
- 365 (2) **Define the Nyquist frequency f_{NQ} :**
 366 The Nyquist f_{NQ} (or cut-off frequency) is considered close to the maximum
 367 frequency of the problem. The Nyquist frequency is to be defined prior to the
 368 filtering.
- 369 (3) **Apply the anti-aliasing filter:**
 370 Low-pass filter the kinematic fields for the value of f_{NQ} . The filter used in all of
 371 the presented cases is an order 8 Chebyshev type I filter.
- 372 (4) **Define the new sampling frequency f_S :**
 373 Compute $f_S = 2 \times f_{NQ}$.
- 374 (5) **Define the new time-step of the input signal Δt_{CA}^{input} :**
 375 Compute $\Delta t_{CA}^{input} = \frac{1}{f_S}$

376 It is important to clarify at this level that the Δt_{CA}^{input} of the input signal should not
 377 be confused with the time-step of the FEM computation. Even if the time integration
 378 is implicit in the FE solution, for reasons of accuracy a smaller time-step $\Delta t_{implicit}$ is
 379 to be considered for the computation. A flow-chart of the aforementioned approach is
 380 given in the Fig. 3.

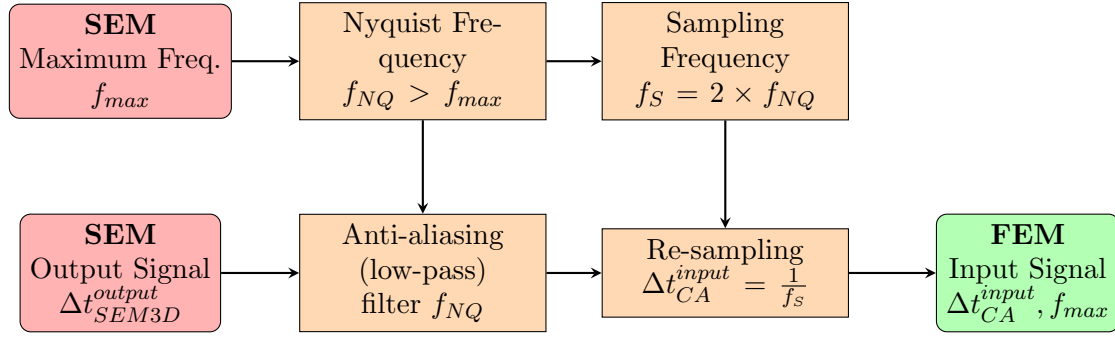


Figure 3.: Optimization procedure of the FEM input signal.

381 2.5. Comparison procedure: Goodness-of-fit (GOF) criteria

382 In order to compare the obtained solution with a solution of reference, efficient compar-
 383 ison criteria taking into account phase as well as amplitude errors should be considered.
 384 The current evaluation of numerical results is based here on the use of the goodness-
 385 of-fit criteria (GOF) proposed by (78, 79). The main advantages of these approaches
 386 is based on the time-frequency representation (TFR) of the seismic signal, which is
 387 obtained after a continuous wavelet transformation. In this context, the evolution of
 388 the frequency content of the signal with respect to time can be easily represented and
 389 thus local time-frequency differences can be identified. Based on the aforementioned,
 390 a single value goodness-of-fit (GOF) criterion, can be defined for the envelope and
 391 the phase of the signals to be compared. This single value GOF criterion will be used
 392 here so as to evaluate the solution obtained from the coupling approach. For the sake
 393 of simplicity, the expression of the GOF for the envelope and phase criteria is briefly
 394 provided here. For more information concerning alternative comparisons and a more
 395 detailed description of the theoretical background of the comparison methods, the
 396 reader should refer to (78, 79).

397 The local time-frequency (TF) envelope and phase difference can be defined from
 398 Eq. 2.10 as follows :

$$\begin{aligned} \Delta E(t, f) &= |W(t, f)| - |W_{REF}(t, f)| \\ \Delta P(t, f) &= |W_{REF}(t, f)| \frac{\{Arg[W(t, f)] - Arg[W_{REF}(t, f)]\}}{\pi} \end{aligned} \quad (2.10)$$

399 where $W(t, f)$, and $W_{REF}(t, f)$ are the continuous wavelet transforms (TFR) of the
 400 signal to be evaluated and the signal of reference respectively.

401 Based on these TFR the single value misfit criteria for the envelope and the phase
 402 are obtained from Eq. 2.11 :

$$\begin{aligned} EM &= \sqrt{\frac{\sum_f \sum_t |\Delta E(t, f)|^2}{\sum_f \sum_t |W_{REF}(t, f)|^2}} \\ PM &= \sqrt{\frac{\sum_f \sum_t |\Delta P(t, f)|^2}{\sum_f \sum_t |W_{REF}(t, f)|^2}} \end{aligned} \quad (2.11)$$

403 Finally, based on these misfit-single value criteria, the GOF can be defined by Eq. 2.12:

$$\begin{aligned}
 EG &= A \exp\{-|EM|^k\} \\
 PG &= A \exp\{-|PM|^k\}
 \end{aligned}
 \quad \text{where } A > 0, \quad k > 0 \quad (2.12)$$

404 where A is a parameter that quantifies the correspondence between the signal of ref-
 405 erence and the computed one and k determines the sensitivity of the GOF value. For
 406 the specific case of $A = 10$ and $k = 1$ the criterion is similar to the formula proposed
 407 by (80). The result provided from this comparison is a score in the scale of 0 to 10
 408 allowing to evaluate the similarity of the two signals: i) for a value of 0 there is no cor-
 409 respondence between the two signals while for a value of 10 a perfect correspondence
 410 can be observed.

411 Finally, according to (80), based on the GOF score, the correspondence between
 412 the two signals can be verbally quantified as presented in Table 1:

Table 1.: Verbal representation of the discrete GOF score (adapted from (80))

Goodness-of-Fit	
Verbal Value	Numerical Value
Excellent	8 - 10
Good	6 - 8
Fair	4 - 6
Poor	0 - 4

413 3. Numerical verification for a canonical case-study

414 For the numerical verification of the coupling procedure, the auxiliary domain problem
 415 (Fig. 1b) is considered identical to the initial problem of reference (Fig. 1a). In this
 416 context, the equivalent nodal forces correspond to the exact solution of the seismic wave
 417 propagation problem and their application on the reduced domain should generate a
 418 soil response, in the reduced domain, that is identical to the one obtained from the
 419 problem of reference. Numerical verification is provided here for the canonical case of
 420 CAN4 (81, 82), and the coupling is verified for an increasing complexity of the dynamic
 421 excitation source in order to evaluate the efficiency of the proposed approach.

422 3.1. Description of the numerical model

423 The geometry of the case-study to be modeled numerically in SEM3D is given in Fig. 4.
 424 It consists of a $22 \times 12 \times 6 \text{ km}^3$ soil domain with a trapezoidal basin on the surface.

425 In SEM3D, 11,800 spectral elements are used to model the problem, with five Gauss-
 426 Lobatto-Legendre (GLL) points in each direction of the element. The minimum ele-
 427 ment size is of $40 \times 40 \times 15 \text{ m}^3$ on the surface, and inside the trapezoidal basin. The
 428 reduced domain (DRM) consists of a $200 \times 200 \times 110 \text{ m}^3$ box represented with 78,700
 429 finite elements. The center of the DRM domain is positioned in the beginning of the
 430 axis O (0.0, 0.0, 0.0) m (red box in Fig. 4).

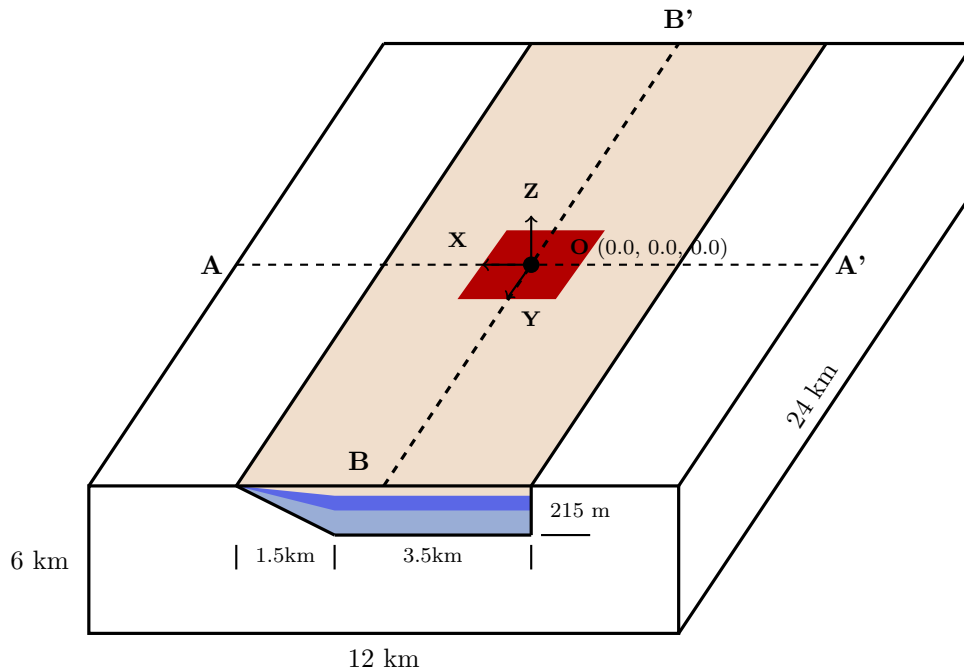


Figure 4.: Canonical case-study CAN4.

431 Mechanical properties of the numerical SEM3D model are given in Table 2. For the
 432 numerical verification purpose, no damping is considered in the numerical model.

Table 2.: Mechanical properties of the numerical model.

	Thickness at O (0, 0, 0)	C_S [m/s]	C_P [m/s]	ρ [kg/m ³]
Soil	15.8	400	1100	1800
	47.4	500	1400	2100
	142.4	650	2500	2200
Rock	5785	2600	4500	2600

433 3.1.1. Dynamic excitation and absorbing boundary conditions

434 Perfectly Matched Layers (PML) (83), is the adopted absorbing boundary condi-
 435 tion ensuring the absorption of spurious waves arriving on the outer boundary of the
 436 SEM3D domain.

437 The dynamic excitation within the SEM3D domain will be introduced based on two
 438 different types of source models: i) a double-couple point-source, and ii) an extended
 439 fault excitation (84).

440 The first type of dynamic excitation used in SEM3D is the one proposed in the
 441 canonical case of CAN4 (82). It consists of a double-couple point-source excitation
 442 with a strike of 22.5° , dip of 90.0° , and rake of 0.0° . The seismic moment of the source
 443 is reduced to $M_0 = 8.7 \cdot 10^{15}$ N.m from the initial value in order to have a lower
 444 magnitude earthquake and the moment time history is presented with Fig. 5. The
 445 hypocenter of the point source is located at (50 m , 0 m, -3000 m).

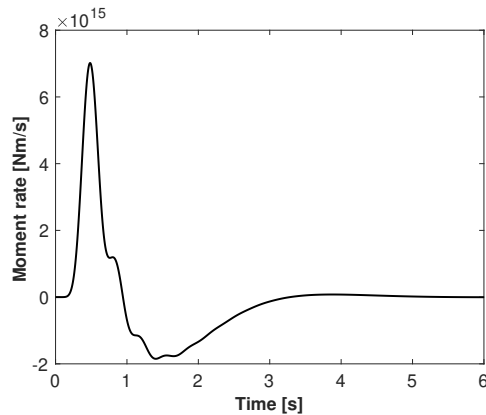


Figure 5.: Moment time history for the point-source (see also CAN4 and (82)).

