

Ground Motion Prediction Equations for Mainland Portugal for different ground types

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Abstract

Ground motion amplitude of future events is usually estimated using empirical equations named ground motion prediction equations. To start, it is presented the methodology used to obtain such equations, such as the soil's non-linear behaviour when submitted to shear wave and the linear equivalent model. Afterwards, a program that contains such methodology is used to obtain the seismic response from reference response spectra and ground profiles. The final results show that stiffer soils increase the frequency in which the amplification is maximum and that attenuation occurs mostly for soft soils, at low periods. To conclude, the main results are discussed and further developments are presented.

Key words: linear equivalent model, ground motion prediction equations, local site effects

1) Introduction

In this work ground motion prediction equations (GMPEs) are derived for Mainland Portugal, from the source to the surface.

These equations contain variables such as magnitude, distance and a set of characteristics that define the tectonic environment and are, usually, estimated from past events in high seismicity areas.

However, the completeness of the Portuguese seismic catalogue is questionable since the recorded events do not reproduce, in a full scale, the seismicity history [1]. In addition, the magnitude and distance ranges of the recorded time histories do not cover the range of interest for civil engineering applications. GMPEs were estimated from theoretical models to derive simulated response spectra of a given seismic scenario. In this project, these simulated response spectra have already been obtained through a finite-fault stochastic model, developed at *Laboratório Nacional de Engenharia Civil* [2]:

- 13 280 horizontal acceleration response spectra for high magnitudes with epicentre at southeast of *São Vicente* Cape, with a distance to the epicentre between 50 and 700 km and magnitudes between 5,5 and 8,7. These spectral histories are classified as type 1, according to the Eurocode 8 [3], for Mainland Portugal;

- 4 843 horizontal acceleration response spectra for medium magnitudes, between 4,1 and 7,5, with a distance to the epicentre below 200 km. These spectral histories are classified as type 2, according to the Eurocode 8, for Mainland Portugal;

The reduced number of GMPEs for Mainland Portugal, adjusted to their seismicity, and the revision of the seismic definition in the Portuguese National Annex of the Eurocode 8 in a near future have motivated the development of this work.

Borehole data from Metropolitan Area of Lisbon and the Algarve region [4, 5] were gathered and classified according to the Eurocode 8 ground types. Seismic wave propagation above the bedrock was modelled by the linear equivalent model.

All ground profiles were subjected to a seismic wave at rock outcrop. These simulations created a database of seismic response at surface for different magnitudes and frequencies of the earthquake, hypocentral distance and ground type.

Finally, GMPEs were obtained through multi-linear regression to the data using the expression: $\log_{10} SA = c_1 + c_2 M + c_3 M^2 + c_4 \log_{10} R + c_5 R \pm \sigma_\varepsilon + f(S)$ in which SA represents the spectral acceleration, M the magnitude, R the hypocentral distance, c the coefficients, σ_ε the standard deviation to the data and $f(S)$ characterizes the seismic wave propagation through the ground above the bedrock.

2) Methodology

2.1) Seismic shear wave propagation

Seismic wave propagation above the bedrock was modelled assuming the vertical propagation of shear waves on horizontally stratified ground [6].

To take into account the soil's non-linear behaviour, due to shear wave propagation, the linear equivalent method was used. In this method, the nonlinear hysteric stress-strain behaviour of cyclically loaded soils can be approximated by equivalent linear soil properties: the shear modulus, G , which represents the stiffness, and the damping ratio, ξ , which represents the energy loss during the hysteresis loop.

The linear equivalent method is an iterative process that matches the soil's dynamic properties with the strain in all its layers.

The relationship between shear modulus and damping ratio, versus the strain, can be expressed through theoretical curves, such as the presented by Darendeli [7], used in the present study.

The LNECLoss model applies the equivalent linear model using the stochastic approach to estimate the ground response at surface [8].

The model requires a stochastic definition of the input excitation and dynamic response, which can be represented by a power spectral density function, $S_a(\bar{\omega})$ [9]. The output ground motion, $S_r(\bar{\omega})$, also a power spectral density function, is obtained through a transfer function, $H(\bar{\omega})$, relating the ground motion at the top of the bedrock to the surface:

$$S_r(\bar{\omega}) = |H(\bar{\omega})|^2 S_a(\bar{\omega}) \quad (1)$$

The equation that obtains the maximum values of the power spectral density function of the output ground motion is:

$$E(p) = \sqrt{2m_0 \left[\ln \left(\frac{d}{2\pi} \sqrt{\frac{m_2}{m_0}} \right) - \ln(-\ln(p)) \right]} \quad (2)$$

