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Response surface models for local site response

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ABSTRACT: In microzonation studies, the evaluation of amplification parameters through detailed numerical models is often a too expensive procedure for urban planning purposes. The paper presents an approximate approach based on the response surface methods and on statistical processing of recorded or numerically obtained data. Comparisons between approximate and exact amplification parameters show that the approach is able to give reasonable estimates of local site response.

INTRODUCTION

The evaluation of local amplification parameters due to subsoil geology or morphological conditions is a very important aspect in the planning of urban development and restoration in seismic areas.

The problem of site effects during earthquakes has been the subject of research and scientific debate among engineers and seismologists for a long time; comprehensive discussions of the various methods available to-date can be found, for example, in state-of-the-art reports recently appeared in the literature (Sanchez-Sesma 1987, Aki 1988, Faccioli 1991).

From the point of view of the application of these methods, quantitative evaluations based on analytical or numerical models of the propagation of seismic waves require expensive geological and geotechnical characterizations of the sites while, on the other hand, simple estimates based on qualitative descriptors often disagree with the data obtained from real earthquakes. For this reason, a research need still exists in the field of the development of approximate methods suitable for inexpensive and reliable use in microzoning activities.

The present paper is aimed to give a contribution in this field, proposing the use of response surfaces, constructed upon the results of detailed numerical models and field observations, as an approximation of the amplification function for the peak ground acceleration at the surface of horizontally layered soil deposits. Modifications of the shape of the response spectra are also described in terms of ranges of the associated soil parameters.

As a matter of fact, even in those cases where the amplification characteristics of the deposit can be easily understood in the frequency domain, consideration of real accelerograms introduces a very high degree of complexity, rendering amplification parameters substantially unpredictable by means of synthetic formulas based on the modeling of the physical phoenomenon.

2 PROPOSED APPROXIMATE MODELS

In a previous research (Del Grosso et al. 1989) the Authors have proposed an approximate approach based on the use of the response surface method described by Box and Draper (Box and Draper 1987).

Soil deposits were hypothetically considered homogeneous horizontal layers resting on an elastic bedrock and classified into six different scenarios based on soil types (sand and clay), ranges of layer thickness and shear wave velocities of both the soil and the bedrock. For each scenario a second order polynomial surface was constructed using a classical response surface technique. For the construction of the surfaces, the response of the deposits was modelled using the nonlinear option of the program SHAKE (Schnabel et al. 1972).

In the above approach, the amplification effect was quantified by the ratio between the peak accelerations at the soil surface and at an outcropping of rock; the control motion applied in the analyses was an artificial time history matching a standard response spectrum for rocky sites.

In the present paper a new model is proposed which considers, besides the amplification in terms of peak acceleration, the modification of the shape of the response spectra.

The model consists in the definition of a site dependent spectrum S(T):

$$S(T) = a\,A(a,H,V)\,R(T) \qquad (1)$$

where a is the peak reference intensity at an outcropping of rock, A (amplification) is the ratio between the peak ground acceleration at the surface of the deposit and the reference intensity a, H and V are respectively the depth and the shear wave velocity of the deposit and R(T) is the normalized response spectrum.

In consideration of the actual distribution of amplification parameters in really observed cases, the ratio A is described by a complex surface, able to cover the entire range of the relevant parameters (H and V). The surface is chosen to give correct results for limiting cases. Scenarios are again used for the definition of proper spectral shapes R(T).

2.1 Collection of experimental data

Published experimental data have been collected into a data base in order to provide evidence and verification to approximate models (Garini 1991). To the purposes of the present research, only cases uniquely involving one-dimensional amplification have been considered.

A total of 314 records have been collected including 136 different sites; for each site sufficient information was available concerning soil stratigraphy and geotechnical characterization. Recorded events were consisting of strong or weak earthquake motions, microtremors and underground nuclear explosions. Response parameters were given in terms of peak ground acceleration or spectral ordinates.

Table 1 shows the distribution of the cases included in the data base.

Table 1. Summary of the experimental data.

	No. of cases	Acc. data	Spectral data
STRONG MOTIONS	136	61	75
WEAK MOTIONS	16	8	8
MICROTREMORS	29	2	27
NUCLEAR EXPL.	133	0	133
TOTAL	314	71	243

The cases have been ordered with respect to the height H of the deposit and to a reference shear wave velocity V as independent parameters. The reference shear wave velocity has been taken as the weighted average of the soil deposit:

$$V = \frac{1}{H}\sum V_i H_i \qquad (2)$$

where V_i and H_i are the shear wave velocity and the height of the i-th homogeneous layer, respectively.