446 Concerning the second verification model, the extended fault of 3×3.5 km has a
 447 Strike of 180° , Dip of 7.8° , Rake of -179° and its hypocenter is located at (2164 m,
 448 0 m, -1772 m) (Fig. 6a). Total seismic moment of the extended fault is equivalent to
 449 $M_0 = 4.63 \cdot 10^{15}$ N.m ($M_w \approx 4.4$). The time distribution of the seismic moment M_0
 450 based on the position of different sub-sources of the fault is given with Fig. 6b. The
 451 maximum slip generated from the fault is around 0.06 m and the slip distribution
 452 along with the triggering time are given in Fig. 6c, while the source time function
 453 is provided in Fig. 6d. The rupture process of this kinematic source is based on a
 454 waveform inversion procedure with the empirical Green function (EGF) as described
 455 in (84).

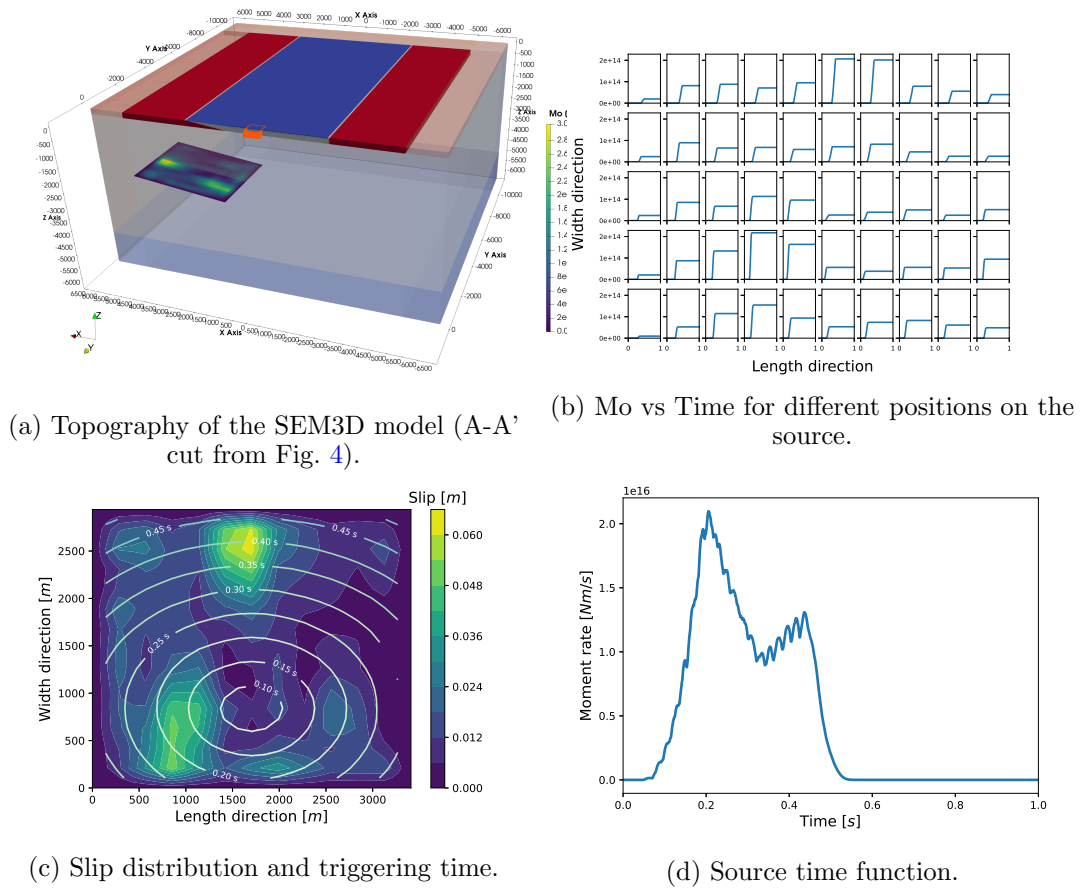


Figure 6.: Description of the extended fault excitation in the SEM domain.

456 3.2. No re-sampling approach

457 The numerical verification of the SEM-FEM weak coupling is provided at first and for
 458 the unprocessed SEM3D output ($\Delta_{SEM3D}^{output} = 0.002s$) where the proposed optimization
 459 procedure (re-sampling) is not adopted for the exported kinematic fields. The goal of
 460 this part is to numerically verify the coupling approach by a direct injection of the
 461 “recorded” signal obtained from SEM3D. Following the coupling description discussed
 462 in subsection 2.4 and based on the mechanical properties of the soil domain (Table 2)
 463 spatial and time discretization of the SEM and FEM numerical models are gathered
 464 in Table 3.

Table 3.: Spatial and temporal discretization - *No re-sampling*.

Model Parameters	
V_S^{min} [m / s]	400
Element size FEM [m]	$4 \times 4 \times 4$
Nb Nodes (Interface)	$4 \times 4 \times 4$
Maximum targeted freq. [Hz]	10
Time-step output signal (SEM3D) [s]	0.002
Nyquist freq. [Hz]	250
Sampling freq. [Hz]	500
Time-step input signal (FEM) [s]	0.002
Time-step computation (FEM) [s]	0.002

465 Based on the value of $f_{max} = 10$ Hz, the output signals at surface from both models
 466 are band-pass filtered between 0.1 - 10 Hz. Comparison of the numerical results is
 467 provided according to the iso-surface of the GOF score of the criteria of (78) presented
 468 in Fig. 7. According to this Fig. 7, the GOF score is equal to almost 10 everywhere
 469 in the soil surface of the reduced domain. Similar results are observed for both types
 470 of excitation source, however only the extended fault excitation is presented in Fig. 7
 471 and for reasons of brevity. Consequently, a good agreement is considered between the
 472 full-SEM3D response and the one from the DRM solution (see also Table 1).

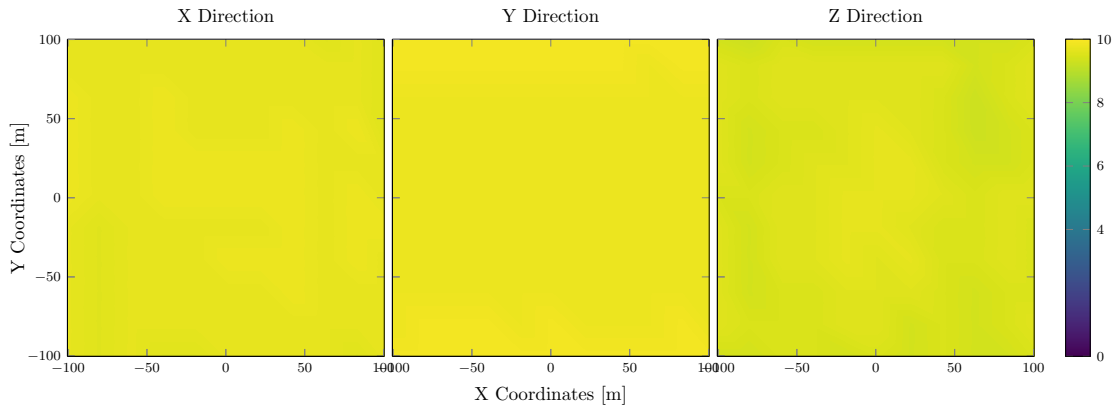


Figure 7.: Iso-surface of the GOF criteria for the extended fault excitation and on the soil surface of the reduced domain.

473 Finally, numerical results are also compared in terms of acceleration time-histories
 474 (Fig. 8) for several points at the surface of the reduced domain and along the BB'
 475 cut in Fig. 4. Similar to the conclusions obtained from the GOF score on the surface,
 476 this figure also shows a good agreement between the full-SEM3D simulation, denoted
 477 as “SEM3D” in Fig. 8, and the SEM-FEM coupled solution denoted as “DRM” on
 478 the same figure.

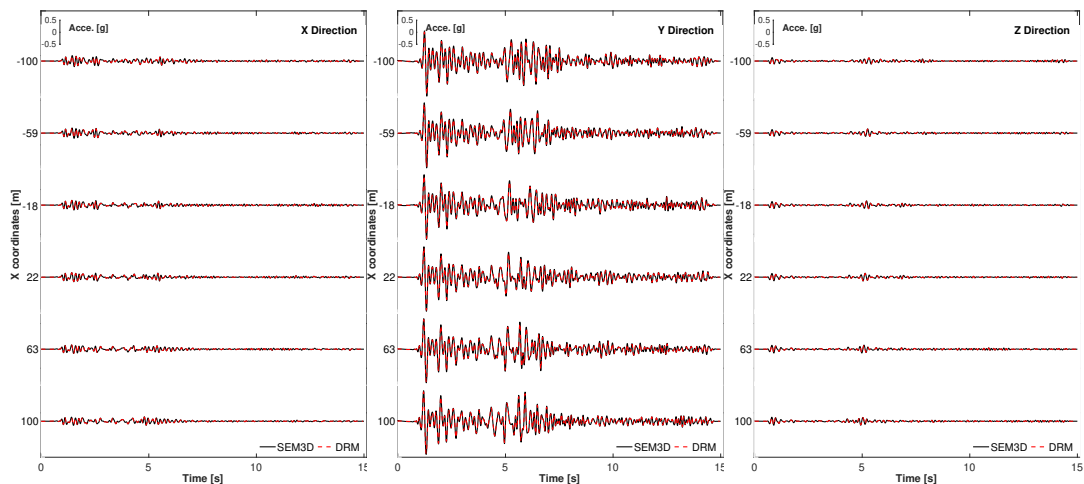


Figure 8.: Comparison of the acceleration time-histories between the “SEM3D” solution and the “DRM” approach: X (left), Y (center), and Z (right) component.

479 **3.3. Optimization approach: re-sampling of the input signal**

480 Following the analysis described in subsection 2.4, the optimization of the transfer
 481 of kinematics fields is adopted here. A parametric study on the Nyquist frequency
 482 definition is considered at first so as to evaluate the impact of this value on the accuracy
 483 of the coupling results. Five different cases are considered and summarized in Table 4
 484 for both types of excitation source.

Table 4.: Spatial and temporal discretization - *re-sampling approach*.

Starting Parameters					
V_S^{min} [m / s]	400				
Element size FEM [m]	$4 \times 4 \times 4$				
Maximum targeted freq. [Hz]	10				
Time-step output signal (SEM3D) [s]	0.002				
Cases	1	2	3	4	5
Nyquist freq. [Hz]	250	40	20	15	12.5
Sampling freq. [Hz]	500	80	40	30	25
Time-step input signal (FEM) [s]	0.002	0.012	0.024	0.032	0.04
Time-step FEM computation (FEM) [s]	0.002	0.002	0.002	0.002	0.002

485 For each one of the five cases, the re-sampled input signal is compared to the initial
 486 one (before re-sampling/obtained from SEM3D), in terms of GOF score. Comparison is
 487 provided everywhere on the boundary of the reduced domain and for the Y component
 488 of the displacement, velocity which are the kinematic fields of interest (see also section
 489 2.3). For the sake of brevity, only the case of the extended fault is presented hereafter.
 490 The score on the lateral boundaries is “flattened” and plotted on the same plane as
 491 the base of the reduced domain, in order to provide an easier visual presentation. For
 492 values of $GOF < 9$ the same color (gray) is used to represent each point (Fig. 9).

