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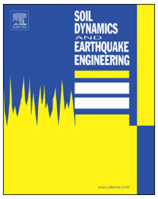

Coupling of topographic and stratigraphic effects on seismic response of slopes through 2*D* linear and equivalent linear analyses

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ABSTRACT

In this paper the seismic response of simple slope geometries under vertically propagating in-plane shear waves (SV waves) is assessed through two-dimensional finite element analyses to investigate the amplification of the ground motion induced by soil topography. Topographic horizontal and vertical amplification factors were evaluated through different sets of analyses focused on slopes in homogeneous half space and on slopes overlying either a rigid or a compliant bedrock. Soil was assumed to behave as a linear visco-elastic or as an equivalent-linear visco-elastic material. In the analyses the effects of slope inclination and of the characteristics of the input motion were also investigated.

In order to calibrate the numerical model, the results obtained in linear visco-elastic analyses were compared with the results of parametric numerical analyses available in the literature, showing a good agreement. The results confirmed that a complex interaction exists between stratigraphic and topographic effects on the amplification of the ground motion and that the two effects cannot be evaluated independently and easily uncoupled. In the case of compliant bedrock the effect of the impedance ratio was also investigated.

The results of the equivalent-linear analyses pointed out the remarkable dependence on soil non-linear behavior and, when compared to the results of linear visco-elastic analyses, showed that without accounting for soil non-linear behavior, topographic amplification factors may result underestimated.

1. Introduction

Evidence of past earthquakes showed that topographic irregularities significantly affect seismic site response and, in many cases, are responsible of large amplifications of the ground motion and of severe damages to structures and lifelines (e.g. [1–6]).

Although a number of studies have been carried out in the attempt to model and predict these effects, seismic amplification due to topography is not completely understood; in fact, its evaluation still represents a complex matter since it is coupled with stratigraphic effects and depends on many factors, among which ground surface geometry, soil profiles and mechanical properties and characteristics of the seismic motion.

Topographic irregularities may affect seismic site response for large distances, hence the availability of recording stations, relatively close to the topographic irregularity, where topographic amplification is negligible or easy to assess, may be scarce. Then, the accuracy of the studies based on the analysis of ground motion records remarkably depends on the reliability of the recorded motions used as a reference to quantify the effects of topography. These difficulties probably explain the quantitative differences between theoretical predictions and observed topographic amplifications (e.g. [7]).

The numerical evaluation of topographic effects is usually performed decoupling the topographic effects and the effects due to heterogeneities in soil profile (hereafter referred to as stratigraphic effects) from the computed site response. To this purpose the results of 2*D* seismic response analyses, accounting for both stratigraphic and topographic amplification, are generally compared with 1*D* analysis results reflecting only stratigraphic effects. The comparison of the computed responses can be performed in the time-domain, introducing a topographic amplification factor defined as the ratio between 2*D* and 1*D* peak ground acceleration values [8], or in the frequency-domain by means of a topographic aggravation factor (TAF) defined comparing the Fourier spectra of the 2*D* and 1*D* motions evaluated at the ground surface [3]. Alternatively, a topographic amplification factor for scaling design spectra can be defined as the average of the ratio of acceleration response spectra [9] or Housner intensities [10].

Studies on seismic response of slopes deal with case-studies (e.g. [2–4,6,7,11]) or are systematic parametric studies carried out

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Table 1
Studies on seismic response of slopes.

Reference	**Analysis method**	***H*** **(m)**	***i*** **(deg)**	**Soil model**	**V_S (m/s)**	**Input motion**	***A*** **(crest)**	***H/λ***
Linear visco-elastic (LVE)								
Idriss and Seed [18]	Finite element	≅ 6.1 ≅ 7.3 ≅ 15.2	27	Homogeneous soil over rigid foundation	≅ 130	1940 El Centro earthquake (scaled) record	1.50–2.50	–
Ashford et al. [8]	Generalized consistent transmitting boundary	30	30–90	Homogeneous half-space	300	Harmonic excitation	1.20–1.60	0.2; 1
Bouckovalas and Papadimitriou [19]	Finite difference	50	30–90	Homogeneous half-space	500	Harmonic excitation and Chang signal	1.20–1.50	0.2; 1
Tripe et al. [17]	Finite element	50	30–90	Homogeneous soil over rigid bedrock	500	Harmonic excitation and Chang signal	1.20–2.75	Variable
Equivalent linear (EL)								
Sitar and Clough [16]	Finite element	25	90	Homogeneous soil over rigid bedrock	Variable	1957 San Francisco earthquake record	1.90	–
Athanasopoulos et al. [2]	Finite element	70	Variable	Heterogeneous soil over rigid bedrock	Variable with depth	1995 Egion earthquake records	1.47	–
Gazetas et al. [3]	Finite element	40	30	Heterogeneous soil over compliant bedrock	Variable with depth	Ricker wavelet. 1999 Parnitha (Athens) earthquake records 1966 Parkfield (California) earthquake records	1.30–1.50	–

Table 2
Summary of the numerical analyses.

