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Re-evaluation of code-specified stratigraphic amplification factors based on Italian experimental records and numerical seismic response analyses

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ABSTRACT

For several engineering and seismological applications, site effects can be synthetically evaluated as a soil amplification factor of the reference ground motion on a rock outcrop leading to the peak ground acceleration and/or the response spectrum expected at a soil site, classified according to its equivalent shear wave velocity, $V_{S,30}$. In this work, nonlinear stratigraphic amplification factors as specified by Eurocode 8 (EC-8) and National Technical Code (NTC) were assessed with reference to selected accelerometric records of the Italian seismic network and well-characterized recording stations classified according to $V_{S,30}$. A first set of 'empirical' amplification factors has been identified, by selecting those stations on deformable soil for which records of the same events exist also at a nearby reference station located on outcropping rock (4 sites, 102 records). A second set of 'semi-empirical' data has been obtained by analysing the accelerograms recorded at stations where the geotechnical characterization was comprehensive and the reference motion could be back-figured by de-convolution to the bedrock (7 sites, 50 records). A third set of 'analytical' data was obtained from 1D numerical simulations of seismic site response performed on virtual stratigraphic profiles, consistent with the ground classification adopted by EC-8 and NTC, and subjected to 80 acceleration time histories of 22 Italian earthquakes, recorded at 19 stations of the Italian Network classified as rock sites. Empirical, semi-empirical and analytical data have been therefore integrated to express the stratigraphic amplification factor of peak ground acceleration and spectral intensity as a function of the corresponding reference ground motion value for each class of subsoil.

1. Introduction

Seismic site amplification is a very complex phenomenon, being controlled by a number of features such as the characteristics of the reference input motion, the surface topography, the geomorphology and depth of the seismic bedrock, the subsoil layering, and, last but not the least, the non-linear stiffness and damping properties of the soil layers overlying the bedrock.

For a reliable seismic design, all up-to-date national and international codes specify to account for the above aspects in site-specific seismic response analyses, based on high-quality geotechnical investigations. Nevertheless, in simplified hazard and site conditions, codes of practice (e.g. [1–3]) usually prescribe alternative rules, based on the adoption of standard amplification factors, to be applied in absence of more refined seismic response analyses. These rules are usually adopted for some typical routine design applications, such as:

– simplified predictions of the site-specific ground motion in terms of response spectra,
– application of empirical charts for liquefaction assessment,
– pseudo-static or simplified displacement-based analysis of slope stability (see for instance [4]).

A similar approach is often adopted for introducing site amplification in ground motion prediction equations used for simplified evaluations of intensity parameters (typically, the peak ground acceleration, but even spectral amplitudes at significant periods), adopted for instance in real-time shakemaps (e.g. [5]) or other simplified seismological tools for the simulation of ground motion.

For level ground (i.e. for flat or gently sloped soil surface), namely when topographic amplification can be neglected, site amplification is purely stratigraphic; the corresponding factor, S_S, to be applied to the reference peak ground acceleration (or a given spectral amplitude) on a stiff rock outcrop, in order to obtain the amplified value on the soil surface, can be basically related to soil properties and to the earthquake intensity measurement. Non-linear and hysteretic soil response is a key factor in controlling the variation of soil amplification factors with increasing level of shaking, since the seismic impedance contrast between

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Table 1
Summary of station pairs found in Italian databases [15,16].

Site	*Station ID*	$V_{S,30}$ [m/s]	*Ground type*	*Relative distance* [m]	*Azimut* [deg.]	*# of records*	*Recording period*
Forgaria – Cornino	FRC	454	B	603	17.5	8	1976–1977
San Rocco	SRC	> 800	A				
Aquila Centro Valle	AQV	545	B	714	69.7	11	2009
Aquila Colle Grilli	AQG	685	~A				
San Giuliano – School	SGP – A	290	C	435	346.0	12	2002
San Giuliano – Church	SGP – B	> 800	A				
Cesi Valle	CESV	169	D	207	70.6	20	1997–1998
Cesi Monte	CESM	> 800	A				