493 Based on the values of the GOF score (Fig. 9), the impact of the re-sampling process
 494 is more important for the velocity field, and practically vanishing for the displacement
 495 field, where higher scores are observed. In addition, according to the same Fig. 9 as
 496 the Nyquist frequency approaches the value of the maximum frequency of the problem
 497 ($F_{NQ} = 40 \rightarrow 12.5\text{Hz}$), the lower is the score of the GOF criteria. This effect is related
 498 to the low-pass filter applied before the re-sampling as the cut-off frequency of the
 499 low-pass filter (or equivalently the Nyquist frequency) does not consist of an exact
 500 limit value for the activation of the filter.

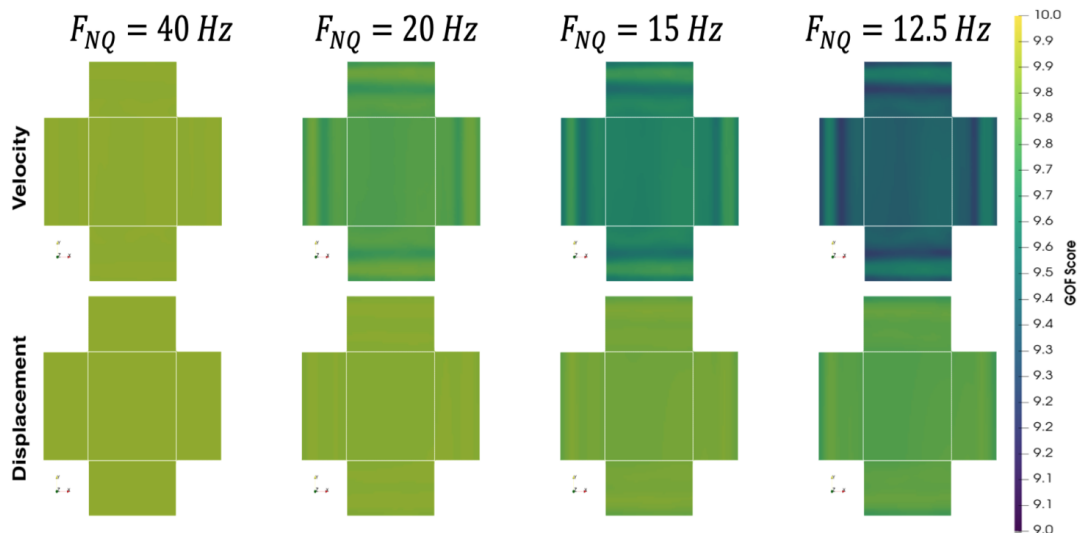


Figure 9.: Score of the GOF criteria on the boundaries of the reduced domain for the Y component. Comparison between the signal or reference (SEM3D) and the re-sampled one. Lateral sides of the reduced domain are flattened on the plane of the base.

501 Naturally, the same Nyquist frequency should provide a higher score of the GOF
 502 criteria for a smaller range of frequencies of interest (0.1 - 8 Hz for example). Fig. 10
 503 shows the score of the GOF criteria based on the position along the AA' line (see also
 504 Fig. 4) on the surface of the reduced domain, and for the five different cases of Table 4.
 505 Two different values of f_{max} are considered for the current case: i) $f_{max} = 10$ Hz in
 506 Fig. 10a, and ii) $f_{max} = 6$ Hz in Fig. 10b.

507 As the Nyquist frequency approaches $f_{max} = 10$ Hz (Fig. 10a), lower values of
 508 GOF score are obtained. Both types of sources provide comparable results in terms
 509 of GOF score with the point-source providing a higher score than the extended fault.
 510 For $F_{NQ} = 20$ Hz ($= 2 \times f_{max}$), $GOF > 9$ for all the control points and all
 511 three directions, while for $F_{NQ} = 12.5$ Hz $GOF < 8.5$ in certain points.

512 Nevertheless, repeating the same exercise for a different $f_{max} = 6$ Hz, generates
 513 higher scores even for a Nyquist frequency of $F_{NQ} = 12.5$ Hz (Fig. 10b). As already
 514 expected, this shows that the re-sampling procedure and the Nyquist frequency depend
 515 on the targeted maximum frequency that needs to be considered in the FE numerical
 516 model.

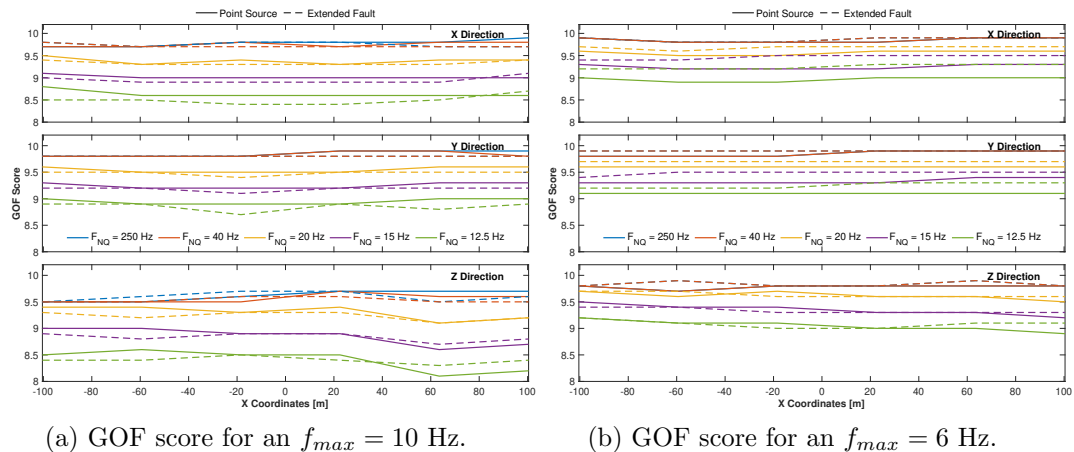


Figure 10.: Evolution of the GOF score along the AA' cut on the soil surface of the reduced domain.

517 From a computational point of view, Fig. 11, presents the evolution of CPU time
 518 and file size of the input data (in FEM), with respect to the Nyquist frequency defined
 519 in the re-sampling approach. As expected, even for the lowest re-sampling value (case
 520 2) the gain on the computation time is around 2.5, while the size of the input files
 521 to be read for the FEM solution is divided by 6. These elements maybe do not seem
 522 so important referring to the size of the current problem, nevertheless they could be
 523 of crucial importance for increasing number of dofs. In order to ensure the quality of
 524 the numerical solution, a score of $GOF > 9$ is required everywhere in the domain. As
 525 a result, the Nyquist frequency $f_{NQ} = 20$ Hz is chosen for this case as it provides a
 526 balance between accuracy of the solution and numerical performance.

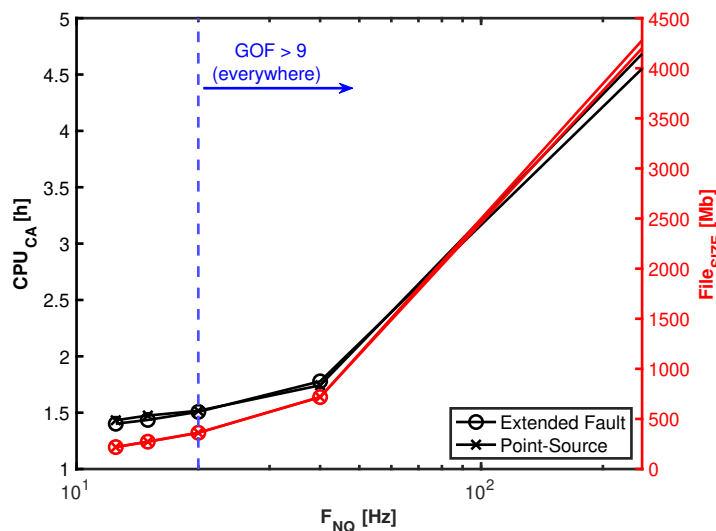


Figure 11.: Evolution of CPU time and file size with respect to the Nyquist frequency.

527 Consequently, adopting $f_{NQ} = 20$ Hz, the numerical results of the coupling (DRM)
 528 are compared to the full-SEM3D wave propagation. Comparison is based on the ac-
 529 celeration time-histories along the AA' line on the soil surface of the reduced domain
 530 and presented in Fig. 12a for the point-source and Fig. 12b for the extended fault. A
 531 perfect correspondence can be observed between the two signals.

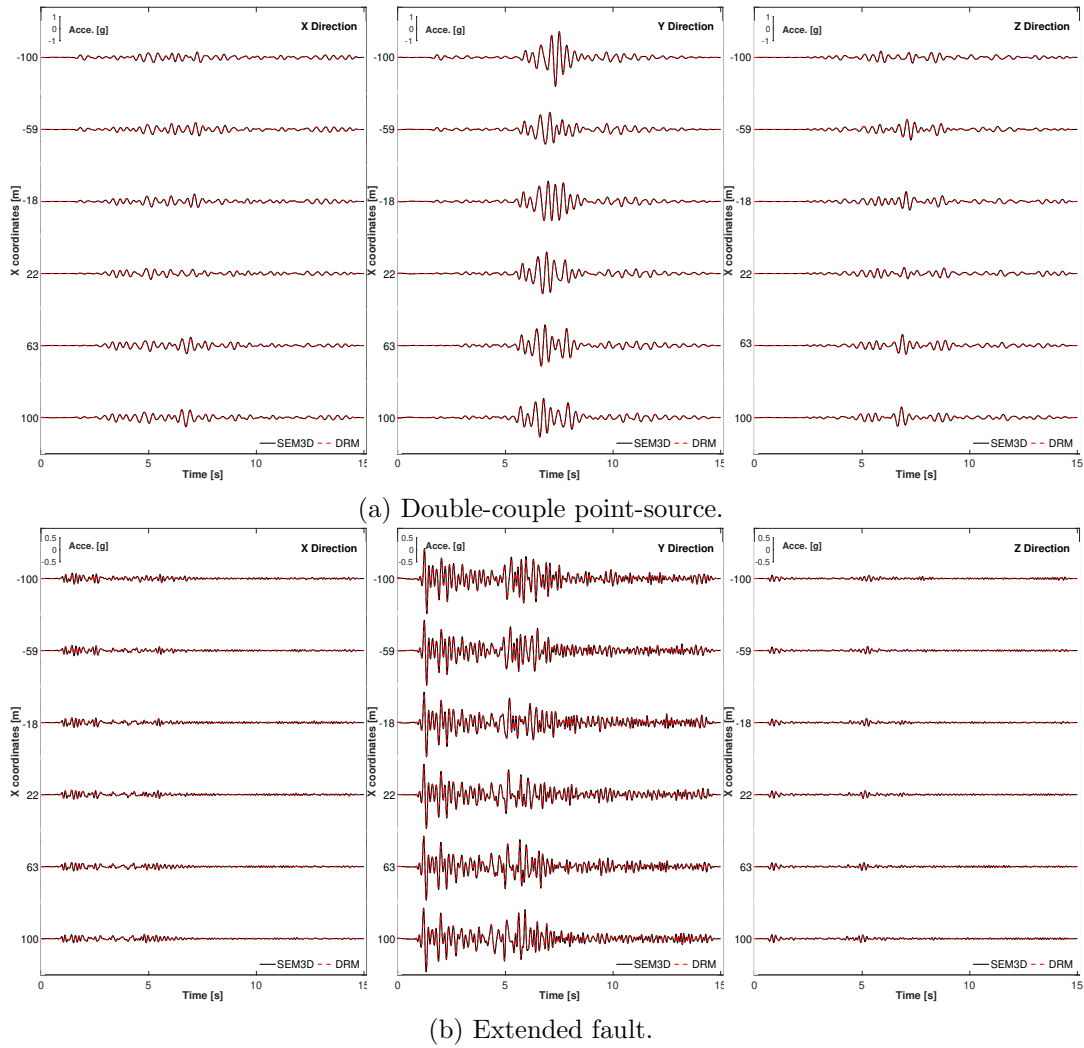
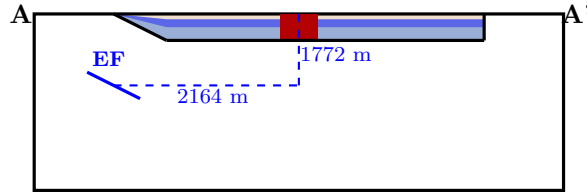


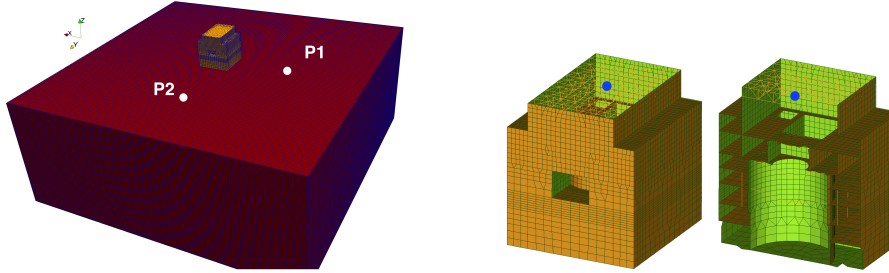
Figure 12.: Comparison of the acceleration time-histories between the “SEM3D” solution and the “DRM” approach: X (left), Y (center), and Z (right) component.