In which d represents the duration of the ground motion, p the percentile and m_j the j^{th} spectral moment:

$$m_j = \int_0^{+\infty} \omega^j S_r(\omega) d\omega \quad (3)$$

2.2) Specific form of the GMPEs

GMPEs are usually represented as a function of the seismic energy released, the distance to the source and a set of proprieties that define the source and the local effects. In the present study, the spectral acceleration, SA, in cm/s², is obtained through the following expression:

$$\log_{10} SA = c_1 + c_2 M + c_3 M^2 + c_4 \log_{10} R + c_5 R \pm \sigma_\varepsilon + f(S) \quad (4)$$

In which,

M represents the earthquake's magnitude;

R defines the hypocentral distance, in km;

c_j , $j = \{1; 2; 3; 4; 5\}$, represents the coefficients that only consider the wave propagation to the top of the bedrock;

σ_ε defines the standard deviation to the results that only consider the wave propagation to the top of the bedrock;

$f(S)$ represents the soils' non-linear behaviour and it was defined according to the non-special ground types described on the Eurocode 8:

$$f(S) = \begin{cases} b_{1,A} + b_{2,A}M + b_{3,A}M^2 + b_{4,A} \log_{10} R + b_{5,A}R \pm \sigma_{\varepsilon,A}, & \text{if the ground type is A} \\ b_{1,B} + b_{2,B}M + b_{3,B}M^2 + b_{4,B} \log_{10} R + b_{5,B}R \pm \sigma_{\varepsilon,B}, & \text{if the ground type is B} \\ b_{1,C} + b_{2,C}M + b_{3,C}M^2 + b_{4,C} \log_{10} R + b_{5,C}R \pm \sigma_{\varepsilon,C}, & \text{if the ground type is C} \\ b_{1,D} + b_{2,D}M + b_{3,D}M^2 + b_{4,D} \log_{10} R + b_{5,D}R \pm \sigma_{\varepsilon,D}, & \text{if the ground type is D} \\ b_{1,E} + b_{2,E}M + b_{3,E}M^2 + b_{4,E} \log_{10} R + b_{5,E}R \pm \sigma_{\varepsilon,E}, & \text{if the ground type is E} \end{cases} \quad (5)$$

In which,

$b_{j,\varphi}$, $j = \{1; 2; 3; 4; 5\}$ and $\varphi = \{A; B; C; D; E\}$, represent the coefficients that only consider the wave propagation above the bedrock;

$\sigma_{\varepsilon,\varphi}$, $\varphi = \{A; B; C; D; E\}$, defines the standard deviation to the results that only consider the wave propagation above the bedrock.

2.3) Classification of the borehole data according to the Eurocode 8

The analysis of the 172 borehole data gathered were classified according to the Eurocode 8's ground types. The distribution of the data through the ground types are presented on the Figure 1.

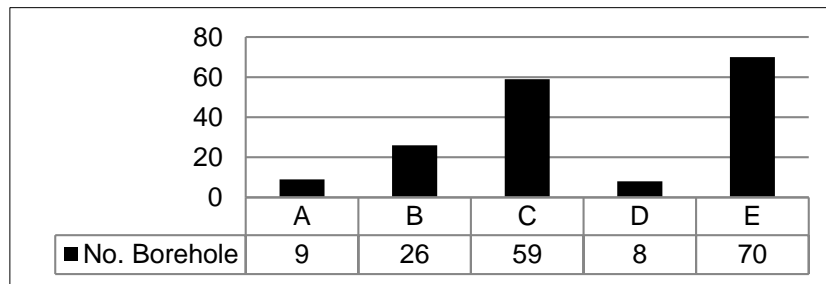


Figure 1 - Distribution of the borehole data through the Eurocode 8 ground type classification

3) Results and discussion

Each borehole data was subjected to a simulated response spectrum at the top of the bedrock, through an algorithm that simulates the stochastic approach of the linear equivalent model, with the variable p of the equation (3) taking the value of 50%.

The LNECLoss model returned a database of spectral histories at the surface of each borehole, for the two types of spectra defined on the Eurocode 8:

- 2 284 160 type 1 horizontal spectral acceleration histories;
- 832 996 type 2 horizontal spectral acceleration histories.

The data acquired was organised by ground type and frequency to apply the multi-linear regression and to obtain values for the coefficients presented at (4) and (5). The results are displayed in the Tables 1 to 6.

