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# Coupled approach for the assessment of basin effects on the seismic demand of nonlinear structures

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## ABSTRACT

Sedimentary materials enclosed in basins modify the ground motion by energy trapping, resonance and surface wave generation at the basin edge. In general, the effects of basin presence are approximated by aggravation factors (AGF), but the particular surface wave part of the ground motion is never explicitly measured. The current study assesses the impact of basin effects on the seismic damage of a nonlinear structure, representing a bridge column, using a complete time-analysis from the earthquake source to the structure. The numerical wave propagation simulation is performed with a coupled 3D SEM-FEM approach using the Domain Reduction Method (DRM), including non-linearities in the structure. Therefore, with this model, the coupled basin effects on the seismic hazard and on the structural demand are quantified and contrasted. The findings indicate that basins' effect on structural damage may be estimated in a simplified form using a combination of a structural behaviour predictor and AFs derived from the free-field ground motions. However, these factors should be correctly predicted, including both basin and source variability.

**Keywords:** basin effects, soil-structure interaction, amplification factors, SEM-FEM modeling

## 1 INTRODUCTION

When dealing with seismic response analyses in soil-structure interaction (SSI) problems, is of high importance to account for the influence of site effects. Commonly, the subsurface comprises layers of sedimentary materials, described with lower density and elastic modulus than the surrounding bedrock. Soft sedimentary materials close to the surface amplify the ground motion due to the decrease of seismic velocities and enclose the seismic energy by reflections, refraction and resonance (Anderson, 2015; Kawase & Aki, 1989). Specifically, the site effects in the seismic hazard analysis are accounted by the defined amplification factors (AF), which as its name suggest, focus on the amplification due to the presence of the soil sediments (Bazzurro & Cornell, 2004; Marafi et al., 2017).

However, these amplification values usually focus directly on the 1D response analysis, while the effects of local 2D/3D analyses (the inclusion of the subsurface geology, in the case of basins) are neglected. In these cases, the geometry can increase the ground shaking by the generation of surface waves and their corresponding rotational components.

Therefore, one of the main challenges when 3D site conditions are to be accounted is the accurate estimation of the ground motion characteristics for the efficient evaluation of the impact on the performance of structures. This aspect is not always considered, since the 3D site conditions usually are of a different order of magnitude

than the evaluation of the structural performance.

In this frame, this investigation focuses on the influence of the basin effects on the seismic demand of nonlinear structures. A performance-based design approach is used with 3D simulations from the earthquake event to the structure. A parametric study is carried out regarding different seismic scenarios affecting the structure, with simplified basin geometries and homogeneous material properties. Two seismic sources are simulated: plane waves with vertical incidence and deep and shallow double-couple point sources. Furthermore, the spatial variability inside the basin is investigated by inserting the bridge column in different positions, hence modifying the ground motion wave field arriving at the base of the structure.

## 2 MODELING APPROACH FOR BASIN EFFECT QUANTIFICATION ON BUILDINGS' RESPONSE

In order to evaluate the beneficial or unfavorable effects of the presence of the basin on the structural response, a two-step dynamic approach is considered with the Domain Reduction Method (DRM) to model the wave propagation response from the earthquake source to the structure. The methodology used in this work was implemented and validated by Korres et al. (2022) for the coupling between the spectral element code SEM3D (CEA, CentraleSupélec, IPGP & CNRS, 2017) and the finite element method (FEM) software CodeAster (Code\_Aster, 2017). The wave field is transferred from

the 3D regional scale model to the boundaries of a closer reduced domain of interest at the scale of the structure using paraxial boundaries. The detailed study of the SEM-FEM coupling is beyond the scope of this work but refer to Korres et al. (2022) for further details about this method.

## 2.1 Comparative approach for basin effect quantification

In order to quantify the basin geometry effects on the structural performance, the computed nonlinear response of the bridge pylon is evaluated in different spatial locations along the basin. Moreover, two different regional models are contrasted: with basin (3D) and without basin (2D), as represented in Figure 1. Since a pure one-dimensional (1D) case is accomplished only in the case where a vertically incident plane wave is used as input motion, the definition of 2D instead of 1D have been selected to account the use of more complex sources, i.e., double couple (DC) point sources.