532 4. An application on the Soil-Structure Interaction problem

533 The proposed methodology is tested here to define the dynamic excitation in a soil-
 534 structure interaction (SSI) analysis (Fig. 13). The study focuses at first on the impact
 535 of the reduced domain size to be used on the SSI model. Model size in terms of accuracy,
 536 and computational efficiency are presented at first in order to evaluate important
 537 elements in the coupling procedure. Once the size is fixed, an analysis of structural
 538 and site response are provided for the current case.



(a) SEM3D model with reduced domain (red square) and the extended fault (EF) excitation.



(b) Reduced domain with the structure. (c) Zoom on the mesh of the structure.

Figure 13.: Representation of the SSI model.

539 In the following, the geology of the soil domain as well as the dynamic source
 540 (extended fault - Fig. 13) are the ones previously described in section 3.1 for the
 541 numerical verification of the coupling approach. The considered structure is the Unit
 542 7 reactor building of Kashiwazaki-Kariwa nuclear power plant, as it is a well studied
 543 structural model thanks to the OCDE/NERA Karisma benchmark (85). For sake of
 544 simplicity, shallow foundation is considered and the structure is located on the surface
 545 and at the center of the reduced domain. The overall dimensions of the building are
 546 (in meters) : $55 \times 55 \times 60$ and it is modeled using beam and shell linear elastic finite
 547 elements. For a more detailed description of the building, the reader may refer to e.g.
 548 (25).

549 4.1. Impact of the reduced domain size

550 One of the main advantages of the DRM approach being the decrease of the size
 551 of the problem in terms of degrees of freedom (DOF), a legitimate question that
 552 quickly comes in mind concerns the size to be used for the dimension of the SSI
 553 model domain. Several authors have been using the DRM approach to introduce a 3D
 554 dynamic excitation on the reduced domain, however in most of these cases, the size of
 555 the reduced domain seems to be arbitrarily chosen without any specific justification.
 556 One of the most common choices consists of considering the boundary where the forces
 557 are applied at a distance that is equal to one time the size of the foundation as it was
 558 proposed by (38, 58, 63) among others. Nevertheless, a starting point of all these
 559 studies is the adoption of an elasto-plastic soil behavior with an associated Rayleigh
 560 damping for the soil media. In a similar framework, (57) considers a reduced domain
 561 extending $3 \times \lambda_S$, where λ_S is the larger shear wave length, in the vertical as well as
 562 horizontal direction for each side of the model. No material damping is considered in
 563 this study.

564 In the present analysis, three different size models (Fig. 14) for the reduced domain
 565 are considered to examine the response of the structure: i) small (200K dofs), ii)

566 medium (2.8M dofs), and iii) large (7M dofs). The different sizes are chosen as a
 567 function of the wavelength $\alpha \times \lambda_S$, where $\lambda_S = 65$ m, and α is a parameter varying for
 568 each model. As previously mentioned, (57) considers an $\alpha = 3$ for the lateral boundary,
 569 while in this study a value of $\alpha = 1, 4, 6.5$ is considered for the small, medium and large
 570 model respectively. Vertical size for the medium and large model are fixed at $3 \times \lambda_S$
 571 as in (57). Large model is considered the solution of reference, and a comparison is
 572 done for the other two model sizes.

573 As in the numerical verification case, no material damping is considered for the soil
 574 layer, which remains linear elastic, and dynamic excitation comes from the extended
 575 fault excitation used in the numerical verification approach.

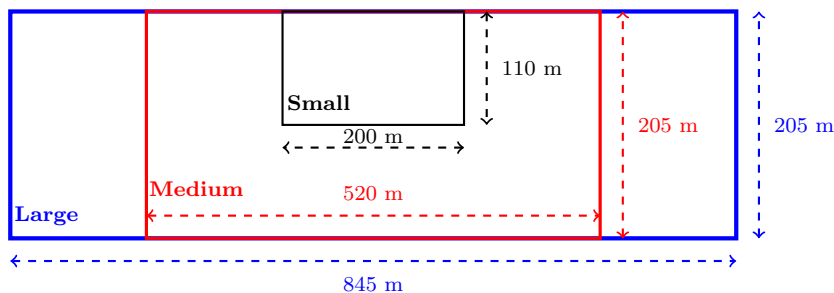


Figure 14.: Different sizes of the reduced domain.

576 The total prediction residual, Δ , for a given intensity measure (IM) expressed with
 577 Eq. 4.1 is used to evaluate the impact of the domain size.

$$\Delta = \ln(IM_{REF}) - \ln(IM_{SIM}) \quad (4.1)$$

578 where, $\ln(IM_{REF})$ is the natural logarithm of the case of reference (model large), and
 579 $\ln(IM_{REF})$ the natural logarithm of the simulated one (small or medium). The IM
 580 chosen in this case is the 5%-damped response spectral acceleration (PSA) for a point
 581 at the top and the base of the structure.

582 Comparison of the numerical results are presented in Fig. 15, in terms of acceleration
 583 time-histories as well as the total residual for the 5%-damped spectral acceleration
 584 (Eq. 4.1). Results are examined for a point at the bottom Fig. 15a and 15c and the
 585 top of the structure Fig. 15b and 15d. According to this Fig. 15, the small model
 586 provides a response that differs from the model of reference while the medium and
 587 large domains provide identical results both in the base as well as at the top of the
 588 structure. As a result the medium model size is considered sufficient to represent
 589 structural response in this specific framework.

590 In addition, to represent the “perturbed” soil volume due to the presence of the
 591 structure, the GOF criterion is computed for the soil volume and for the three different
 592 sizes of the domain. The comparison for the Y component of the excitation is presented
 593 in Fig. 16, where it can be seen that in the small domain, the presence of the structure
 594 has an important impact on the perturbation of the neighboring soil domain. On the
 595 contrary, the medium as well as the large domain provide higher scores closer to the
 596 boundary and the perturbation is localized on the center near the structure. As a
 597 result, it can be said that the seismic input introduced in the medium and large model
 598 is almost equivalent as the diffracted waves from the structure do not impact this zone.

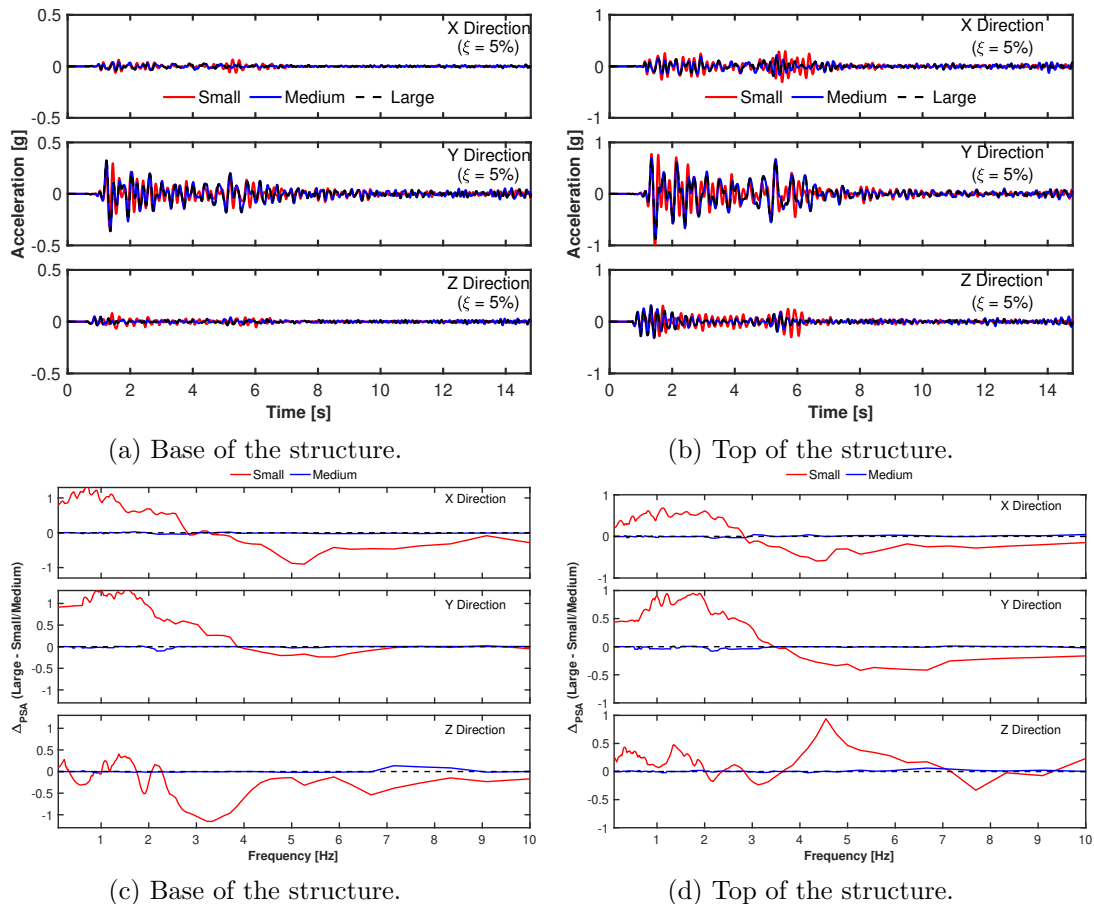


Figure 15.: Comparison for different model sizes: acceleration time-histories (top row), and total residual for the 5%-damped spectral acceleration (bottom row).

599 This last observation also explains why structural response from medium and large
600 models is practically the same.

601 Consequently, when no material damping is considered in the numerical model,
602 an one-bay width reduced domain is considered insufficient for the description of the
603 structural response. On the contrary, when a boundary-structure distance larger than
604 $4 \times \lambda_S$ is considered in each side of the structure, a convergence is observed on structural
605 response. The results hold for the specific framework of the examined case-study.