The plot of A versus H and V is depicted in Figure 1. Obviously, the plot has been obtained by considering only those cases in which accelerometric data were available; however, the summary of the data in Table 1 shows that the cases are reasonably homogeneous. In addition, the cases collected cover a very wide range of values for H and V.

The surface has been fitted on the experimental data using a standard geostatistical technique (Davis 1986).

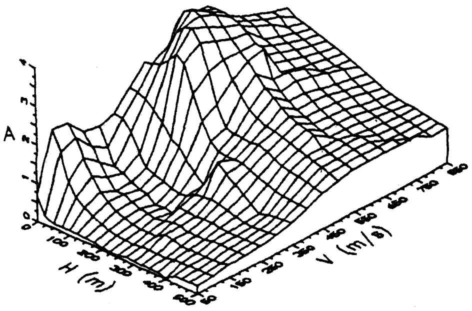

Figure 1. Plot of amplification A versus height H and reference velocity V of the deposit (71 observed cases).

The consideration of the information presented in Figure 1 has suggested that the response of a horizontal soil deposit to ground motion could be empirically approximated by a single surface of appropriate shape, described by the two parameters H and V.

The data collected do not allow to trace analogous informations concerning the response spectral shape. Consequently, the spectral modifications introduced by site effects will be approximately modeled by means of numerical analyses as described in paragraph 3.

2.2 Choice of the approximating surface

To derive the mathematical structure of the approximating surface, the following considerations have been taken into account.

1. The amplification ratio A should be 1 when the height of the deposit vanishes.
2. The amplification ratio A should be 0 for deposits of very very large depth.
3. The amplification ratio A tends to 1 for very very large values of the reference velocity.

4. For each value of the reference velocity the maximum amplification δ is obtained for the deposit exhibiting a fundamental period $T=0.2$ s ($T=4H/V$).

5. Different surfaces must be defined for different levels of the reference intensity a, due to non linear effects.

Consequently, the following mathematical expression is assumed:

$$A = \alpha\ (\beta\ T^n + \gamma)\ \exp[-(\beta\ T^n + \gamma)] \qquad (3)$$

where:

$$\alpha = e\ \delta \qquad (4.1)$$

$$\beta = 5^n (e\delta - 2)/(e\delta - 1) \qquad (4.2)$$

$$\gamma = 1/(e\delta - 1) \qquad (4.3)$$

$$\delta = 1 + (A_{max} - 1)\, e\, (V/V_{max})^m \exp[-(V/V_{max})^m] \qquad (4.4)$$

and e is the base of natural logarithms. The free parameters in the above expression are: n, m, V_{max} and A_{max}, being V_{max} the reference velocity for which the maximum amplification A_{max} is reached.

The shape of the surface given by expression (3) is represented in Figure 2.

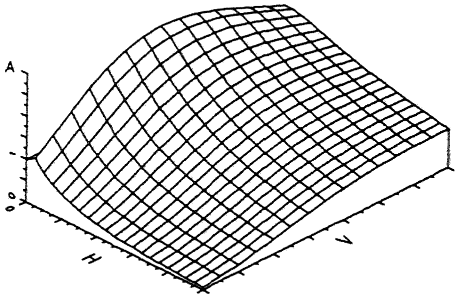

Figure 2. Plot of the approximating surface for the amplification A.

3 NUMERICAL ANALYSIS AND EXPERIMENTAL VERIFICATION

To actually define the approximate model, the results of an extensive numerical investigation have been used. This procedure has been considered necessary because the accelerometric data contained in the data base were not sufficient to sustain a complete regression analysis and the spectral data were non referred to parameters consistent with engineering application practices.

Therefore, the numerical analysis had the scope of generating data for subsequent processing aimed to the definition of both the approximation of A(a,H,V) and the normalized spectrum R(T).

The analysis has been performed with the computer program SHAKE. The cases analyzed were consisting of homogeneous layers with variable height and shear wave velocity, subjected to artificial earthquakes given at an outcropping of rock.

The input motions have been generated by modifying three real time histories recorded during the Friuli 1976 and the Irpinia 1980 earthquakes in order to match a standard response spectrum for rocky sites.