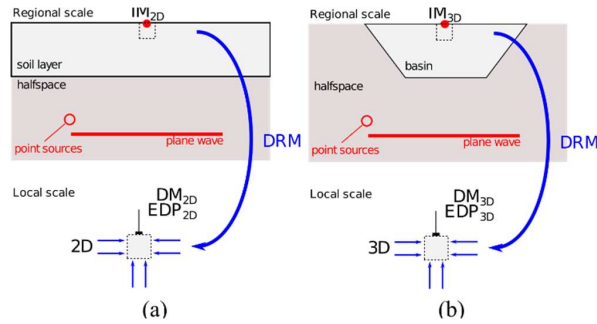


Fig. 1. Schematic representation of the modeling approach of the regional 3D models: (a) Layered case, where the sediment material constituting the basin is extended infinitely in both horizontal directions. This model is the one used traditionally for the site-effects assessment. (b) Analogous to the latter, the 3D basin, where the basin geometry is included.

It is crucial to note that the two approaches consider the soil and the material non linearities (NL) of structure. The 2D approach considers the fully seismic soil-structure interaction problem, the non-linear behavior of superstructure and the induced surface waves from the sources depth but neglects all interaction effects with the basin and the induced surface waves from the basin edges. This comparative approach was developed in order to provide two groups of consistent responses. Moreover, to highlight the effects of surface waves on the induced damage, only the NL is considered in the structure and the soil remains elastic.

## 3 INTRODUCTION OF BASIN EFFECTS ON THE STRUCTURAL PERFORMANCE FOLLOWING THE PBEE METHODOLOGY

The performance-based design or PBEE methodology formulation (Porter, 2003) can be represented an integral formulation. The structural and

damage analysis of the PBEE formulation rely on the definition of an engineering demand parameter ( $EDP$ ) and damage parameter ( $DP$ ) conditioned to the intensity measure ( $IM$ ) defined earlier in the hazard analysis.

Traditionally, the seismic hazard analysis relates the ground motion level ( $IM$ ) with its mean annual rate of exceedance, where all the faults in the area, all the potential earthquakes scenarios on each source are accounted. In this work, since simplified nonrealistic cases are used, the estimation of  $IM$  is computed in terms of the complementary cumulative distribution function ( $CCDF$ , Bazzurro & Cornell, 2004) described by the integral

$$CCDF_{IM} = \int_m \int_r P[IM > im | m, r] \cdot f_{m,r}(m, r) \cdot dm \cdot dr \quad (1)$$

The aim of a seismic hazard analysis is to first evaluate the  $IM$  prediction (in terms of GMPE or any other way of  $IM$  estimation) on standard rock, to which then the 1D linear site response is first considered, and in a following step the underground geometry (3D) (Bard, 2021).

Therefore, in this work, to account for site effects, an additional term is added, i.e.,

$$CCDF_{IM,UG}(im) = \int_m \int_r P[IM > im | m, r, UG] \cdot f_{m,r,UG}(m, r, UG) \cdot dm \cdot dr \quad (2)$$

where  $UG = [2D, 3D]$  represents the site term, if a one-dimensional layer or the whole basin are considered.

Correspondingly, the probabilistic evaluation of seismic demand is computed as

$$CCDF_{DP,UG}(d) = \int_d P[DP > d | EDP_{UG}] \cdot CCDF_{EDP,UG} \cdot dd \quad (3)$$

where  $CCDF_{EDP,UG}(im)$  is the complementary cumulative distribution function represented by

$$CCDF_{EDP,UG}(edp) = \int_{edp} P[EDP > edp | IM_{UG}] \cdot CCDF_{IM,UG} \cdot dedp \quad (4)$$

Since a coupled approach is performed here as described in Section 2, all the  $CCDF$  curves can be obtained directly from the simulations (de Silva, 2020).