606 Finally, in order to bring to surface the importance of the optimization procedure
607 discussed in the previous section and inspired by the work of (8), a performance
608 indicator is used based on Eq. 4.2.

$$I = \frac{CPU_{FEM} \cdot File_{SIZE}}{DOF \cdot Memory_{FEM}} \left[\frac{h \cdot Mb}{Mb} \right] \quad (4.2)$$

609 where CPU_{FEM} is the computational time for the FEM resolution, $File_{SIZE}$ is the
610 size of the transferred data between SEM-FEM, DOF is the degrees-of-freedom of the
611 model, and $Memory_{FEM}$ is the memory used in the FEM model for the resolution.

612 The idea here is to show the gain in terms of CPU time, memory demand on the
613 FEM computation as well as the size of the input data for a specific size of the problem

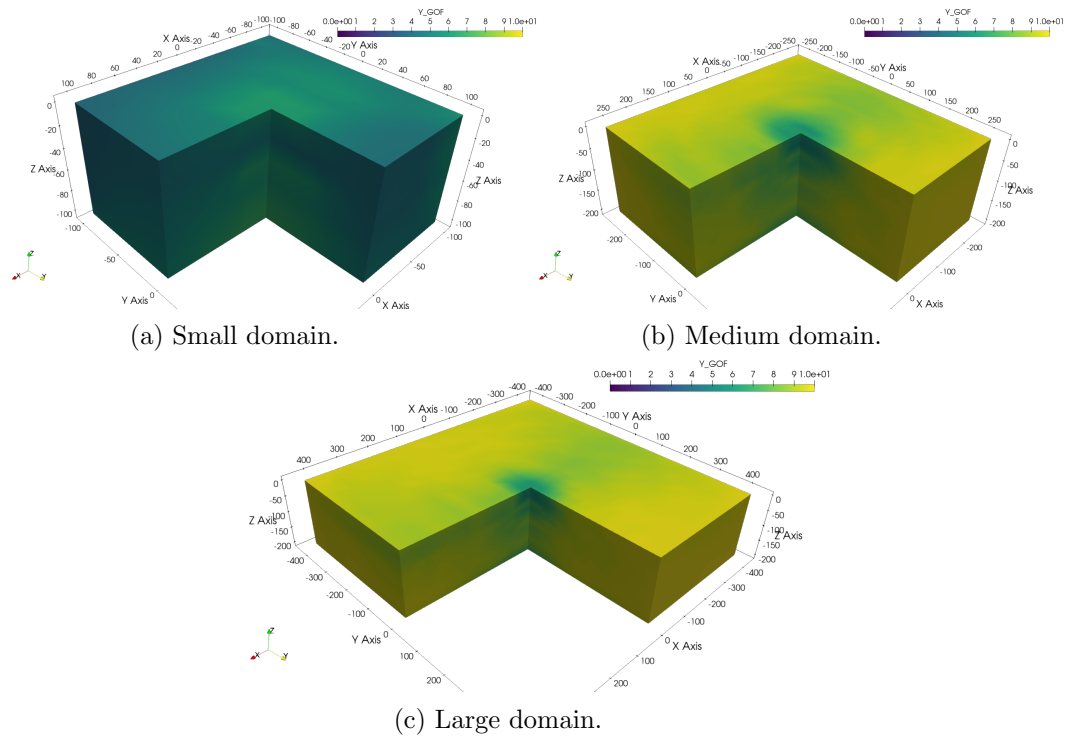


Figure 16.: GOF score on the soil volume for the 3 sizes of the reduced domain.

614 in terms of DOFs. The indicator I of Eq. 4.2, is plotted with respect to the evolution
 615 of the Nyquist frequency for the different values of F_{NQ} and for the different sizes of
 616 the reduced domain model. Results are presented in Fig. 17, for all the cases of the
 617 small model (point source - PS, and extended fault - EF) as well as for 4 cases of the
 618 medium model and one case for the large model. Two main conclusions can be drawn
 619 according to this Fig. 17 : i) an important decrease of the indicator I is observed
 620 using the decimation approach ($I_{F_{NQ}=250\text{ Hz}} \approx 10 \cdot I_{F_{NQ}=40\text{ Hz}}$), and ii) for the same
 621 decrease in F_{NQ} a coherent impact is observed among the different sizes of the model.
 622 For example, $I_{F_{NQ}=40\text{ Hz}} \approx 2 \cdot I_{F_{NQ}=20\text{ Hz}}$ for all three Small-EF/PS, and Medium-EF.

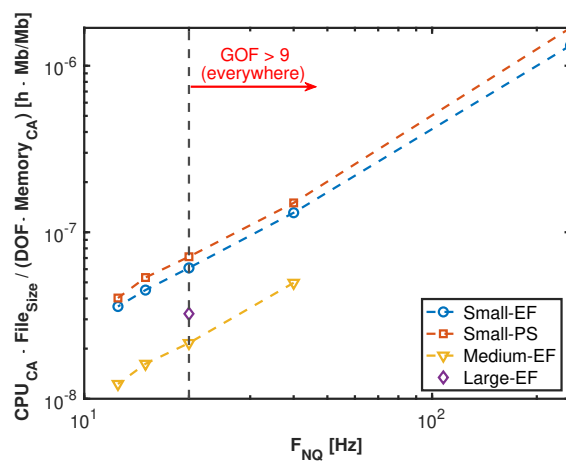


Figure 17.: Performance indicator over the Nyquist frequency.

623 4.2. Structure and soil response

624 In practice, the most classical way to introduce the dynamic seismic excitation in the
625 SSI problem is the plane wave excitation with vertical incidence (*i.e.* incident wave
626 front is considered homogeneous at the base of the model). In order to highlight the
627 differences of taking into account the complexity of 3D input excitation, the plane
628 wave solution is compared here with the one obtained via the DRM approach.

629 So as to approximate the plane wave condition from the SEM3D simulation, a
630 borehole condition will be used, for the boundary at the bottom of the reduced domain.
631 With this regard, the incident wave field corresponds to the 3 components of the
632 signal recorded in a unique sensor point located at the center and the base of the
633 reduced domain. In addition, it is supposed that this signal corresponds to a vertically
634 incident plane-wave front at the bottom boundary. Nevertheless, in order to properly
635 define the equivalent response for the borehole boundaries it is necessary to satisfy the
636 radiation condition for the incompatible outgoing (diffracted) waves. Consequently, an
637 absorbing boundary needs to be added following an approach close to the one proposed
638 by (8, 12, 30). As previously discussed, the paraxial elements, capable to impose the
639 dynamic excitation as well as to absorb the outgoing (diffracted) waves are used in
640 this study. Finally, concerning the lateral boundaries of the finite domain, paraxial
641 elements are used only to absorb outgoing waves diffracted from the structure.

642 Based on the hypothesis of the previous section, the medium model size ($520 \times$
643 520×205 m³ box) is chosen in order to study the SSI in the reduced domain for the
644 extended fault excitation. The impact is examined at first for a point at the top of the
645 structure (blue point in Fig. 13c), and the comparison is made using the prediction
646 residual of Eq. 4.1.

647 According to Fig. 18, the 3D input excitation introduced via the DRM generates
648 a higher movement than the plane wave excitation ($\Delta_{PSA} > 0$). This is related to
649 the fact that effects of a 3D excitation (e.g directivity effect, surface wave generation)
650 cannot be represented with the simpler plane wave excitation of vertical incidence.
651 Differences are observed in all three directions with higher values observed for the two
652 horizontal X and Y components.

653 It is well known that one of the most important aspects accounted in a 3D complex
654 excitation is the presence of surface waves. In order to show the presence of these
655 surface waves in the basin and their impact on the level of the structure, Fig. 19a
656 presents an analysis of the velocity motion in Fig. 19a for two different points P1 and
657 P2 (see also Fig. 13b) and the rocking of the building foundation in Fig. 19b.

658 The surface wave component is “extracted” using the empirical approach proposed
659 by (86) which is adopted here. According to this approach, the horizontal (XY plane)
660 velocity time-histories are band-pass filtered for a period of 1-5 s and plotted in
661 Fig. 19a. In addition, rocking is examined here based on the differential displacement
662 computed for two opposite points on the foundation of the structure. This differential
663 displacement is then normalized by the length of the foundation (distance between
664 the two opposite points) and is presented as the rotation angle of the foundation. The
665 same analysis is done along the X and Y axis of the foundation and plotted with
666 respect to time.

667 It can be observed from Fig 19a that surface waves are present for the dynamic
668 excitation imposed via the DRM approach (*i.e.* both the incident surface wave and
669 the one induced by the rocking of the structure - solid line in Fig. 19a) and practically
670 absent when the plane wave excitation is used (*i.e.* only the surface waves generated
671 by the rocking of the structure - dashed line in the Fig. 19a). For the DRM case, the

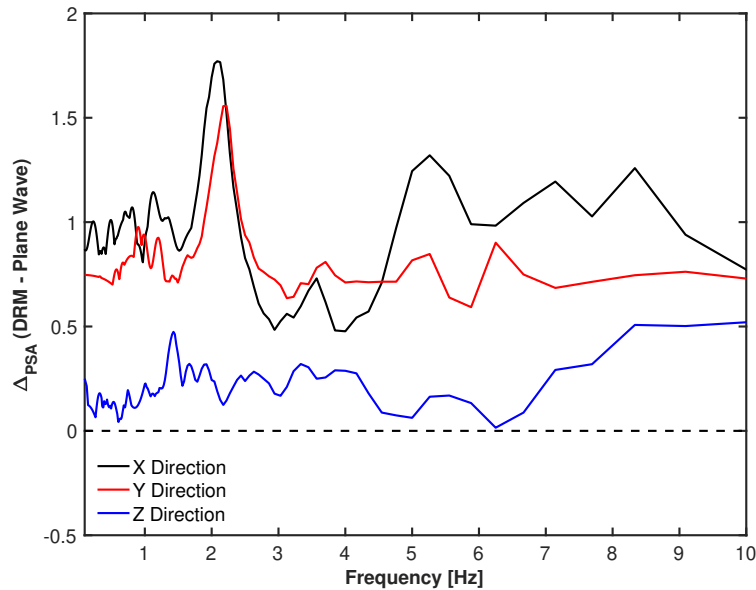


Figure 18.: Response prediction residual for a point at the top of the structure (damping $\xi = 5\%$).

672 amplitude is more important along the Y component (direction of the excitation) and
 673 smaller along the X direction which is related to the presence of the basin.

674 Similar results are obtained from Fig. 19b, showing that rotation is more important
 675 along the Y axis which is the principal direction of the excitation, while a smaller
 676 rotation is observed in the X axis which is related to the surface waves generated from
 677 the trapezoidal basin. In this case also, the plane wave excitation cannot account for
 678 the complexity of a 3D excitation and a weaker rotation is obtained for the structure.
 679 The aforementioned results are in accordance with the work of (46) that showed that
 680 a 3D excitation cannot be replaced by a simple decomposition of the seismic signal in
 681 X, Y and Z components.

682 Finally, a graphical representation of the deformed shape of the model for the DRM
 683 excitation is given in Fig. 20 for a time frame at $T = 2.4$ s, where the displacement
 684 field on the reduced domain is presented. For visualization purposes the displacement
 685 field is multiplied by a factor of 500 in order to better visualize the movement of the
 686 structure and the soil domain. It can be seen from this Fig. 20 that the rocking of
 687 the building is mainly in the Y direction, with a smaller displacement along the X
 688 component.