Table 1 – GMPEs coefficients for type 1 and 2 spectra, at the top of the bedrock

f (Hz)	Type 2 spectra						Type 2 spectra					
	c_1	c_2	c_3	c_4	c_5	σ_ε	c_1	c_2	c_3	c_4	c_5	σ_ε
0,201	-8,261	2,297	-0,110	-0,657	-0,001	0,205	-7,457	2,176	-0,090	-1,298	0,002	0,218
0,240	-8,178	2,313	-0,114	-0,617	-0,001	0,202	-7,765	2,329	-0,106	-1,235	0,002	0,218
0,334	-7,585	2,230	-0,112	-0,549	-0,001	0,201	-8,217	2,589	-0,133	-1,124	0,001	0,219
0,522	-5,875	1,872	-0,093	-0,465	-0,001	0,201	-7,983	2,686	-0,150	-0,991	0,000	0,221
0,954	-3,927	1,455	-0,069	-0,401	-0,002	0,208	-7,114	2,606	-0,154	-0,906	0,000	0,226
1,285	-2,898	1,237	-0,055	-0,410	-0,002	0,210	-6,256	2,411	-0,142	-0,879	-0,001	0,228
1,669	-1,431	0,926	-0,035	-0,478	-0,002	0,213	-5,371	2,192	-0,128	-0,866	-0,001	0,230
1,953	-0,986	0,832	-0,029	-0,489	-0,002	0,215	-4,765	2,036	-0,117	-0,867	-0,001	0,233
2,421	-0,591	0,747	-0,024	-0,494	-0,002	0,217	-3,953	1,821	-0,102	-0,875	-0,001	0,236
3,311	-0,241	0,672	-0,019	-0,492	-0,002	0,220	-2,992	1,571	-0,083	-0,893	-0,001	0,240
3,906	-0,116	0,645	-0,017	-0,489	-0,002	0,221	-2,522	1,447	-0,074	-0,910	-0,001	0,242
5,025	0,022	0,614	-0,015	-0,486	-0,003	0,222	-1,980	1,305	-0,064	-0,929	-0,001	0,245
6,250	0,110	0,595	-0,014	-0,482	-0,003	0,223	-1,562	1,202	-0,056	-0,963	-0,002	0,247
7,299	0,116	0,589	-0,014	-0,496	-0,003	0,223	-1,360	1,152	-0,052	-0,982	-0,002	0,249
8,403	0,120	0,585	-0,014	-0,510	-0,002	0,223	-1,211	1,113	-0,049	-0,994	-0,002	0,251
9,901	0,127	0,580	-0,013	-0,526	-0,002	0,223	-1,068	1,076	-0,046	-1,004	-0,002	0,254
12,5	0,138	0,573	-0,013	-0,548	-0,002	0,223	-1,037	1,067	-0,045	-1,036	-0,002	0,256
14,925	0,149	0,569	-0,012	-0,564	-0,002	0,224	-1,016	1,060	-0,045	-1,059	-0,002	0,258
20,0	0,167	0,562	-0,012	-0,588	-0,002	0,224	-0,985	1,050	-0,044	-1,091	-0,002	0,263
22,222	0,174	0,560	-0,012	-0,597	-0,002	0,225	-1,081	1,071	-0,045	-1,098	-0,002	0,261

25,0	0,183	0,557	-0,012	-0,607	-0,002	0,225	-1,210	1,101	-0,047	-1,107	-0,001	0,259
30,303	0,194	0,554	-0,011	-0,619	-0,002	0,226	-1,382	1,142	-0,050	-1,118	-0,001	0,256
40,0	0,210	0,549	-0,011	-0,636	-0,002	0,227	-1,683	1,216	-0,056	-1,136	-0,001	0,252
50,0	0,135	0,564	-0,012	-0,629	-0,002	0,226	-1,722	1,220	-0,056	-1,131	-0,001	0,251

Table 2 – GMPEs coefficients for type 1 and 2 spectra, at the top of a ground type A