## 4 STUDIED CASE DESCRIPTION AND MODELING

### 4.1 Regional basin

The regional model is a three-dimensional sedimentary basin inserted into a homogeneous half

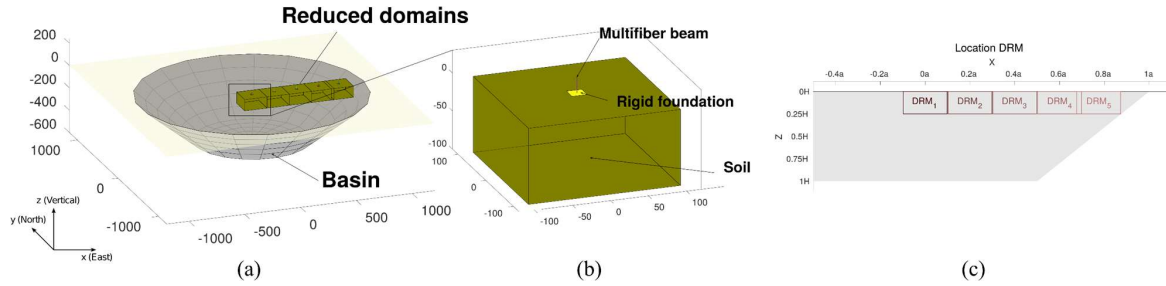


Fig. 2. Geometry of studied model: (a) basin including the reduced domains and (b) an example of a reduced domain including the infrastructure, all dimensions are in meters. (c) Locations of 5 reduced domains (DRM1 to DRM5) in order to evaluate the spatial variability of the structural demand in different zones of the basin, normalized by the basin radius  $a=1000$ m and depth  $H=400$ m.

space. The domain's total size is 40 by 40 by 40 km<sup>3</sup> to avoid possible reflections at the edges of the domain and to allow far-source ground motions. A non-honoring meshing procedure is used, where the mechanical properties are interpolated at each Gauss-Lobatto-Legendre (GLL) point, so the mesh does not necessarily follow the geometry. The size of the elements was adapted to the wavelength for a maximum target frequency of 8 Hz, using five integration points per element in each direction.

Table 1: Geotechnical properties used.

Layer	$\rho$	$V_s$ [m/s]	$V_p$ [m/s]
Basin soil	2100	900	1684
Bedrock	2600	2600	4700

In order to study the shape of the basin's influence on the ground motion and seismic demand, the basin and halfspace will have a single homogeneous, linear elastic material. No material attenuation is introduced to the model. The mechanical material properties inside the basin and half space are given in Table 1. The geometry of the basin, depicted in Figure 2a, is a trapezoidal 3D cone, of circular surface section of radius  $a=1000$  m and a depth  $H=400$  m. The horizontal dimension of the edge of the basin is  $e=500$  m.

#### 4.2 Seismic sources

In most aggravation studies, the incidence of the input motion is assumed either as a vertically incident plane wave (Riga et al., 2016) or as an obliquely incident wave (Amini et al., 2022; Narayan, 2012). In order to evaluate the basin response to more realistic source scenarios, the seismic input will be imposed inside the domain using a kinematic assumption, as two types: a vertically incident plane shear wave polarized in the X direction and multiple independent double-couple (DC) point sources. The extended fault used for the plane wave consists in a distribution of DC point-wise sources along the fault plane. The DC points sources have a strike of 22°, dip of 90° and rake of 0°, which results in polarization motion in the three components (x,y,z), contrasted to the plane wave. The epicenter is located 4km in the west direction from the center of the basin, resulting in a motion propagating from west to east (in

+x). The effects of source depth in basin amplification and surface wave generation are analyzed by nine different vertical positions, varying between 0.8 and 14 km.

#### 4.3 Infrastructure

In order to quantify the basin effects on tall structures, a simplified FE superstructure model is used, representing a bridge pylon. The model was proposed by (Chatzigogos & Meza Fajardo, 2020): a uniform bridge pier of height  $H = 21$  m, with a cross section of circular form of diameter  $D = 3$  m. The superstructure is completed by nodal masses at the top of the beam representing the deck section of the bridge. A nonlinear constitutive law is implemented in the structure with an elastoplastic perfect behavior, with an initial elastic Young Modulus  $E = 30$  GPa, a yield stress  $f_y = 16.22$  MPa. The nonlinearities will be observed in the bending moment,  $M$ , versus curvature,  $\phi$ . More information about the structural model can be found in the references. In the original work, the foundation-soil domain is modeled by a macroelement. In this work, conversely, the soil portion is modeled with 3D volumetric elements in the FE code in order to have a direct coupling of soil and structure (Figure 2b). The dimensions (x,y,z) of the soil domain are 200 by 200 by 100 m<sup>3</sup> and the structure is positioned at the center of the soil domain. The connection of the superstructure with the soil portion is generated by a rigid square foundation modeled with 2D plate elements. For the sake of simplicity, this foundation is fully attached to the ground, which allows all ground displacements to be transmitted to the superstructure.