Since the nonlinear material option of the program SHAKE has been used in all the analyses, the input motions have been scaled to three increasing levels of intensity: 0.05 g, 0.15 g and 0.30 g.

Globally, a total of 242 different cases have been considered in the analysis. Their use in the definition of the approximate model is described in the following subparagraphs.

3.1 Amplification of the intensity

The amplification ratio A has been defined by fitting the upper envelope of the data points obtained by the numerical analysis with the surface given by expression (3). This choice has been made in order to obtain a worst estimate for the amplification expected at a given site.

Fitting has been performed by minimization of an error function. Table 2 presents the estimated parameters for the three different surfaces.

Table 2. Estimated parameters for the three surfaces A.

a	n	m	A_{max}	V_{max}
0.05 g	0.40	1.4	3.3	450 m/s
0.15 g	0.47	1.5	2.8	450 m/s
0.30 g	0.54	1.6	2.3	450 m/s

The results have been plotted in form of contour lines in Figure 3. Figures 3 a), b) and c) depict the surfaces corresponding, respectively, to the three different levels of intensity.

It is noted that the contour lines A=1 represent the loci of the points where no amplification (or deamplification) takes place. By comparing the three figures, the effect of dissipation of energy due to the nonlinearities is seen very clearly.

To verify the practical applicability of the approach, the experimental values of the amplification ratios contained in the data base have been superimposed to the surfaces obtained by numerical simulation. Available data have been grouped in three categories