<i>f</i> (Hz)	Type 1 spectra						Type 2 spectra					
	<i>b</i> _{1,A}	<i>b</i> _{2,A}	<i>b</i> _{3,A}	<i>b</i> _{4,A}	<i>b</i> _{5,A}	$\sigma_{\varepsilon,A}$	<i>b</i> _{1,A}	<i>b</i> _{2,A}	<i>b</i> _{3,A}	<i>b</i> _{4,A}	<i>b</i> _{5,A}	$\sigma_{\varepsilon,A}$
0,201	0,029	-0,006	0,000	-0,002	0,000	0,000	0,106	-0,022	0,002	-0,017	0,000	0,000
0,240	0,027	-0,006	0,000	-0,002	0,000	0,000	0,102	-0,022	0,002	-0,015	0,000	0,000
0,334	0,022	-0,005	0,000	-0,002	0,000	0,000	0,098	-0,023	0,002	-0,012	0,000	0,000
0,522	0,016	-0,003	0,000	-0,001	0,000	0,000	0,079	-0,019	0,001	-0,010	0,000	0,000
0,954	0,016	-0,003	0,000	-0,002	0,000	0,000	0,056	-0,013	0,001	-0,008	0,000	0,000
1,285	0,029	-0,006	0,000	-0,003	0,000	0,000	0,047	-0,009	0,001	-0,009	0,000	0,000
1,669	0,026	-0,005	0,000	-0,003	0,000	0,001	0,043	-0,007	0,001	-0,010	0,000	0,000
1,953	0,034	-0,006	0,001	-0,004	0,000	0,001	0,042	-0,006	0,000	-0,011	0,000	0,000
2,421	0,050	-0,009	0,001	-0,006	0,000	0,001	0,046	-0,005	0,000	-0,014	0,000	0,000
3,311	0,089	-0,017	0,001	-0,011	0,000	0,003	0,064	-0,004	0,000	-0,021	0,000	0,001
3,906	0,121	-0,023	0,002	-0,015	0,000	0,004	0,080	-0,004	0,000	-0,027	0,000	0,001
5,025	0,188	-0,034	0,003	-0,023	0,000	0,007	0,117	-0,006	0,000	-0,039	0,000	0,002
6,250	0,265	-0,047	0,004	-0,033	0,000	0,012	0,163	-0,008	0,001	-0,050	0,000	0,005
7,299	0,332	-0,057	0,005	-0,041	0,000	0,017	0,206	-0,012	0,001	-0,056	0,000	0,009
8,403	0,393	-0,063	0,005	-0,049	0,000	0,026	0,252	-0,016	0,001	-0,058	0,000	0,016
9,901	0,432	-0,059	0,005	-0,051	0,000	0,043	0,304	-0,021	0,002	-0,050	0,000	0,032
12,5	0,471	-0,046	0,003	-0,025	0,000	0,080	0,382	-0,027	0,002	-0,009	0,000	0,082
14,925	0,537	-0,044	0,003	-0,013	0,000	0,079	0,452	-0,040	0,003	0,036	0,000	0,082
20,0	0,224	0,044	-0,005	0,102	0,000	0,095	0,484	-0,057	0,003	0,162	-0,001	0,113
22,222	0,256	0,020	-0,004	0,107	0,000	0,058	0,501	-0,072	0,004	0,162	-0,001	0,082
25,0	0,286	-0,002	-0,002	0,081	0,000	0,017	0,510	-0,087	0,005	0,134	-0,001	0,038
30,303	0,259	-0,006	-0,001	0,070	0,000	0,008	0,533	-0,099	0,007	0,112	-0,001	0,022
40,0	0,585	-0,091	0,004	0,050	0,000	0,017	0,723	-0,142	0,009	0,094	-0,001	0,024
50,0	0,638	-0,094	0,005	0,026	0,000	0,044	0,732	-0,144	0,009	0,087	-0,001	0,036

Table 3 – GMPEs coefficients for type 1 and 2 spectra, at the top of a ground type B