### 5 BASIN EFFECTS ON THE INDUCED STRUCTURAL DAMAGE

The effect of the spatial variability on the structural response is evaluated by inserting the structure in five different positions of the basin, from DRM<sub>1</sub>, at the basin center to DRM<sub>5</sub> at the basin edge (Figure 2c), distributed along the X axis. In order to have a comparable amplitude in the results from every source, a reference model without the basin (only the bedrock) is simulated, and the ground motion at the position [0,0,0] m is

obtained. A normalizing factor  $F$  is computed for every source, such that the horizontal peak ground displacement, defined as the square root of the sum of squares (SRSS) of the two horizontal seismic components is equal to a reference value of  $PGD_{H,Rock} = 3$  cm in this reference model. Then, factor  $F$  multiplies the input forces and displacements when applied to the reduced domain computation in CodeAster.

To find the coupled basin effects on the seismic hazard and on the structural demand, first, the ground motion variability is computed in terms of the amplification factor for the 5 locations. Second, the variability is assessed in the structural seismic demand. Finally, the basin effects on the seismic hazard and demand are discussed.

### 5.1 Ground motion variability

Inside the basin, the ground motion response at a specific location will be a combination of source and basin geometry effects. The amplification factor is computed as

$$AF = \frac{PSa_{UG}(T=T_{st}, 5\%)}{PSa_{Rock}(T=T_{st}, 5\%)} \quad (5)$$

where  $PSa(T=T_{st}, 5\%)$  is the geometric mean of response spectrum evaluated in the period of the structure,  $T_{st} = 1.313$  [s], of both horizontal components.

Table 2: Average values of amplification factors

DRM Location	$AF_{2D}$	$AF_{3D}$
DRM1	$1.714 \pm 0.076$	$4.318 \pm 0.915$
DRM2	$1.716 \pm 0.085$	$5.407 \pm 0.807$
DRM3	$1.715 \pm 0.082$	$5.879 \pm 2.024$
DRM4	$1.737 \pm 0.117$	$4.675 \pm 2.207$
DRM5	$1.786 \pm 0.180$	$4.121 \pm 1.800$
average	$1.730 \pm 0.109$	$4.819 \pm 1.751$

The distribution patterns of the  $AF$  in the layered (2D) and basin (3D) models are displayed in Table 2, where it is observed the remarkable influence of the basin edges inclusion, where the  $AF$  increases up to three times, due to constructive interference when the wave arrives from the west and reflects on the eastern edge. Due to the steep edge used in the study, higher amplification will be observed in the central region of the basin, in the positions of DRM2 and DRM3. In the layered model,  $AF_{2D}$  also have some variability due to the source impact (incident angle). The results highlight the complexity of the ground shaking when a basin edge is considered added to the double couple point sources.

### 5.2 Effect of basin edge on the seismic demand

The influence of the inclusion of the basin on the structural demand is computed through the maximum

relative displacement at the top of the bridge pier,  $u_{top}$ . The Fig. 3 contrast  $u_{top}$  as EDP to the selected IM,  $PSa(T=T_{st}, 5\%)$ , for the two modeled regional cases: layered (2D) in green and basin (3D) in orange. As expected, higher values of EDP are obtained for the 3D case, when the basin is added.