689 5. Conclusion

690 The numerical analysis of 3D dynamic soil-structure interaction for seismic risk mit-
 691 igation of important infrastructures such as nuclear power plants, dams and bridges
 692 is a quite challenging task that is of crucial importance from an economic and social
 693 stand point. Soil topography, characterization of soil geology, and the definition of the
 694 dynamic excitation are some of the main sources of uncertainty. In addition, when
 695 non-linearity needs to be taken into account, the finite element method consists of
 696 the most efficient approach to account for nonlinear behavior. Nevertheless, in the
 697 FEM framework, the size of the model in terms of degrees of freedom may rapidly

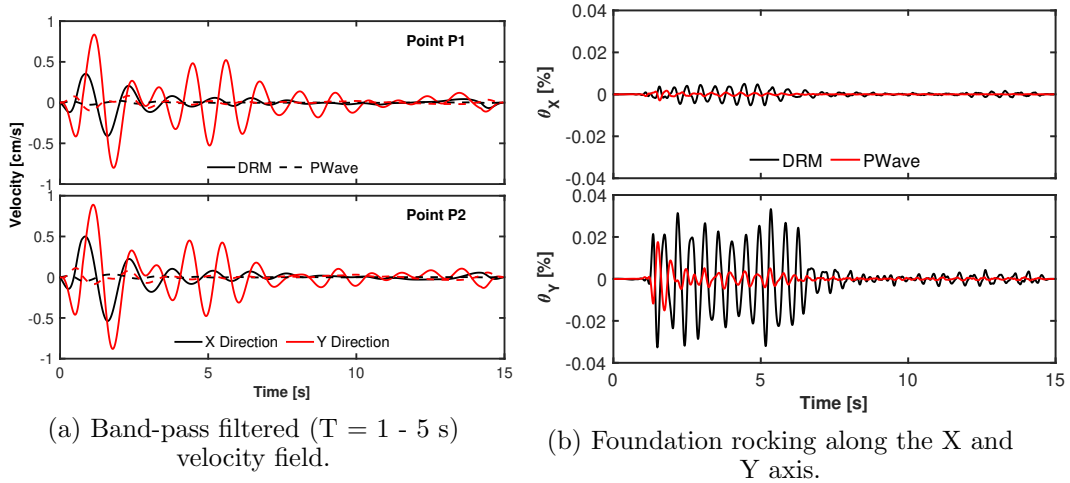


Figure 19.: Impact of surface waves on the reduced domain.

Time: 2.40

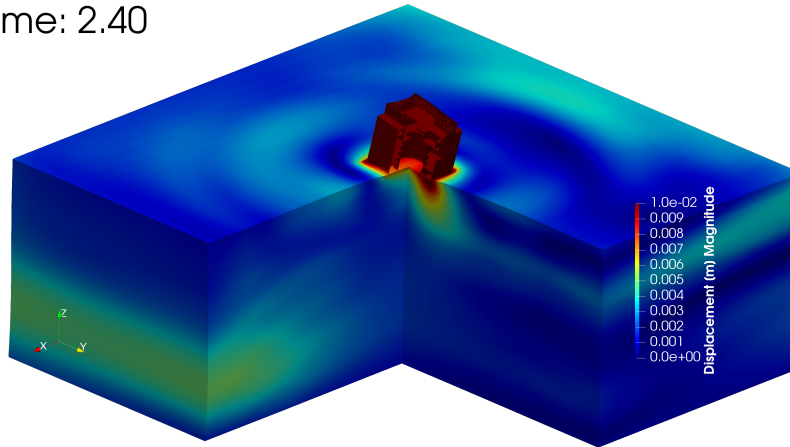


Figure 20.: Deformed shape of the reduced domain (multiplication factor of 500 for visualization purposes).

698 impact the efficiency of the method, and thus in engineering practice FEM is used in
 699 a small/reduced soil domain in order to study 3D nonlinear soil-structure interaction.
 700 In this context the dynamic excitation used as an input in FEM solution needs to be a
 701 realistic 3D complex wave field, accounting for the: i) complexity of a realistic source,
 702 ii) wave propagation path, and iii) local site effects.

703 In this article, the domain reduction method approach introduced by (30), is used
 704 in a spectral element method (SEM) - finite element method (FEM) weak coupling
 705 in order to ensure the input of a realistic excitation in a FEM framework. The first
 706 part of the work focuses on the numerical verification of the SEM-FEM coupling for a
 707 canonical case-study with a stratified trapezoidal basin and an increasing complexity of
 708 the dynamic excitation source: i) point-source, and ii) extended fault. Considering the
 709 different time integration schemes used by the two software, an optimization approach
 710 of the transferred kinematic fields is proposed here in order to obtain an equilibrium
 711 of accuracy and speed of the numerical solution. The obtained solution based on the
 712 proposed optimization approach shows a good correspondence with the solution of
 713 reference along with an optimization of the computational cost in terms of CPU time

714 consumption and memory demand.

715 In the second part of the work, an application to the soil-structure interaction
716 problem with an extended fault excitation, is presented in order to discuss the impact
717 of the reduced domain size on structural response. In contrast to other published
718 studies, no material or numerical damping is considered in this work. For the linear
719 elastic case, a domain size with lateral boundaries larger than $4 \times \lambda_S$ where λ_S the
720 minimum wavelength inside the domain is considered sufficient to represent accurately
721 the structural response. Once the size is fixed, structural response is examined in order
722 to show the capacity of the SEM-FEM weak coupling to introduce a complex wave-field
723 as an input on the FEM structural model.

724 The proposed methodology links the 3D physics-based geophysical simulations and
725 the engineering approach of the dynamic analysis of structures. It is a powerful numer-
726 ical tool, allowing the direct fault-to-structure wave propagation and can be applied
727 in an earthquake-hazard analysis for seismic risk mitigation. This study considers a
728 linear elastic material behavior, with a horizontally stratified soil medium. Neverthe-
729 less, from a methodological point of view the proposed SEM-FEM weak coupling can
730 readily incorporate an arbitrary heterogeneous soil geology, and account for a non-
731 linear soil behavior in order to ensure a more realistic site-specific SSI analysis. The
732 aforementioned elements are to be examined in future works by the authors.

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739 References

- 740 (1) Berge-Thierry, C.; Voldoire, F.; Ragueneau, F.; Lopez-Caballero, F.; Le Maoult, A. Main
741 Achievements of the Multidisciplinary SINAPS@ Research Project: Towards an Inte-
742 grated Approach to Perform Seismic Safety Analysis of Nuclear Facilities, *Pure and*
743 *Applied Geophysics* **2020**, *177* (5), 2299–2351. [https://doi.org/10.1007/s00024-](https://doi.org/10.1007/s00024-019-02194-4)
744 [019-02194-4](https://doi.org/10.1007/s00024-019-02194-4).
- 745 (2) Poursartip, B.; Fathi, A.; Tassoulas, J.L. Large-scale simulation of seismic wave motion:
746 A review, *Soil Dynamics and Earthquake Engineering* **2020**, *129*, 105909. [https://](https://www.sciencedirect.com/science/article/pii/S0267726118314386)
747 www.sciencedirect.com/science/article/pii/S0267726118314386.
- 748 (3) Rodgers, A.J.; Pitarka, A.; Petersson, N.A.; Sjogreen, B.; Pankajakshan, R. GPU-Based
749 Simulation of Earthquake Ground Motions in the San Francisco Bay Area: Path and Site
750 Effects from Suites of Ruptures and Evaluation of the USGS 3D Model with Moderate
751 Magnitude Earthquakes, In *AGU Fall Meeting Abstracts*, 2019; pp S31C–0519.
- 752 (4) Castro-Cruz, D.; Gatti, F.; Lopez-Caballero, F. High-fidelity broad-band prediction of
753 regional seismic response: a hybrid coupling of Physics-Based synthetic simulation and
754 Empirical Green’s functions, *Natural Hazards* **2020**, **In Press**.
- 755 (5) Faccioli, E.; Maggio, F.; Paolucci, R.; Quarteroni, A. 2D and 3D elastic wave propagation
756 by a pseudo-spectral domain decomposition method, *Journal of Seismology* **1997**, *1* (3),
757 237–251.
- 758 (6) Pitarka, A. Strong Ground Motion Simulations of the M7.1 Kumamoto, Japan Earth-
759 quake Using Characterized Heterogeneous Source Models, *Technical Report: Lawrence*

- 760 *Livermore National Lab. (LLNL), Livermore, CA (United States)* **2018**. [https://](https://www.osti.gov/biblio/1430931)
761 www.osti.gov/biblio/1430931.
- 762 (7) Ichimura, T.; Fujita, K.; Yoshiyuki, A.; Quinay, P.E.; Hori, M.; Sakanoue, T. Performance
763 enhancement of three-dimensional soil structure model via optimization for estimating
764 seismic behavior of buried pipelines, *Journal of Earthquake and Tsunami* **2017**, *11* (05),
765 1750019.
- 766 (8) McCallen, D.; Petersson, A.; Rodgers, A.; Pitarka, A.; Miah, M.; Petrone, F.; Sjogreen, B.;
767 Abrahamson, N.; Tang, H. EQSIM—A multidisciplinary framework for fault-to-structure
768 earthquake simulations on exascale computers part I: Computational models and work-
769 flow, *Earthquake Spectra* **2020**.
- 770 (9) McCallen, D.; Petrone, F.; Miah, M.; Pitarka, A.; Rodgers, A.; Abrahamson, N.
771 EQSIM—A multidisciplinary framework for fault-to-structure earthquake simulations
772 on exascale computers, part II: Regional simulations of building response, *Earthquake*
773 *Spectra* **2020**.
- 774 (10) Zhang, W.; Taciroglu, E. 3D time-domain nonlinear analysis of soil-structure sys-
775 tems subjected to obliquely incident SV waves in layered soil media, *Earth-*
776 *quake Engineering & Structural Dynamics* **2021**, *50* (8), 2156–2173. [https://](https://onlinelibrary.wiley.com/doi/abs/10.1002/eqe.3443)
777 onlinelibrary.wiley.com/doi/abs/10.1002/eqe.3443.
- 778 (11) Zhang, W.; Restrepo, D.; Crempien, J.; Erkmén, B.; Taborda, R.; Kurtuluş, A.; Taciroglu,
779 E. A computational workflow for rupture-to-structural-response simulation and its appli-
780 cation to Istanbul, *Earthquake Engineering & Structural Dynamics* **2020**, *50*, 1–20.
- 781 (12) Bielak, J.; Christiano, P. On the effective seismic input for non-linear soil-structure inter-
782 action systems, *Earthquake Engineering & Structural Dynamics* **1984**, *12* (1), 107–119.
- 783 (13) Festa, G.; Vilotte, J.P. The Newmark scheme as velocity–stress time-staggering: an ef-
784 ficient PML implementation for spectral element simulations of elastodynamics, *Geo-*
785 *physical Journal International* **2005**, *161* (3), 789–812. [https://doi.org/10.1111/](https://doi.org/10.1111/j.1365-246X.2005.02601.x)
786 [j.1365-246X.2005.02601.x](https://doi.org/10.1111/j.1365-246X.2005.02601.x).
- 787 (14) Léger, P.; Boughoufalah, M. Earthquake input mechanisms for time-domain analysis
788 of dam–foundation systems, *Engineering Structures* **1989**, *11* (1), 37–46. [https://](https://linkinghub.elsevier.com/retrieve/pii/014102968990031X)
789 linkinghub.elsevier.com/retrieve/pii/014102968990031X.
- 790 (15) Tarantola, A. *Inverse problem theory and methods for model parameter estimation*;
791 Society for Industrial and Applied Mathematics: Philadelphia, PA, 2005; OCLC:
792 ocm56672375.
- 793 (16) Bradley, B.A.; Pettinga, D.; Baker, J.W.; Fraser, J. Guidance on the utilization of
794 earthquake-induced ground motion simulations in engineering practice, *Earthquake Spec-*
795 *tra* **2017**, *33* (3), 809–835.
- 796 (17) Pecker, A.; Paolucci, R.; Chatzigogos, C.; Correia, A.; Figini, R. The role of non-linear
797 dynamic soil-foundation interaction on the seismic response of structures, *Bulletin of*
798 *Earthquake Engineering* **2014**, *12* (3), 1157–1176.
- 799 (18) Babuska, I.; Oden, J. Verification and validation in computational engineering and
800 science: basic concepts, *Computer Methods in Applied Mechanics and Engineer-*
801 *ing* **2004**, *193* (36), 4057–4066. [https://www.sciencedirect.com/science/](https://www.sciencedirect.com/science/article/pii/S0045782504001781)
802 [article/pii/S0045782504001781](https://www.sciencedirect.com/science/article/pii/S0045782504001781).
- 803 (19) Fardis, M.; Carvalho, E.; Elnashai, A.; Faccioli, E.; Pinto, P.; Plumier, A. *Designers’*
804 *Guide to EN 1998-1 and 1998-5. Eurocode 8: Design Provisions for Earthquake Resistant*
805 *Structures*; Thomas Telford Publishing, 2005.
- 806 (20) Ghaemian, M.; Noorzad, A.; Mohammadnezhad, H. Assessment of Foundation Mass and
807 Earthquake Input Mechanism Effect on Dam–Reservoir–Foundation System Response,
808 *International Journal of Civil Engineering* **2019**, *17* (4), 473–480.
- 809 (21) Sotoudeh, P.; Ghaemian, M.; Mohammadnezhad, H. Seismic analysis of reservoir-
810 gravity dam-massed layered foundation system due to vertically propagating earth-
811 quake, *Soil Dynamics and Earthquake Engineering* **2019**, *116*, 174–184. [https://](https://www.sciencedirect.com/science/article/pii/S0267726118304883)
812 www.sciencedirect.com/science/article/pii/S0267726118304883.
- 813 (22) Zienkiewicz, O.C.; Bicanic, N.; Shen, F.Q. Earthquake Input Definition and the