<i>f</i> (Hz)	Type 1 spectra						Type 2 spectra					
	<i>b</i> _{1,B}	<i>b</i> _{2,B}	<i>b</i> _{3,B}	<i>b</i> _{4,B}	<i>b</i> _{5,B}	$\sigma_{\varepsilon,B}$	<i>b</i> _{1,B}	<i>b</i> _{2,B}	<i>b</i> _{3,B}	<i>b</i> _{4,B}	<i>b</i> _{5,B}	$\sigma_{\varepsilon,B}$
0,201	0,193	-0,047	0,003	-0,005	0,000	0,004	0,227	-0,056	0,004	-0,004	0,000	0,007
0,240	0,193	-0,046	0,003	-0,006	0,000	0,007	0,227	-0,057	0,004	-0,005	0,000	0,008
0,334	0,130	-0,027	0,002	-0,005	0,000	0,015	0,230	-0,058	0,004	-0,007	0,000	0,013
0,522	-0,045	0,024	-0,002	0,008	0,000	0,031	0,143	-0,028	0,002	-0,004	0,000	0,036
0,954	0,113	-0,021	0,001	-0,003	0,000	0,007	0,092	-0,014	0,000	-0,004	0,000	0,012
1,285	0,064	-0,006	0,000	-0,012	0,000	0,004	0,107	-0,020	0,001	-0,014	0,000	0,002
1,669	0,026	0,007	-0,001	-0,006	0,000	0,012	0,080	-0,005	0,000	-0,015	0,000	0,012
1,953	0,050	0,002	0,000	-0,005	0,000	0,014	0,084	-0,003	0,000	-0,015	0,000	0,012
2,421	0,052	0,003	-0,001	-0,006	0,000	0,016	0,088	0,000	-0,001	-0,019	0,000	0,012
3,311	-0,046	0,034	-0,003	-0,001	0,000	0,024	0,119	-0,005	0,000	-0,022	0,000	0,010
3,906	-0,002	0,024	-0,002	0,012	0,000	0,033	0,088	0,013	-0,002	-0,016	0,000	0,019
5,025	-0,066	0,044	-0,004	0,034	0,000	0,048	0,083	0,018	-0,002	-0,004	0,000	0,032
6,250	-0,034	0,038	-0,004	0,050	0,000	0,062	0,102	0,018	-0,003	0,018	0,000	0,049
7,299	-0,031	0,042	-0,005	0,059	0,000	0,065	0,137	0,008	-0,002	0,038	0,000	0,048
8,403	-0,131	0,072	-0,007	0,077	0,000	0,071	0,126	0,010	-0,002	0,061	0,000	0,048
9,901	-0,262	0,107	-0,010	0,120	0,000	0,082	0,087	0,020	-0,003	0,100	0,000	0,068
12,5	-0,222	0,094	-0,010	0,161	0,000	0,064	0,085	0,020	-0,004	0,141	0,000	0,056
14,925	-0,089	0,056	-0,008	0,167	0,000	0,050	0,096	0,015	-0,004	0,161	-0,001	0,037
20,0	0,061	0,018	-0,005	0,144	0,000	0,046	0,192	-0,027	-0,001	0,183	-0,001	0,028

30,303	-0,042	0,036	-0,005	0,141	0,000	0,031	0,249	-0,058	0,002	0,185	-0,001	0,015
40,0	0,011	0,010	-0,003	0,135	0,000	0,014	0,335	-0,087	0,004	0,175	-0,001	0,004
50,0	0,053	-0,001	-0,002	0,124	0,000	0,015	0,324	-0,084	0,004	0,166	-0,001	0,007

Table 4 – GMPEs coefficients for type 1 and 2 spectra, at the top of a ground type C

f (Hz)	Type 1 spectra						Type 2 spectra					
	$b_{1,C}$	$b_{2,C}$	$b_{3,C}$	$b_{4,C}$	$b_{5,C}$	$\sigma_{\varepsilon,C}$	$b_{1,C}$	$b_{2,C}$	$b_{3,C}$	$b_{4,C}$	$b_{5,C}$	$\sigma_{\varepsilon,C}$
0,201	0,792	-0,194	0,013	-0,006	0,000	0,004	0,852	-0,243	0,016	0,058	0,000	0,004
0,240	0,846	-0,208	0,014	-0,011	0,000	0,006	0,846	-0,240	0,016	0,047	0,000	0,004
0,334	0,953	-0,231	0,016	-0,030	0,000	0,014	0,842	-0,233	0,017	0,025	0,000	0,006
0,522	0,801	-0,172	0,013	-0,057	0,000	0,033	0,694	-0,172	0,013	-0,012	0,000	0,018
0,954	-0,172	0,124	-0,009	0,017	0,000	0,046	0,483	-0,073	0,006	-0,005	0,000	0,048
1,285	-0,472	0,206	-0,018	0,098	0,000	0,049	0,273	0,009	-0,002	0,034	0,000	0,050
1,669	-0,575	0,216	-0,020	0,159	0,000	0,057	0,103	0,063	-0,008	0,067	0,000	0,062
1,953	-0,634	0,219	-0,021	0,178	0,000	0,055	0,027	0,080	-0,009	0,078	0,000	0,064
2,421	-0,735	0,231	-0,022	0,190	0,000	0,045	-0,083	0,102	-0,011	0,083	0,000	0,064
3,311	-1,035	0,299	-0,027	0,205	0,000	0,012	-0,177	0,112	-0,012	0,085	0,000	0,025
3,906	-1,191	0,333	-0,030	0,231	0,000	0,008	-0,223	0,118	-0,013	0,099	0,000	0,018
5,025	-1,311	0,347	-0,033	0,291	0,000	0,006	-0,325	0,143	-0,016	0,134	0,000	0,020
6,250	-1,422	0,360	-0,034	0,329	0,000	0,007	-0,344	0,132	-0,015	0,169	0,000	0,017
7,299	-1,262	0,305	-0,031	0,351	0,000	-0,006	-0,436	0,155	-0,018	0,195	0,000	0,008
8,403	-1,124	0,258	-0,028	0,340	0,000	-0,014	-0,427	0,139	-0,017	0,204	0,000	-0,005
9,901	-1,220	0,276	-0,028	0,340	0,000	-0,010	-0,502	0,142	-0,017	0,209	0,000	-0,005
12,5	-1,071	0,222	-0,024	0,358	0,000	-0,013	-0,545	0,143	-0,018	0,251	0,000	-0,007
14,925	-1,116	0,227	-0,024	0,358	0,000	-0,014	-0,609	0,143	-0,017	0,266	0,000	-0,008
20,0	-1,102	0,214	-0,023	0,362	0,000	-0,018	-0,667	0,140	-0,017	0,298	0,000	-0,014
30,303	-1,240	0,243	-0,024	0,371	0,000	-0,019	-0,708	0,143	-0,016	0,311	0,000	-0,018
40,0	-1,336	0,265	-0,025	0,379	0,000	-0,019	-0,670	0,135	-0,015	0,317	0,000	-0,017
50,0	-1,315	0,262	-0,024	0,369	0,000	-0,020	-0,676	0,137	-0,015	0,313	0,000	-0,014