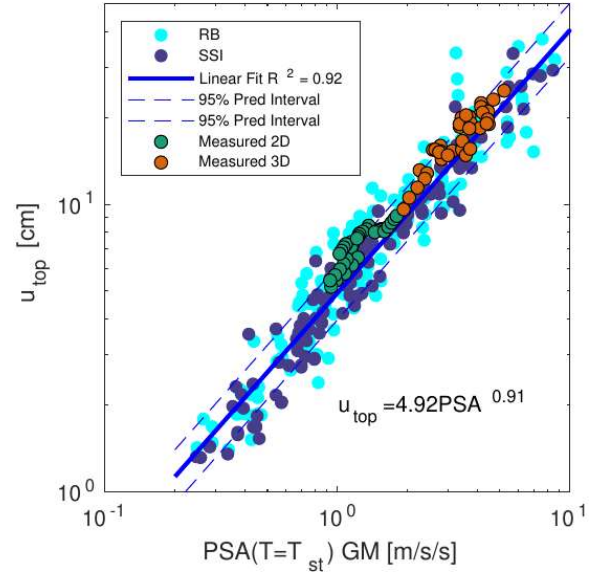


Fig. 3. IM-EDP relationship of the soil-structure domain used in this work, for the layered case (2D, in green) and basin case (3D, in orange). The results are superposed to the 1D plane wave dynamic response, which can be summarized by the equation presented on the bottom right of the figure.

Moreover, the result can be further contrasted with the 1D plane wave dynamic response ( $DR_{PW}$ ) of the soil-structure domain: hundreds of real signals are applied at the base (SH wave) of the domain in order to reconstruct the IM-EDP relationship, given by

$$u_{top} = 4.91 PSA^{0.91} \quad (6)$$

### 5.3 Integration of basin effects on the PBEE framework

The CCDF curves are computed from the aggregated results first for the hazard,  $CCDF_{IM,UG}$ , characterized by the spectral response at the period of the structure as IM in Fig. 4. The site term plays a significant role in the hazard as observed. It is clear that the inclusion of a layer of soil increases the spectral hazard, but the biggest change is observed for the 3D case. For instance, the PSA with a 25% probability of exceedance is about 1 m/s<sup>2</sup> for rock conditions, versus 1.6 and 4.2 m/s<sup>2</sup> for 2D and 3D cases, respectively. The effects of the soil layering could be accounted in the hazard curves directly by the amplification factor.

Accordingly, the demand  $CCDF_{EDP,UG}$  curves

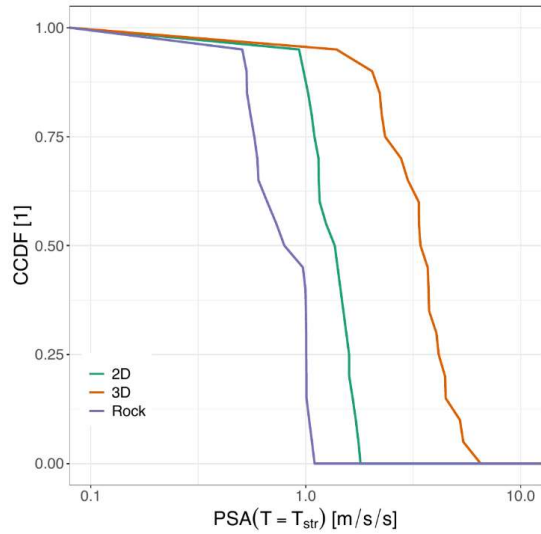


Fig. 4. Complementary cumulative distribution function of hazard  $CCDF_{IM,UG}$  for the studied model and the three regional geologies: Rock (in lavender), layered 2D (in green) and basin 3D (in orange).

can be measured directly from the coupled modelling technique, in the sense that the wave propagation process goes directly from the source to the structure with the DRM, including the complex wavefield produced by basins, as observed in the continuous lines of Figure 5.

Finally, to conclude the analysis of the structure, these results can be further contrasted with an estimation using the IM-EDP relation obtained in the  $DR_{PW}$  (Equation 6). The following steps are used to estimate basin effects on the uncoupled demand:

1. First, the hazard curves are determined for the selected IM in the 2D and 3D cases (Figure 4). In this case they are directly the ones obtained from the numerical simulations, but they could also be estimated only with the  $CCDF_{IM,Rock}$  and then consider the site effect with amplification factors (such as the ones presented in Table 2).
2. Then, the estimated  $CCDF_{EDP,UG}$  curves can be obtained by the convolution of the probability of exceeding the demand (Equation 6) with the hazard curves of Figure 4.