Preliminary analyses

Analyses	**Soil behavior/ properties**	**Model/bedrock**	***H*** **(m)**	***i*** (deg)	***D*** **(m)**	***L/H***	**a_o (g)**	***f*** **(Hz)**	**Figure**
2*D*	LVE $\gamma=20$ kN/m^3, $\nu=1/3$, $V_s=500$ m/s, $\xi=5\%$	homogeneous half space ($I_R=1$)	50	30	250	20,	0.1	2	2
						30			3
				10, 30, 45, 60, 90		30			2, 3
1*D* (supplementary)			0 50		250		0.1	2	

2*D* **analysis (H=50 m, *D*=250 m, *L/H*=30)**[a]

	Effect	**Model**	**Soil properties**	**Bedrock properties**	***i*** **(deg)**	**a_o (g)**	***f*** **(Hz)**	**Figure**
LVE	Frequency *f*	homogeneous half space ($I_R=1$)	$\gamma=20$ kN/m^3, $\nu=1/3$, $V_s=500$ m/s, $\xi=5\%$	–	30, 45, 60, 75, 90	0.1	0.1, 0.5, 1, 2, 3, 4.5, 7	4, 5
LVERB	Coupling	Homogeneous soil layer ($D=200$ m) over rigid bedrock ($I_R=0$)	$\gamma=20$ kN/m^3, $\nu=1/3$, $V_s=500$ m/s, $\xi=5\%$	–	90	0.1	0.1, 0.5, 1, 1.5, 2, 3, 5, 10	6
LVEB	Frequency *f*	Homogeneous soil layer over compliant bedrock ($I_R=0.2$)	$\gamma=20$ kN/m^3, $\nu=1/3$, $V_s=500$ m/s, $\xi=5\%$	$\gamma_b=20$ kN/m^3, $\nu_b=1/3$, $V_{s,b}=800$ m/s	30, 45, 60	0.1	2, 3, 4.5	7, 8
					45		0.5, 1, 2, 3, 4.5, 10	9
	Impedance ratio I_R	Homogeneous soil layer over compliant bedrock ($I_R=0.625$) ($I_R=0.4$) ($I_R=0.2$) ($I_R=0.1$)	$\gamma=20$ kN/m^3, $\nu=1/3$, $V_s=500$ m/s, $\xi=5\%$	$\gamma_b=20$ kN/m^3, $\nu_b=1/3$ $V_{s,b}=800$ m/s $V_{s,b}=1250$ m/s $V_{s,b}=2500$ m/s $V_{s,b}=5000$ m/s	45	0.1	0.5, 1, 2, 4.5, 10	10
EL	Coupling, plasticity index PI	Homogeneous soil layer (PI=30%, 50%, 100%, 200%) over compliant bedrock ($I_R=0.2$)	$\gamma=20$ kN/m^3, $\nu=1/3$, $V_s=500$ m/s	$\gamma_b=20$ kN/m^3, $\nu_b=1/3$, $V_{s,b}=2500$ m/s	30, 45, 60	0.1	2, 3, 4.5	11
	Soil non-linear behavior	Homogeneous soil layer (PI=30%) over compliant bedrock ($I_R=0.2$)	$\gamma=20$ kN/m^3, $\nu=1/3$, $V_s=500$ m/s	$\gamma_b=20$ kN/m^3, $\nu_b=1/3$, $V_{s,b}=2500$ m/s	45	0.1	3	12
						0.2		13
						0.3		14
		Homogeneous soil layer (PI=30%, 50%, 100%) over compliant bedrock ($I_R=0.2$)			45	0.1	0.5	15
		Homogeneous soil layer (PI=30%, 50%, 100%, 200%) over compliant bedrock ($I_R=0.2$)			45	0.1	0.5, 2	16
					45	0.1		17
	Frequency *f*	Homogeneous soil layer (PI=30%) over compliant bedrock ($I_R=0.2$)	$\gamma=20$ kN/m^3, $\nu=1/3$, $V_s=500$ m/s	$\gamma_b=20$ kN/m^3, $\nu_b=1/3$, $V_{s,b}=2500$ m/s	45	0.1	2, 3, 4.5	18
					45	0.1	0.5, 1.25, 2, 4.5, 10	19

[a] *D*=200 m in the LVERB analyses.