Table 5 – GMPEs coefficients for type 1 and 2 spectra, at the top of a ground type D

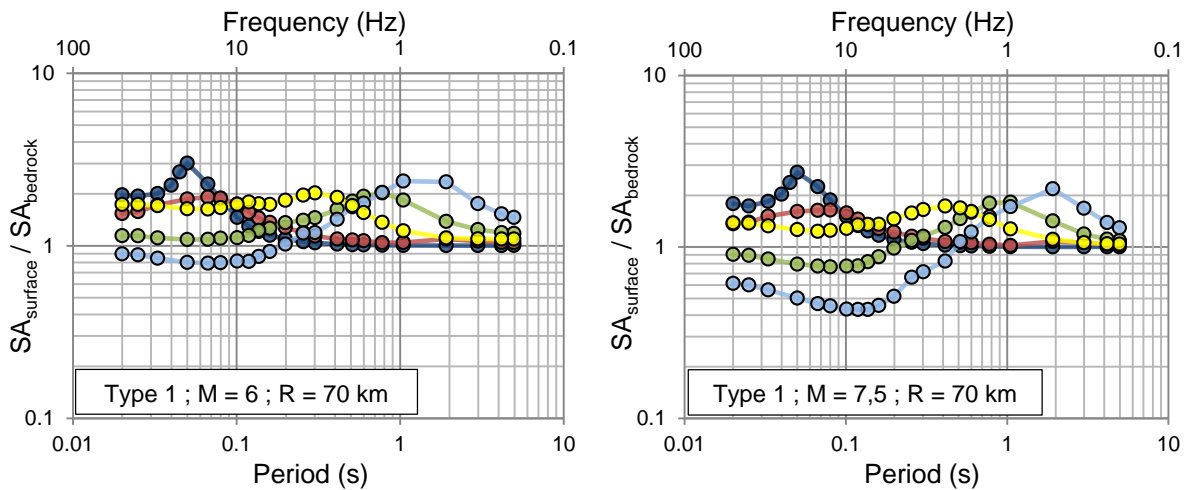
f (Hz)	Type 1 spectra						Type 2 spectra					
	$b_{1,D}$	$b_{2,D}$	$b_{3,D}$	$b_{4,D}$	$b_{5,D}$	$\sigma_{\varepsilon,D}$	$b_{1,D}$	$b_{2,D}$	$b_{3,D}$	$b_{4,D}$	$b_{5,D}$	$\sigma_{\varepsilon,D}$
0,201	1,577	-0,403	0,027	0,013	0,000	0,017	1,046	-0,279	0,017	0,129	-0,001	0,015
0,240	1,503	-0,377	0,026	0,008	0,000	0,025	1,103	-0,292	0,019	0,103	-0,001	0,018
0,334	0,999	-0,218	0,015	0,004	0,000	0,041	1,171	-0,302	0,022	0,055	-0,001	0,032
0,522	-0,356	0,191	-0,016	0,078	0,000	0,066	0,617	-0,085	0,006	0,026	0,000	0,075
0,954	-0,541	0,248	-0,025	0,183	0,000	0,012	0,016	0,148	-0,018	0,094	0,000	0,021
1,285	-1,453	0,473	-0,042	0,229	0,000	0,028	-0,109	0,145	-0,016	0,091	0,000	0,036
1,669	-1,949	0,585	-0,051	0,286	0,000	0,012	-0,213	0,162	-0,018	0,113	0,000	0,029
1,953	-1,963	0,571	-0,052	0,342	0,000	0,003	-0,473	0,238	-0,025	0,140	0,000	0,006
2,421	-1,301	0,367	-0,039	0,353	0,000	0,000	-0,525	0,262	-0,030	0,175	0,000	0,010
3,311	-2,052	0,546	-0,051	0,381	0,000	0,013	-0,634	0,255	-0,028	0,168	0,000	0,002
3,906	-2,279	0,598	-0,057	0,435	0,000	0,018	-0,625	0,233	-0,027	0,214	0,000	0,013
5,025	-1,520	0,361	-0,041	0,464	0,000	-0,017	-0,674	0,251	-0,032	0,271	0,000	-0,024
6,250	-1,514	0,335	-0,040	0,495	0,000	-0,013	-0,900	0,293	-0,035	0,300	0,000	-0,022
7,299	-1,301	0,263	-0,034	0,488	0,000	-0,019	-0,892	0,271	-0,034	0,323	0,000	-0,020
8,403	-1,438	0,292	-0,035	0,466	0,000	-0,026	-0,868	0,234	-0,030	0,327	0,000	-0,024
9,901	-1,243	0,227	-0,030	0,480	0,000	-0,032	-0,948	0,251	-0,032	0,359	0,000	-0,026
12,5	-1,411	0,265	-0,032	0,470	0,000	-0,037	-1,015	0,240	-0,029	0,371	0,000	-0,029
14,925	-1,467	0,274	-0,032	0,467	0,000	-0,042	-0,994	0,214	-0,027	0,391	0,000	-0,036
20,0	-1,726	0,339	-0,035	0,465	0,000	-0,044	-1,175	0,242	-0,028	0,403	0,000	-0,041
30,303	-1,994	0,408	-0,039	0,477	0,000	-0,044	-1,276	0,273	-0,029	0,406	0,000	-0,042
40,0	-2,113	0,438	-0,041	0,488	0,000	-0,044	-1,176	0,251	-0,026	0,414	0,000	-0,041
50,0	-2,100	0,439	-0,041	0,478	0,000	-0,044	-1,186	0,258	-0,027	0,408	0,000	-0,038