The term ‘uncoupled’ means that first the seismic hazard is computed and then, in an independent step, the structural demand. Therefore, the discrepancies in the measured (subscript M, coupled) versus estimated (subscript E, uncoupled) demand CCDFs come from (i) the differences in the ground motion characteristics not accounted with the selected IM (for instance,  $PSa(T=T_{st}, 5\%)$  accounts for horizontal part of surface waves but not for vertical or rotational

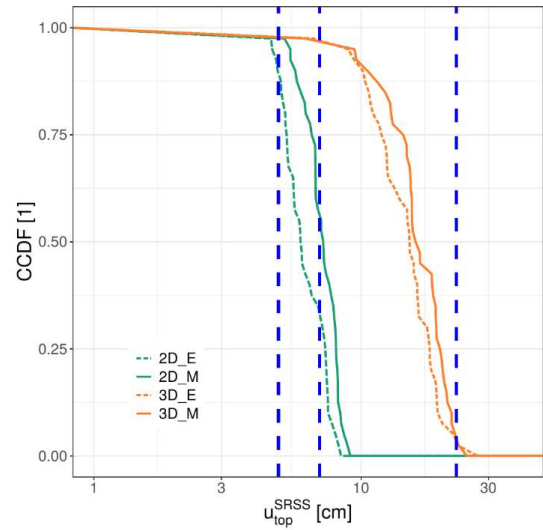


Fig. 5. Complementary cumulative distribution function of demand  $CCDF_{EDP,UG}$ , when a 1D layer of soil is used (2D) versus when the basin edges are considered (3D). The continuous lines results from the coupled modelling (M, measured) in contrast with the estimated from an uncoupled approach (E, estimated).

components) and (ii) the efficiency and sufficiency of the selected IM for the selected EDP. The soil-structure interaction is partially included in the simple approach because the EDP-IM relationship has been calculated from models including the soil and the structure.

The comparison of the estimated (continuous line) versus measured (dashed line) CCDFs for the seismic demand of structures is plotted in Fig. 5. for the layered (2D, in green) and the basin (3D, in orange) geometries. The threshold values for slight, moderate and extensive damage are also presented. It is observed that the estimated values of  $u_{top}^{SRSS}$  are only slightly lower than the ones measured. This finding demonstrates that most of the differences on the measured structural demand between the 2D and 3D cases come directly from the increase in the ground motion which is characterized by the pseudo-spectral acceleration as IM. This IM is computed only with horizontal components. For a moderate damage, in the 2D case, the simple approach provides an underestimation of the structural demand ( $\approx 35\%$ ) compared to the measured value ( $\approx 50\%$ ). The differences are observable for the 2D and 3D cases and come from the complex 3D excitation imposed by the coupled approach, including not only the horizontal components but also vertical and rotational components, which may lead to higher damages for the structure. To recall, complex ground motions are present in the 2D case due to the nonvertical incidence of waves and in the 3D case plus the basin geometry.



## 6 CONCLUSIONS

This paper presents a framework to evaluate the effect of the basin geometry on the strong ground motion amplification as well as on the seismic demand of nonlinear structures with a coupled simulation from the earthquake fault to a nonlinear infrastructure. As expected, the inclusion of the basin geometry edges increases the hazard in comparison to a layered model, due to the generation of a more complex 3D ground motion, including both body and surface waves. The amplification of the ground motion is correspondingly observable in the structural response, with a three-dimensional damage pattern associated to directionality effects. The inclusion of the underground geometry generates a general shift in the observable damage limit state, passing from a Slight to a Moderate level. This finding highlights the importance of the consideration of the basin geometry for seismic design. Finally, the results were contrasted to a simple approach, where the seismic hazard and structural demand were predicted in two separate steps, i.e., the hazard is convoluted with the nonlinear response of the structure, similar to the work of (Bazzurro & Cornell, 2004). It was observed a good accuracy with this approximative method, revealing that most of the differences on the damage between the 2D and 3D models can be explained by the increase of the hazard in the latter case, accounted by the horizontal spectral acceleration component. This increase is a combination of amplification due to the sediment materials plus the horizontal components of surface waves. Therefore, for this specific source, basin and infrastructural setting, the structural demand is not particularly affected by 3D ground motions considering rotational components of surface waves. Hereby, the demand or damage prediction could be estimated from amplification factors obtained from ground motions.

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