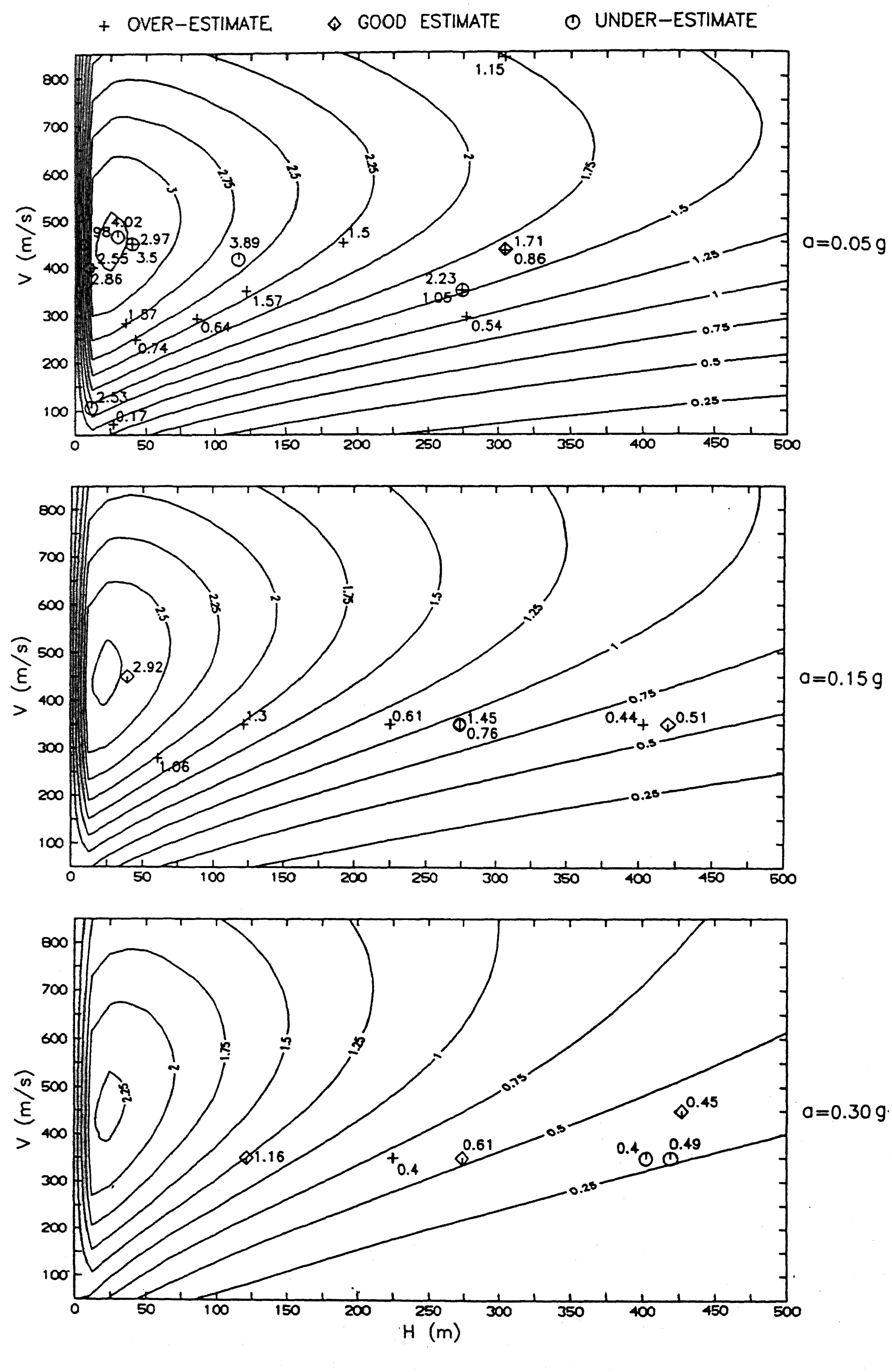

Figure 3. Amplification A for different values of the intensity a.

according to the range of the recorded peak acceleration. The records used in this comparison are plotted in Figures 3 a), b) and c); the events are respectively summarized in Tables 3, 4 and 5.

Table 3. Experimental data for a≈0.05 g.

SITE	a	H	V	A
ALEXANDER BUILD.	0.068	42.7	248	0.735
SOUTH. PACIFIC B.	0.074	86.7	292	0.635
OAKLAND CITY HALL	0.039	304.8	840	1.154
TOKYO - site 1	0.007	304.7	435	1.714
TOKYO - site 2	0.007	304.7	433	0.857
OSAKA - site 1	0.010	115.7	416.5	3.895
UNION BAY (a)	0.003	11.6	107	2.526
UNION BAY (b)	0.003	27.1	72	0.167
CALTECH LIBRARY	0.090	274.3	350	2.231
JET PROP. LABOR.	0.090	121.9	350	1.573
CALTECH ATHENAEUM	0.090	274.3	350	1.051
S.FRANCISCO BAY	0.008	36.2	283	1.573
COALINGA, Ca.	0.040	40.0	450	3.500
McGEE CREEK, Ca.	0.032	30.0	466	4.022
LENINAKAN	0.058	277.2	294	0.544
SKOPJE (a)	-	6.0	450	1.980
SKOPJE (b)	-	40.0	450	2.970
SKOPJE (c)	-	190.0	450	1.500
SKOPJE (d)	-	13.0	400	2.550
SKOPJE (e)	-	10.0	400	2.860

Table 4. Experimental data for a≈0.15 g.

SITE	a	H	V	A
STATE BUILDING	0.094	61.1	279	1.064
JET PROP. LABOR.	0.150	121.9	350	1.304
CALTECH LIBRARY	0.150	274.3	350	1.446
CALTECH ATHENAEUM	0.150	274.3	350	0.764
OROVILLE (a)	0.235	420.0	350	0.509
OROVILLE (b)	0.230	402.8	350	0.435
OROVILLE (c)	0.230	225.3	350	0.609
COALINGA, Ca.	0.150	40.0	450	2.917

Table 5. Experimental data for a≈0.30 g.

SITE	a	H	V	A
JET PROP. LABOR.	0.182	121.9	350	1.159
CALTECH ATHENAEUM	0.182	274.3	350	0.608
OROVILLE (a)	0.303	420.0	350	0.495
OROVILLE (b)	0.303	402.8	350	0.396
OROVILLE (c)	0.303	225.3	350	0.396
OROVILLE (d)	0.303	427.2	450	0.450

Comparison shows substantially good agreement between expected and recorded values of the amplification ratio. It is pointed out that the cases in which the discrepancy is more significant refer to very low intensity events. It is recognized that in these cases the nonlinear behavior of soils may not have taken place.

3.2 Response spectra

The response spectra resulting from the numerical analysis have been grouped into six different categories according to the value of the fundamental period of the deposit T. The six categories are showed in Table 6.

Table 6. Categorization of the response spectra.

T (s)	No. of cases	$\bar{A}$
$T \leq 0.25$	27	2.27
$0.25 \leq T \leq 0.5$	25	2.21
$0.5 \leq T \leq 1$	42	1.93
$1 \leq T \leq 2$	58	1.46
$2 \leq T \leq 3$	44	1.08
$3 \leq T \leq 5$	43	0.74

Table 6 also reproduces the values of the average amplification ratio $\bar{A}$, in the case a=0.15 g, for every range of the fundamental period.