Table 6 – GMPEs coefficients for type 1 and 2 spectra, at the top of a ground type E

f (Hz)	Type 1 spectra						Type 2 spectra					
	$b_{1,E}$	$b_{2,E}$	$b_{3,E}$	$b_{4,E}$	$b_{5,E}$	$\sigma_{\varepsilon,E}$	$b_{1,E}$	$b_{2,E}$	$b_{3,E}$	$b_{4,E}$	$b_{5,E}$	$\sigma_{\varepsilon,E}$
0,201	0,510	-0,118	0,008	-0,020	0,000	0,003	0,893	-0,260	0,019	0,017	0,000	0,005
0,240	0,529	-0,124	0,008	-0,021	0,000	0,003	0,872	-0,254	0,018	0,013	0,000	0,004
0,334	0,574	-0,136	0,009	-0,029	0,000	0,006	0,840	-0,244	0,018	0,005	0,000	0,004
0,522	0,551	-0,125	0,009	-0,046	0,000	0,011	0,676	-0,190	0,014	-0,013	0,000	0,004
0,954	0,469	-0,084	0,007	-0,073	0,000	0,027	0,658	-0,172	0,014	-0,035	0,000	0,011
1,285	0,227	-0,003	0,001	-0,066	0,000	0,042	0,638	-0,153	0,013	-0,043	0,000	0,024
1,669	-0,211	0,118	-0,008	-0,009	0,000	0,060	0,560	-0,116	0,010	-0,032	0,000	0,050
1,953	-0,343	0,152	-0,012	0,044	0,000	0,072	0,455	-0,071	0,006	-0,012	0,000	0,076
2,421	-0,440	0,173	-0,015	0,119	0,000	0,076	0,351	-0,023	0,001	0,028	0,000	0,090
3,311	-0,493	0,172	-0,017	0,207	0,000	0,069	0,174	0,042	-0,006	0,088	0,000	0,080
3,906	-0,615	0,196	-0,019	0,230	0,000	0,060	0,094	0,057	-0,008	0,107	0,000	0,062
5,025	-0,834	0,241	-0,023	0,256	0,000	0,059	-0,047	0,082	-0,009	0,126	0,000	0,055
6,250	-0,943	0,259	-0,024	0,277	0,000	0,060	-0,157	0,102	-0,011	0,148	0,000	0,057
7,299	-1,041	0,277	-0,026	0,303	0,000	0,053	-0,202	0,105	-0,011	0,167	0,000	0,050
8,403	-1,035	0,267	-0,026	0,337	0,000	0,049	-0,261	0,118	-0,013	0,192	0,000	0,053
9,901	-0,874	0,216	-0,023	0,342	0,000	0,025	-0,257	0,112	-0,013	0,209	0,000	0,036
12,5	-0,891	0,210	-0,022	0,343	0,000	-0,002	-0,308	0,107	-0,013	0,226	0,000	-0,001
14,925	-0,811	0,183	-0,020	0,342	0,000	-0,007	-0,322	0,101	-0,012	0,245	0,000	-0,007
20,0	-0,807	0,176	-0,019	0,345	0,000	-0,008	-0,396	0,106	-0,013	0,273	0,000	-0,010
30,303	-0,766	0,159	-0,017	0,361	0,000	-0,012	-0,352	0,088	-0,011	0,305	-0,001	-0,014
40,0	-0,811	0,166	-0,017	0,367	0,000	-0,013	-0,280	0,067	-0,009	0,314	-0,001	-0,015
50,0	-0,763	0,155	-0,016	0,360	0,000	-0,014	-0,285	0,069	-0,010	0,312	-0,001	-0,012

