Engineering Geology 114 (2010) 109–115

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Seismic site amplification induced by topographic irregularity: Results of a numerical analysis on 2D synthetic models

Vincenzo Di Fiore *

Istituto per l'Ambiente Marino Costiero (IAMC), Consiglio Nazionale delle Ricerche (CNR), Calata Porta di Massa, Porto di Napoli, 80133, Naples, Italy

ARTICLE INFO

Article history:
Received 30 July 2009
Received in revised form 29 March 2010
Accepted 12 May 2010
Available online 24 May 2010

Keywords:
Topographic effect
Seismic site response
Finite element method

ABSTRACT

This study concerns the evaluation of seismic site effects and their relation to the local topographical characteristics of a slope. The seismic amplification (SA) on the free surface is calculated by a numerical model using the finite elements (FE) method. Synthetic models by utilized in the FE analysis represent a slope with an inclination ranging from 10° to 41°. At the crest and valley of the slope the models were considered horizontal and indefinite. The site effects were calculated on the free surface in several nodal points. The input motion used in the analysis was a SV seismic wave with variable frequency between 0.5 and 32 Hz. The seismic site analysis confirmed that in absence of sediments, ground motion is more amplified at the upper slope break than in other points of the model.

In regard to seismic amplification vs. the frequency we can affirm that seismic amplification reaches its maxima in the band 4–16 Hz and with slope angle value computed at the highest degree. It is also clear that a nonlinear seismic amplification response in the crest and valley zone while SA would seem to have a linear response in other zones. We propose an empirical method to estimate the SA in the regular slope far from the crest and valley zone.

Contents

Introduction

The seismic amplification (SA) due to topographic irregularity involves the assessment of seismic hazard in many city centers built on hills, land dam, natural and artificial slopes.

Several papers deal with this situation and the related earthquakes: Alaska 1964 (Idriss and Seed, 1967; Idriss, 1968), Irpinia 1980 (Siro, 1982), Northridge 1994 (Celebi, 1995; Bouchon and Barker, 1996), Umbria–Marche 1997 (Rovelli, 1998; Marsan et al., 2000), Eje Cafetero–Colombia 1999 (Rastremo and Cowan, 2000), Athens 1999 (Athanasopoulos et al., 2001; Kallou et al., 2001), Mid-Niigata Prefecture Earthquake in 2004 (Shiho Asano et al., 2006). In Nguyen and Gatmiri (2007), an extensive numerical study was conducted on the 2D scattering of seismic waves in relation to local topography, using the direct boundary element method. These results, show how topographic condition influence on the spatial variation of the ground motion. Gatmiri et al. (2008) have studied, by means of HYBRID (hybrid numerical program combining finite elements and boundary elements method) the main effects caused by topographical characteristics. They found that ground motion is amplified at the crest of ridges and at the upper corners of slopes.

Ashford et al. (1997a,b), analyze the effects of topography separately from the effects related to the natural frequency of the deposit. This is advantageous to the development of a simplified method to estimate topographic effects.

In this work, an extensive parametric study of 2D wave scattering due to incident SV waves is carried out by using a general-purpose finite element method (Idriss et al., 1994). The purpose is to provide

* Tel.: +39 081 5423856; fax: +39 081 5423888.
E-mail address: vincenzo.difiore@iamc.cnr.it.

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doi:10.1016/j.enggeo.2010.05.006

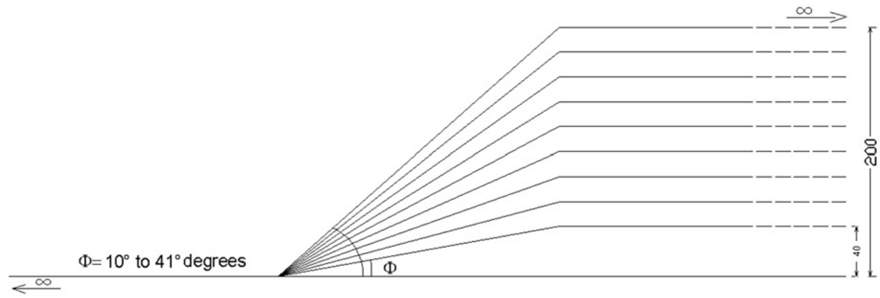

Fig. 1. Synthetic model utilized for seismic site effects with variable slope angles between 10 and 41°.

information on the range of possible ground responses and the attributes affecting wave scattering. Several slopes with different inclinations (from 10 to 41°) were considered in the 2D analysis. The fundamental role of the 2D slope effect with respect to seismic site amplification were analyzed and discussed.

Method of analysis and modelling

Finite element (FE) method program (Idriss et al., 1994) used for dynamic analysis, was developed in Fortran for dynamic analysis of earth structures in plain-strain. The equivalent linear method used in the program, involves direct step-by-step integration of the equations of motion. In all elements, strain compatible damping and shear modulus are used.