- 814 Transmitting Boundary Conditions. In *Advances in Computational Nonlinear Me-*
815 *chanics*; Doltsinis, I.S., Ed.; Springer Vienna: Vienna, 1989; pp 109–138. [http://](http://link.springer.com/10.1007/978-3-7091-2828-2_3)
816 link.springer.com/10.1007/978-3-7091-2828-2_3.
- 817 (23) Gajan, S.; Raychowdhury, P.; Hutchinson, T.C.; Kutter, B.L.; Stewart, J.P. Applica-
818 tion and validation of practical tools for nonlinear soil-foundation interaction analysis,
819 *Earthquake Spectra* **2010**, *26* (1), 111–129.
- 820 (24) Devésa, G.; Guyonvarh, V. Use of coupled and regulatory method in Soil-Structure In-
821 teraction and Soil-Fluid-Structure Interaction for nuclear plants and dams, In *First Eu-*
822 *ropean Conference on Earthquake Engineering and Seismology*, Geneva, 2006; pp 3–8.
- 823 (25) Alves Fernandes, V.A.; Banci, F.; Devesa, G.; Greffet, N.; Jacquet, M.; Kham, M.; Nieto-
824 Ferro, A.; Voltaire, F.; Zentner, I. Dynamic soil-structure interaction modeling strategies
825 applied to Kashiwazaki-Kariwa nuclear power plant case-study, *COMPdyn 2017 - Pro-*
826 *ceedings of the 6th International Conference on Computational Methods in Structural*
827 *Dynamics and Earthquake Engineering* **2017**, *1* (June), 2330–2342.
- 828 (26) Nieto Ferro, A.; Clouteau, D.; Greffet, N.; Devésa, G. On a hybrid Laplace-time domain
829 approach to dynamic interaction problems, *European Journal of Computational Mechan-*
830 *ics* **2012**, *21* (3-6), 290–299.
- 831 (27) Gatti, F.; Touhami, S.; Lopez-Caballero, F.; Paolucci, R.; Clouteau, D.; Fernandes, V.A.;
832 Kham, M.; Voltaire, F. Broad-band 3-D earthquake simulation at nuclear site by an
833 all-embracing source-to-structure approach, *Soil Dynamics and Earthquake Engineering*
834 **2018**, *115*, 263–280.
- 835 (28) Abell, J.A.; Orbović, N.; McCallen, D.B.; Jeremic, B. Earthquake soil-structure interac-
836 tion of nuclear power plants, differences in response to 3D, $3 \times 1D$, and 1D excitations,
837 *Earthquake Engineering & Structural Dynamics* **2018**, *47* (6), 1478–1495.
- 838 (29) Dello Russo, A.; Sica, S.; Del Gaudio, S.; De Matteis, R.; Zollo, A. Near-source effects
839 on the ground motion occurred at the Conza Dam site (Italy) during the 1980 Irpinia
840 earthquake, *Bulletin of Earthquake Engineering* **2017**, *15* (10), 4009–4037.
- 841 (30) Bielak, J.; Yoshimura, C.; Hisada, Y.; Fernández, A. Domain Reduction Method for
842 Three-Dimensional Earthquake Modeling in Localized Regions, Part I: Theory, *Bulletin*
843 *of the Seismological Society of America* **2003**, *93* (2), 825–840.
- 844 (31) De Martin, F.; Modaresi, H.; Aochi, H. Coupling of FDM and FEM in seismic wave prop-
845 agation, In *4th International Conference on Earthquake Geotechnical Engineering*, Thes-
846 saloniki, Greece, June, 2007; [https://hal-brgm.archives-ouvertes.fr/hal-](https://hal-brgm.archives-ouvertes.fr/hal-00560540)
847 [00560540](https://hal-brgm.archives-ouvertes.fr/hal-00560540).
- 848 (32) Quinay, P.E.B.; Ichimura, T.; Hori, M.; Nishida, A.; Yoshimura, S. Seismic Structural
849 Response Estimates of a Fault-Structure System Model with Fine Resolution Using Mul-
850 tiscale Analysis with Parallel Simulation of Seismic-Wave Propagation, *Bulletin of the*
851 *Seismological Society of America* **2013**, *103* (3), 2094–2110. Doi: 10.1785/0120120216.
- 852 (33) Jeremić, B.; Jie, G.; Preisig, M.; Tafazzoli, N. Time domain simulation of soil–founda-
853 tion–structure interaction in non-uniform soils, *Earthquake Engineering & Structural Dynam-*
854 *ics* **2009**, *38* (5), 699–718.
- 855 (34) Kontoe, S.; Zdravkovic, L.; Potts, D. The domain reduction method for dynamic coupled
856 consolidation problems in geotechnical engineering, *International journal for numerical*
857 *and analytical methods in geomechanics* **2008**, *32* (6), 659–680.
- 858 (35) Luo, C.; Lou, M.; Gui, G.; Wang, H. A modified domain reduction method for numer-
859 ical simulation of wave propagation in localized regions, *Earthquake Engineering and*
860 *Engineering Vibration* **2019**, *18* (1), 35–52.
- 861 (36) Preisig, M.; Jeremic, B. *Nonlinear finite element analysis of dynamic soil-foundation-*
862 *structure interaction*; Technical Report, 2005.
- 863 (37) Solberg, J.M.; Hossain, Q.; Mseis, G. Nonlinear time-domain soil–structure interaction
864 analysis of embedded reactor structures subjected to earthquake loads, *Nuclear Engi-*
865 *neering and Design* **2016**, *304*, 100–124.
- 866 (38) Wang, H.; Yang, H.; Sinha, S.K.; Luo, C.; Jeremic, B. 3-D Non-Linear Earthquake Soil-
867 Structure Interaction Modeling of Embedded Small Modular Reactor (SMR), In *Proceed-*

- ings of the 24th International Conference on Structural Mechanics in Reactor Technology (SMiRT 24)', Busan, South Korea, 2017.
- 870 (39) Casadei, F.; Gabellini, E. *Implementation of a 3D Coupled Spectral Element/finite Element Solver for Wave Propagation and Soil-structure Interaction Simulations: Numerical*
871 *Examples*; Office for Official Publications of the European Communities, 1998.
- 872 (40) Zuchowski, L.; Brun, M.; De Martin, F. Co-simulation coupling spectral/finite elements
873 for 3D soil/structure interaction problems, *Comptes Rendus - Mecanique* **2018**, 346 (5),
874 408–422.
- 875 (41) Brun, M.; De Martin, F.; Richart, N. Hybrid asynchronous SEM/FEM co-simulation for
876 seismic nonlinear analysis of concrete gravity dams, *Computers and Structures* **2021**,
877 245, 106459. <https://doi.org/10.1016/j.compstruc.2020.106459>.
- 878 (42) Combescure, A.; Gravouil, A. A numerical scheme to couple subdomains with differ-
879 ent time-steps for predominantly linear transient analysis, *Computer methods in applied*
880 *mechanics and engineering* **2002**, 191 (11-12), 1129–1157.
- 881 (43) Gravouil, A.; Combescure, A. Multi-time-step explicit–implicit method for non-linear
882 structural dynamics, *International Journal for Numerical Methods in Engineering* **2001**,
883 50 (1), 199–225.
- 884 (44) Bernardi, C.; Debit, N.; Maday, Y. Coupling finite element and spectral methods: First
885 results, *Mathematics of Computation* **1990**, 54 (189), 21–39.
- 886 (45) Matsumoto, M.; Arakawa, T.; Kitayama, T.; Mori, F.; Okuda, H.; Furumura, T.;
887 Nakajima, K. Multi-scale coupling simulation of seismic waves and building vibra-
888 tions using ppOpen-HPC, *Procedia Computer Science* **2015**, 51 (1), 1514–1523. <http://dx.doi.org/10.1016/j.procs.2015.05.341>.
- 889 (46) Abell, J.A.; Orbović, N.; McCallen, D.B.; Jeremić, B. Earthquake soil-structure interac-
890 tion of nuclear power plants, differences in response to 3-D, 3 1-D, and 1-D excitations,
891 *Earthquake Engineering and Structural Dynamics* **2018**. [https://doi.org/10.1002/](https://doi.org/10.1002/eqe.3026)
892 [eqe.3026](https://doi.org/10.1002/eqe.3026).
- 893 (47) Fu, H.; He, C.; Chen, B.; Yin, Z.; Zhang, Z.; Zhang, W.; Zhang, T.; Xue, W.; Liu, W.; Yin,
894 W.; et al. 18.9-Pflops Nonlinear Earthquake Simulation on Sunway TaihuLight: Enabling
895 Depiction of 18-Hz and 8-Meter Scenarios, *Proceedings of the International Conference*
896 *for High Performance Computing, Networking, Storage and Analysis, SC 2017* **2017**.
- 897 (48) Ichimura, T.; Agata, R.; Hori, T.; Hirahara, K.; Hashimoto, C.; Hori, M.; Fukahata, Y.
898 An elastic/viscoelastic finite element analysis method for crustal deformation using a
899 3-D island-scale high-fidelity model, *Geophysical Journal International* **2016**, 206 (1),
900 114–129.
- 901 (49) Ichimura, T.; Agata, R.; Hori, T.; Satake, K.; Ando, K.; Baba, T.; Hori, M. Tsunami
902 analysis method with high-fidelity crustal structure and geometry model, *Journal of*
903 *Earthquake and Tsunami* **2017**, 11 (5), 1–18.
- 904 (50) Ichimura, T.; Fujita, K.; Horikoshi, M.; Meadows, L.; Nakajima, K.; Yamaguchi, T.;
905 Koyama, K.; Inoue, H.; Naruse, A.; Katsushima, K.; et al. A fast scalable implicit solver
906 with concentrated computation for nonlinear time-evolution problems on low-order un-
907 structured finite elements, In *2018 IEEE International Parallel and Distributed Process-*
908 *ing Symposium (IPDPS)*, IEEE, 2018; pp 620–629.
- 909 (51) Komatitsch, D.; Tromp, J. Introduction to the spectral element method for three-
910 dimensional seismic wave propagation, *Geophysical journal international* **1999**, 139 (3),
911 806–822.
- 912 (52) Komatitsch, D.; Vilotte, J.P.; Vai, R.; Castillo-Covarrubias, J.M.; Sánchez-Sesma, F.J.
913 The spectral element method for elastic wave equations—application to 2-D and 3-D seis-
914 mic problems, *International Journal for numerical methods in engineering* **1999**, 45 (9),
915 1139–1164.
- 916 (53) Cupillard, P.; Delavaud, E.; Burgos, G.; Festa, G.; Vilotte, J.P.; Capdeville, Y.; Montag-
917 ner, J.P. RegSEM: a versatile code based on the spectral element method to compute
918 seismic wave propagation at the regional scale, *Geophysical Journal International* **2012**,
919 188 (3), 1203–1220. <https://doi.org/10.1111/j.1365-246X.2011.05311.x>.
- 920
921