Within each category, the mean and mean plus one standard deviation spectra at 5% damping have been computed for the three levels of intensity. Figures 4 a), b), c), d) and f) show the spectra computed for the acceleration level a=0.15 g.

First category spectra ($T \leq 0.25$ s) have not been shown because, as expected, they do not exhibit significant modifications with respect to the reference spectrum for the outcropping of rock. Sites belonging to this category are however exhibiting large values of the amplification ratio.

Comparisons performed with the spectra computed for the acceleration levels of 0.05 g and 0.30 g have not evidenced significant differences.

It is pointed out that the categorization of the response spectra with respect to the (equivalent) fundamental period of the deposit allows the definition of scenarios based on this parameter.

4 CONCLUSIONS

An approximate model for the evaluation of the amplification characteristics of a deposit of horizontally layered soils underlined by a stiff formation has been presented in the paper. The model has been based

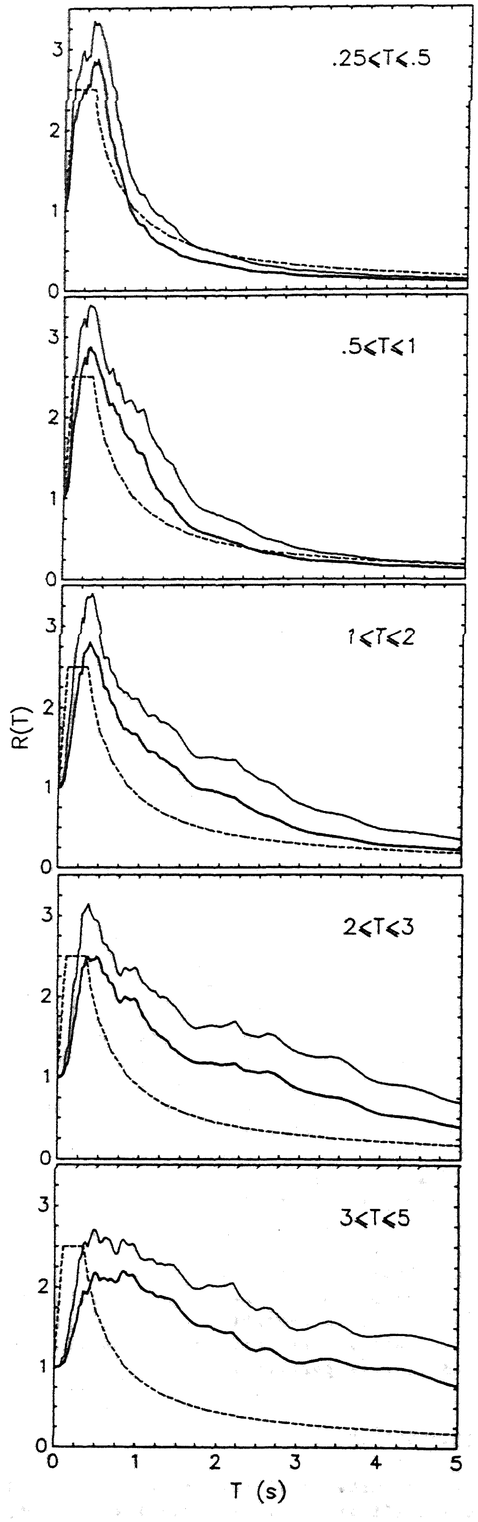

Figure 4. Response spectra R(T) for the last five categories of Table 6 (a=0.15 g).

upon extensive numerical simulations of the dynamic effect of the deposit on the acceleration characteristic and spectral shape of earthquake motions.

The mathematical structure of the model has been derived from a collection of real observations published in the literature. The validity of the predictions has also been verified with respect to observed data; good agreement between predicted and observed data has been found.

The model has the aim of providing a quick and inexpensive tool at the preliminary stage of a seismic microzoning activity, or in urban planning studies.

The informations needed to run the model uniquely consist of the height of the deposit and a reference shear wave velocity to be interpreted as a weighted average. It is pointed out that such informations may not be known exactly, although they could be obtained by relatively simple field investigations.

Further confidence on the applicability of the method can be obtained by extending the data base. The approach can be extended to other types of site effects, such as the ones due to morphological conditions.

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