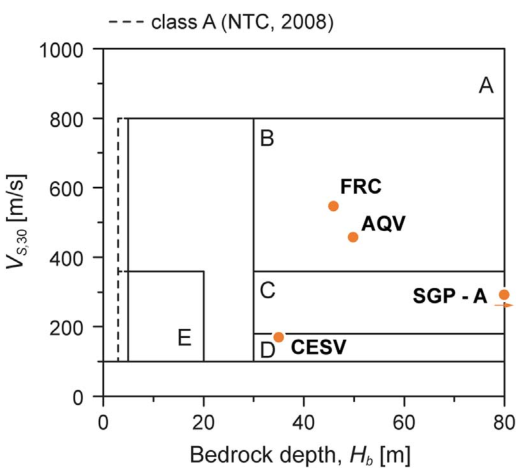

Fig. 1. Ground type classification for the soil sites of the stations considered for the empirical amplification factors.

the bedrock and the overlying soil, as well as the energy dissipation, both increase with shear strain level, hence with the ground motion amplitude.

The pioneer studies by [6], based on the first historical instrumental records, pointed out that the degree of sensitivity of amplification to soil non-linear behaviour increases with soil deformability; the same authors envisaged that the softest soils can show an inversion of tendency from amplification (i.e. S_S greater than unity) to attenuation (i.e. $S_S < 1$) of the reference peak ground acceleration, with the increase of this latter, as later demonstrated by [7]. After these basic studies and others such as [8], the use of non-linear stratigraphic amplification factors was gradually introduced into the codes of practice [9], by relating S_S to subsoil classification criteria based on the 'equivalent shear wave velocity' in the first 30 m of depth, $V_{S,30}$; for each soil class, S_S has been typically expressed as decreasing with the reference peak ground acceleration, often in a stepwise manner.

For instance, stratigraphic amplification factors prescribed by EC-8 and related national seismic codes, such as that adopted in Italy since 2008 ([3]), are mainly based on the interpretation of seismic records, integrated with the use of attenuation laws, as in the pilot study by [10].

More recently, a number of studies has been carried out in order to suggest modifications of soil classification criteria, amplification factors and response spectra adopted in EC-8 and related National Codes of Standards (see for instance [11]). These studies have been based on statistical analyses of observed data (e.g. [12]), on numerical studies involving non-linear seismic site response analyses (e.g. [13]) and on both observed data and numerical analyses (e.g. [14]). From some of these studies, it appears that a more suitable definition of amplification factors should imply a more refined subdivision of soil classes, taking also into account other parameters, such as index soil properties and the fundamental frequency of the soil layering.

In the following, a re-evaluation of stratigraphic amplification factors of EC-8 and NTC is proposed, as directly and indirectly based on experimental records, integrated with numerical seismic site response analyses. The selected seismic records are restricted to the Italian database, but it is believed that the approach followed can be viewed as representative of a general philosophy for calibrating stratigraphic amplification factors with more extended validity.

2. Methodology

This study has been focused on site stratigraphic amplification, as represented by the direct comparison between the acceleration time history either recorded or back-figured on a stiff rock outcrop with that recorded or analytically simulated at a soil site.

Three different approaches have been followed, collecting and merging empirical, semi-empirical and analytical datasets to evaluate relationships relating for different classes of subsoil profiles. Accelerometric records of the Italian network were selected from ITACA [15] and SISMA [16] on-line databases. Each recording station was assigned to the site classes A, B, C and D according to the well-known criteria specified by the European [2] and Italian National Technical Code [3]. In the following, the procedures related to the three different

Table 2
Selected records for the station SRC (reference rock site) and FRC (soil site, class B) (data from [15]).

Event		M_L	M_W	r_{epi} [km]	*Peak ground acceleration, PGA [g]*			
Date [dd/mm/yyyy]	Time [hh.mm.ss UTC]				SRC		FRC	
					NS	WE	NS	WE
18/05/1976	1.30.08	4.1	4.1	10.4	0.034	0.050	0.062	0.065
9/06/1976	18.48.15	4.1	4.3	14.7	0.026	0.040	0.072	0.058
11/06/1976	17.16.40	4.3	4.5	5.1	0.055	0.036	0.098	0.087
11/09/1976	16.31.10	5.5	5.1	15.7	0.032	0.071	0.097	0.112
11/09/1976	16.35.01	5.8	5.6	25.8	0.080	0.097	0.128	0.235
15/09/1976	3.15.18	6.1	5.9	16.9	0.052	0.138	0.266	0.216
15/09/1976	9.21.18	6.0	5.9	16.4	0.132	0.249	0.352	0.340
16/09/1977	23.48.07	5.3	5.3	6.1	0.099	0.090	0.245	0.203