- 922 (54) De Basabe, J.D.; Sen, M.K. A comparison of finite-difference and spectral-element meth-
923 ods for elastic wave propagation in media with a fluid-solid interface, *Geophysical Journal*
924 *International* **2014**, *200* (1), 278–298. <https://doi.org/10.1093/gji/ggu389>.
- 925 (55) Lax, P.D.; Wendroff, B. Difference schemes for hyperbolic equations with high order of
926 accuracy, *Communications on Pure and Applied Mathematics* **1964**, *17* (3), 381–398.
927 <https://onlinelibrary.wiley.com/doi/abs/10.1002/cpa.3160170311>.
- 928 (56) Maday, Y.; Patera, A.T. Spectral element methods for the incompressible Navier-Stokes
929 equations, In *IN: State-of-the-art surveys on computational mechanics (A90-47176 21-*
930 *64)*. New York, American Society of Mechanical Engineers, 1989, p. 71–143. *Research*
931 *supported by DARPA.*, 1989; pp 71–143.
- 932 (57) Poursartip, B.; Fathi, A.; Kallivokas, L.F. Seismic wave amplification by topo-
933 graphic features: A parametric study, *Soil Dynamics and Earthquake Engineering*
934 **2017**, *92*, 503–527. [https://www.sciencedirect.com/science/article/pii/](https://www.sciencedirect.com/science/article/pii/S0267726116304559)
935 [S0267726116304559](https://www.sciencedirect.com/science/article/pii/S0267726116304559).
- 936 (58) Sinha, S.K.; Feng, Y.; Yang, H.; Wang, H.; Jeremic, B. 3-d non-linear modeling and its
937 effects in earthquake soil-structure interaction, In *Proceedings of the 24th International*
938 *Conference on Structural Mechanics in Reactor Technology (SMiRT 24)*, Busan, South
939 Korea, 2017.
- 940 (59) Wang, H.; Yang, H.; Sinha, S.K.; Luo, C.; Jeremic, B. 3D non-linear earthquake soil-
941 structure interaction modeling of embedded small modular reactor (SMR), In *Proceedings*
942 *of the 24th International Conference on Structural Mechanics in Reactor Technology*
943 *(SMiRT 24)*, Busan, South Korea, 2017.
- 944 (60) Clayton, R.; Engquist, B. Absorbing boundary conditions for acoustic and elastic wave
945 equations, *Bulletin of the seismological society of America* **1977**, *67* (6), 1529–1540.
- 946 (61) Engquist, B.; Majda, A. Absorbing boundary conditions for the numerical simulation of
947 waves, *Math. Comput* **1977**, *31*, 629–651.
- 948 (62) Modaressi, H.; Benzenati, I. Paraxial approximation for poroelastic media, *Soil Dynamics*
949 *and Earthquake Engineering* **1994**, *13* (2), 117–129.
- 950 (63) Wu, S.; Eckert, E.; Huang, J.; Mccallen, D. *Evaluation of the Domain Reduction Method*
951 *applied to broad-band, near-fault earthquake ground motions with inter-code comparisons*;
952 Technical Report; 07, 2020.
- 953 (64) Herrera, I.; Bielak, J. Soil-structure interaction as a diffraction problem, In *Proceedings*
954 *of the 6th World Conference on Earthquake Engineering. New Delhi, India, 1977*; Vol. 2,
955 pp 1467–1472.
- 956 (65) Yoshimura, C.; Bielak, J.; Hisada, Y.; Fernández, A. Domain reduction method for three-
957 dimensional earthquake modeling in localized regions, part II: Verification and applica-
958 tions, *Bulletin of the seismological Society of America* **2003**, *93* (2), 825–841.
- 959 (66) Petropoulos, G. Soil-Structure Interaction Analysis Using High-Performance Parallel
960 Computation, *Thesis* **2008**, *44*.
- 961 (67) Semblat, J.F.; Lenti, L.; Gandomzadeh, A. A simple multi-directional absorbing layer
962 method to simulate elastic wave propagation in unbounded domains, *International*
963 *Journal for Numerical Methods in Engineering* **2011**, *85* (12), 1543–1563. <https://onlinelibrary.wiley.com/doi/abs/10.1002/nme.3035>.
- 964 (68) Poursartip, B.; Kallivokas, L.F. Model dimensionality effects on the amplification of seis-
965 mic waves, *Soil Dynamics and Earthquake Engineering* **2018**, *113* (July), 572–592.
- 966 (69) Cremonini, M.G.; Christiano, P.; Bielak, J. Implementation of effective seismic input
967 for soil-structure interaction systems, *Earthquake Engineering & Structural Dynamics*
968 **1988**, *16* (4), 615–625. [https://onlinelibrary.wiley.com/doi/abs/10.1002/](https://onlinelibrary.wiley.com/doi/abs/10.1002/eqe.4290160411)
969 [eqe.4290160411](https://onlinelibrary.wiley.com/doi/abs/10.1002/eqe.4290160411).
- 970 (70) Code_Aster. *General public licensed structural mechanics finite element software, included*
971 *in the Salomé-Méca simulation platform. Website* <http://www.code-aster.org>. *En partic-*
972 *ulier : [R4.02.05] Éléments de frontière absorbante*; Technical Report, 2017.
- 973 (71) Bamberger, A.; Engquist, B.; Halpern, L.; Joly, P. Higher Order Paraxial Wave Equation
974 Approximations in Heterogeneous Media, *SIAM Journal on Applied Mathematics* **1988**,

- 976 48 (1), 129–154. <http://www.jstor.org/stable/2101501>.
- 977 (72) MED. “MEDCoupling developer’s guide”, SALOME-platform, [Online] Available:
978 <http://docs.salome-platform.org/latest/dev/MEDCoupling/developer/index.html>, [Ac-
979 cessed 17 04 2020], 2019.
- 980 (73) Komatitsch, D.; Tromp, J. Introduction to the spectral element method for three-
981 dimensional seismic wave propagation, *Geophysical Journal International* **1999**, 139 (3),
982 806–822.
- 983 (74) Seriani, G.; Priolo, E. Spectral element method for acoustic wave simulation in hetero-
984 geneous media, *Finite Elements in Analysis and Design* **1994**, 16 (3-4), 337–348.
- 985 (75) Watanabe, K.; Pisanò, F.; Jeremić, B. Discretization effects in the finite element simu-
986 lation of seismic waves in elastic and elastic-plastic media, *Engineering with Computers*
987 **2017**, 33 (3), 519–545.
- 988 (76) Zhang, L.; Wang, J.T.; Xu, Y.J.; He, C.H.; Zhang, C.H. A procedure for 3D seismic
989 simulation from rupture to structures by coupling SEM and FEM, *Bulletin of the Seis-
990 mological Society of America* **2020**, 110 (3), 1134–1148.
- 991 (77) Code_Aster. General public licensed structural mechanics finite element software, in-
992 cluded in the Salomé-Méca simulation platform. Website <http://www.code-aster.org>.
993 **2017**.
- 994 (78) Kristeková, M.; Kristek, J.; Moczo, P. Time-frequency misfit and goodness-of-fit criteria
995 for quantitative comparison of time signals, *Geophysical Journal International* **2009**,
996 178 (2), 813–825.
- 997 (79) Kristeková, M.; Kristek, J.; Moczo, P.; Day, S.M. Misfit criteria for quantitative com-
998 parison of seismograms, *Bulletin of the seismological Society of America* **2006**, 96 (5),
999 1836–1850.
- 1000 (80) Anderson, J.G. Quantitative measure of the goodness-of-fit of synthetic seismograms,
1001 In *13th world conference on earthquake engineering conference proceedings, Vancouver,*
1002 *Canada, Paper*, Vancouver, B.C., Canada, 2004; [http://www.iitk.ac.in/nicee/
1003 wcee/article/13{ }243.pdf](http://www.iitk.ac.in/nicee/wcee/article/13{ }243.pdf).
- 1004 (81) Chaljub, E.; Maufroy, E.; Moczo, P.; Kristek, J.; Hollender, F.; Bard, P.Y.; Priolo, E.;
1005 Klin, P.; De Martin, F.; Zhang, Z.; et al. 3-D numerical simulations of earthquake ground
1006 motion in sedimentary basins: testing accuracy through stringent models, *Geophysical*
1007 *Journal International* **2015**, 201 (1), 90–111.
- 1008 (82) Hollender, F.; Manakou, M.; Bard, P.; Chaljub, E.; Raptakis, D.; Ptilakis, K.; Tsuno, S.
1009 Euroseistest verification and validation project: an international effort to evaluate ground
1010 motion numerical simulation relevance, *Seism. Res. Lett.* **2010**, 81, 322.
- 1011 (83) Berenger, J.P.; et al. A perfectly matched layer for the absorption of electromagnetic
1012 waves, *Journal of computational physics* **1994**, 114 (2), 185–200.
- 1013 (84) Ide, S. Complex source processes and the interaction of moderate earthquakes during the
1014 earthquake swarm in the Hida-Mountains, Japan, 1998, *Tectonophysics* **2001**, 334 (1),
1015 35–54.
- 1016 (85) *Review of Seismic Evaluation Methodologies for Nuclear Power Plants Based on a Bench-*
1017 *mark Exercise*; TECDOC Series 1722; International Atomic Energy Agency: Vienna,
1018 2014; [https://www.iaea.org/publications/10580/review-of-seismic-
1019 evaluation-methodologies-for-nuclear-power-plants-based-on-a-
1020 benchmark-exercise](https://www.iaea.org/publications/10580/review-of-seismic-evaluation-methodologies-for-nuclear-power-plants-based-on-a-benchmark-exercise).
- 1021 (86) Miura, H.; Okamura, T.; Matsuoka, M.; Leal, M.; García, H.; Pulido, N. Empirical Models
1022 for Surface-and Body-Wave Amplifications of Response Spectra in the Bogotá Basin,
1023 Colombia, *Bulletin of the Seismological Society of America* **2019**, 109 (3), 987–1004.