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Seismic site effects by an optimized 2D BE/FE method I. Theory, numerical optimization and application to topographical irregularities

B. Gatmiri[a,b], C. Arson[b,*], K.V. Nguyen[b]

[a]*University of Tehran, Tehran, Iran*

[b]*CERMES, Ecole Nationale des Ponts et Chaussées, Cité Descartes, Champs-sur-Marne, 6–8 avenue Blaise Pascal, 77455 Marne-la-Vallée cedex 2, France*

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Abstract

This paper deals with the evaluation of seismic site effects due to the local topographical and geotechnical characteristics. The amplification of surface motions is calculated by a numerical method combining finite elements in the near field and boundary elements in the far field (FEM/BEM). The numerical technique is improved by time truncation. In the first part of this article, the accuracy and the relevance of this optimized method are presented. Moreover, parametric studies are done on slopes, ridges and canyons to characterize topographical site effects. The second part deals with sedimentary valleys. The complexity of the combination of geometrical and sedimentary effects is underlined. Extensive parametrical studies are done to discriminate the topographical and geotechnical effects on seismic ground movement amplifications in two-dimensional irregular configurations. Characteristic coefficients are defined to predict the amplifications of horizontal displacements. The accuracy of this quantitative evaluation technique is tested and discussed.

Keywords: Hybrid numerical technique; Time truncation; Convergence criterion; CPU time; Mesh size; Elastodynamics; Seismic amplification; 2D site effects; Topographical irregularities; Parametric study

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1. Introduction

It has often been reported, after destructive earthquakes in mountain areas, that buildings located at the top of cliffs or hills suffer much more intensive damage than those located at the base. For example, the 1968 Tokachi-Oki earthquake in Japan produced considerable damage to buildings close to the edge of a cliff, contrary to buildings located relatively far from the edge. The 1995 Kozani earthquake in Greece brought the evidence of serious damage for villages built on hills. Particularly, high accelerations were recorded at the crest of the Pacoima Dam (around 1.25 g) during the 1971 San Fernando earthquake in California [1]. Experimental studies dealing with topographical effects are also reported in [2,3]. A state of the art is also done in [4,5].

A considerable amount of theoretical work has been reported in the literature of geotechnics and seismology, in order to model, quantify and predict the effects of the basin topography. As the subject is complex, analytical solutions can only be derived for a very limited number of simple configurations. The exact solutions found by Sanchez-Sesma for triangular wedges are exposed in [6,7]. Analytical solutions for semi-circular and semi-elliptical canyons are presented in [8,9].

In order to model site effects in more realistic circumstances (for P-SV waves and for an arbitrary shape of topographical feature), numerical methods have to be used. The finite difference method [10–12], the finite element method (FEM) [13,14], the discrete wavenumber method [15,16], and the boundary element method (BEM) [5,17–23] are the most frequently used. Domain-based methods such as the FEM represent excellent tools in analyzing heterogeneity and non-linearity in the soil.

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[*] Corresponding author. CERMES, Ecole Nationale des Ponts et Chaussées, Cité Descartes, Champs-sur-Marne, 6–8 avenue Blaise Pascal, 77455 Marne-la-Vallée cedex 2, France. Tel.: +33 1 64 15 35 66 or +33 1 64 15 35 24; fax: +33 1 64 15 35 62.

E-mail addresses: gatmiri@cermes.enpc.fr (B. Gatmiri), arson@cermes.enpc.fr (C. Arson).

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Nomenclature

c	wave velocity
c_{L}	longitudinal wave velocity
c_{T}	transversal wave velocity
c_{ij}	discontinuity term depending on the local geometry of the boundary at ξ and on Poisson's ratio
f	frequency of the input signal
m	number of time steps limiting the integration process in the domain by the time-truncation method
q	tolerance coefficient limiting the number of iterations in the calculation of $c \cdot u_N$ in the time-truncation technique: $\psi_m^q < L_m$
t_i	amplitude of the ith component of the traction vector at the boundary
u_i	amplitude of the ith component of the displacement vector at the boundary
ux	maximal amplitude of ground displacements in x-direction
uy	maximal amplitude of ground displacements in y-direction
x	abscissa of the observation point
$F^{t(k)}$	force calculated by the behavior law of the material at the kth iteration
F_{ij}	fundamental solution representing the traction at x in direction i due to a unit point force applied at ξ in the j-direction
G_{ij}	fundamental solution representing the displacement at x in direction i due to a unit point force applied at ξ in the j-direction
H	height of a slope or depth of a canyon
K^t	rigidity matrix at instant t
L	half-width at the surface of a canyon
L_1	half-width at the base of a canyon
L_{C}	characteristic dimension of the geometry: $L_{\mathrm{C}} = H$ for a slope (height), and $L_{\mathrm{C}} = L$ for a canyon or a ridge (half-width)
L_m	convergence criterion used in the time-truncation technique
M	mass matrix
N	number of intervals dividing the time axis so that $t = N\Delta t$
$R^{t+\Delta t}$	load increment imposed at $t+\Delta t$
$U^{t+\Delta t(k)}$	displacement vector for the kth iteration done to reach the load increment $R^{t+\Delta t}$ imposed at $t+\Delta t$
α	characteristic inclination angle of the topography
ξ	source point
η	dimensionless frequency
λ	wavelength of the input signal
v	Poisson's ratio
ρ	volumetric mass
σ_{nn}	normal stress
τ	tangential stress
x	field point
ψ_m	scalar parameter used to control the number of iterations in the calculation of domain integrals by the time-truncation technique, for m time steps: $\psi_m = \left[\int_\Omega G_{ij}^{m-1} \cdot \mathrm{d}\Omega\right]^{-1} \cdot \int_\Omega G_{ij}^{m} \cdot \mathrm{d}\Omega$

However, the size of the problem can easily exceed computing capacities and time because of the difficulty of modelling wave propagation in unbounded domains. In recent years, the BEMs, based on the discretization of integral equations, have gained importance in the resolution of wave propagation problems. These techniques can avoid the introduction of fictitious boundaries and reduce the dimensionality of the problem. In order to benefit from the advantages of both domain- and boundary-based methods, the BEM was coupled with the FEM [24] and the finite difference method [25]. Extension of BEM to unsaturated porous media has been achieved recently in [26,27].

In this paper, the two-dimensional wave scattering due to the presence of topographical irregularities is studied with the aid of a hybrid numerical technique, combining finite elements in the near field and boundary elements in the far field. The program used is HYBRID, developed by Gatmiri and his coworkers [24,28–30]. The integration process is approximated in the domain by time truncation [31]. Hence, calculations are performed faster, with a good accuracy compared with traditional boundary integration methods. Several types of topography (slope, canyon or ridge) are considered. The role of some key parameters, such as exciting frequency, depth and shape of the relief, are described and discussed.

2. An optimized hybrid numerical technique

2.1. Formulation of problems combining BEM and FEM

The FEM is particularly adapted to work with anelastic or non-linear soils. The BEM reduces the problem by one dimension and is relevant for half-plane problems. The study of site effects requires the resolution of mechanical wave radiation equations in irregular configurations, defined by specific topographical and geotechnical conditions. That is why hybrid models combing both methods are often used. In our study, sediments are modelled by finite elements. Substratum is represented by boundary elements, which is adapted to the study in the far field. The region of interest is a half-space and must be enclosed with