The software procedure follows a set of shear moduli and damping values estimated for each soil element of the finite element model. In each iteration the system analyzed these parameters and the shear strain history is computed for each element.

The method solves the motion equations at the nodal points of a discrete grid and is able to predict a strong generation of Rayleigh waves at dipping bedrock when SV waves are incident.

Fig. 1 shows the synthetic models utilized in the FE analysis. These models represent a slope with inclination ranging from 10° to 41°. At the crest and valley of the slope the models are considered horizontal and indefinite.

Fig. 2 displays the nodes that were utilized for the comparison of seismic site amplification. The site effects were calculated on the free surface in nodal points from 1 to 18.

Several quadrilateral and triangular elements (from 900 to 2400) were considered for the FE mesh; a ratio of the mesh to crest width of about 2 was adopted to minimize boundary effects on soil response. The mesh was fixed at the base, modeled as a transmitting boundary, and restrained only vertically at the sides to model the free field conditions.

The height elements were estimated by the formula (Lysmer and Drake, 1972):

$$dh = \lambda/K = Vs_{\min} / K * f_{\max}; \quad (1)$$

where dh is element height; λ is the wavelength; K is the stability non-dimensional coefficient ($K = 5$ near free surface and $K = 4$ elsewhere); $f_{\max}$ is the maximum frequency of propagation; $Vs_{\min}$ is the minimum shear wave velocity.

In order to compute the seismic site response, the 2D algorithm solves the following set of Eq. (2):

$$[M]\left(\partial^2 u / \partial t^2\right) + [D](\partial u / \partial t) + [K](u) = I(t) \quad (2)$$

where $[M]$ is the mass matrix; $[D]$ is the damping matrix; $[K]$ is the stiffness matrix; u is the nodal displacement vector and $I(t)$ is the earthquake load vector (input motion).

Synthetic accelerogram was used as input motion. It was generated for each frequency (0.5,1,2,4,8,16,32 Hz) using normalized amplitude of 0.1 g which was windowed by the Hanning function (3):

$$w(n) = 0.5(1 - \cos(2\pi n/N)); \; 0 \le n \le N \quad (3)$$

$w(n)$ is the Hanning function window; N is the window function samples number.

Table 1 reports the parameters used to generate the artificial seismogram.

Fig. 3a–c shows the Hanning windows in time domain and the frequency response for 1 Hz case.

As we should evaluate the seismic topographic effect only, the shear wave velocity was set to 1000 m/s for entire section (Vs(soil) = Vs (bedrock)) thus eliminating the effects due to Vs contrast between soil and bedrock. The bottom boundary of the model is set at 30 m below the valley sector and it is horizontal (Fig. 2).

Table 2 summarizes the parameters used for the calculation.

Results and discussion

Fig. 4a,i shows the results of the analysis performed for the different slope inclinations (10°–41°). On the ordinates axis is reported the seismic amplification (SA), which it express the free surface and input motion spectral ratio. All diagrams still include the

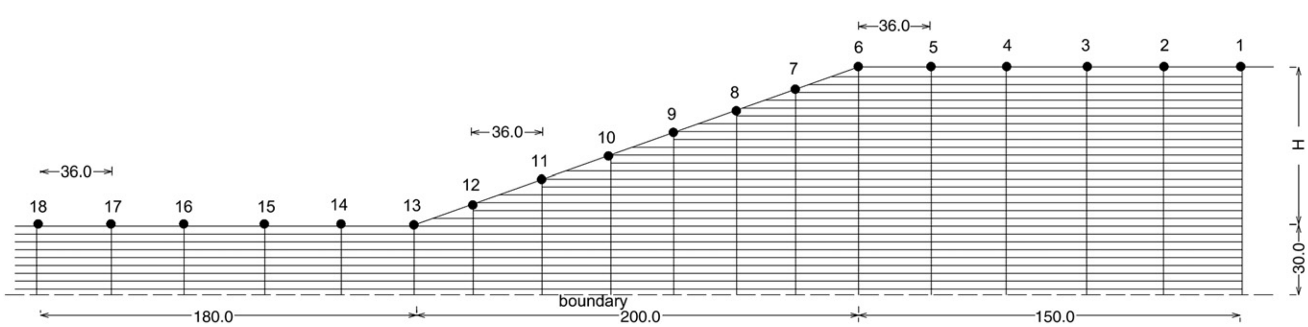

Fig. 2. Numerical configuration model and localization of the analyzed nodal points. FE mesh consisted of a minimal of 900 up to 2400 quadrilateral and triangular elements. The nodal point horizontal interval is 36 m and the boundary model is located at 30 m under the Xv surface.