The coefficients $b_{5,\varphi}$ from the Tables 2 to 6 were disregarded from the analysis.

To analyse the differences between the five ground types for diverse seismic scenarios, the figures 2 and 3 display the ratio between spectral acceleration at the surface of each ground type and at the top of the bedrock.



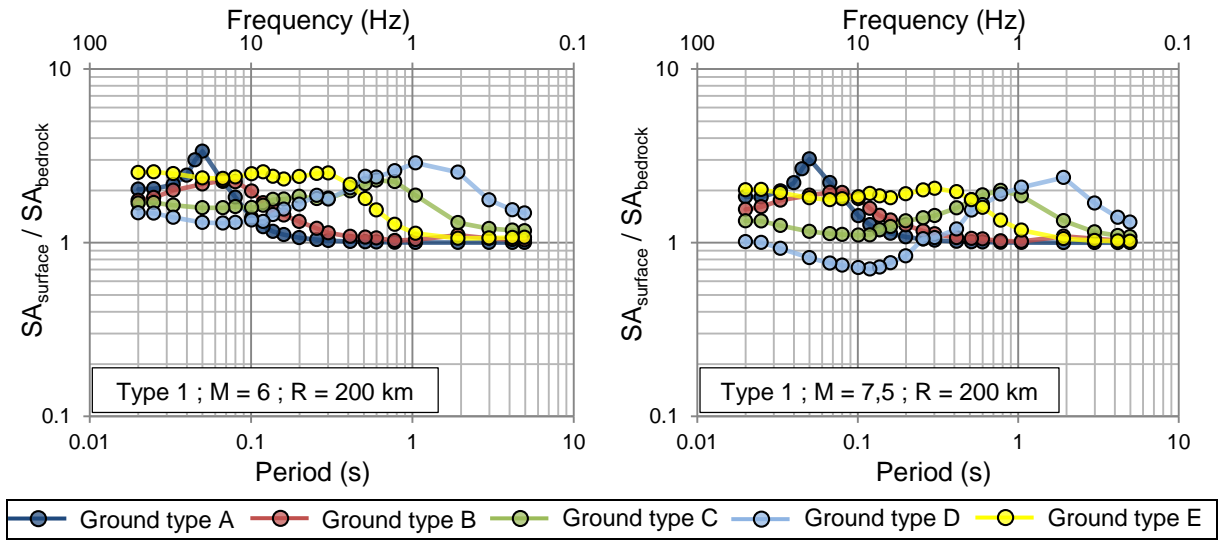


Figure 2 – Ratio between spectral acceleration at the surface and at the top of the bedrock, for Eurocode 8 ground types A to E, considering the GMPEs obtained for type 1 spectra, with $M = \{6; 7,5\}$ and $R = \{70; 200\}$ km

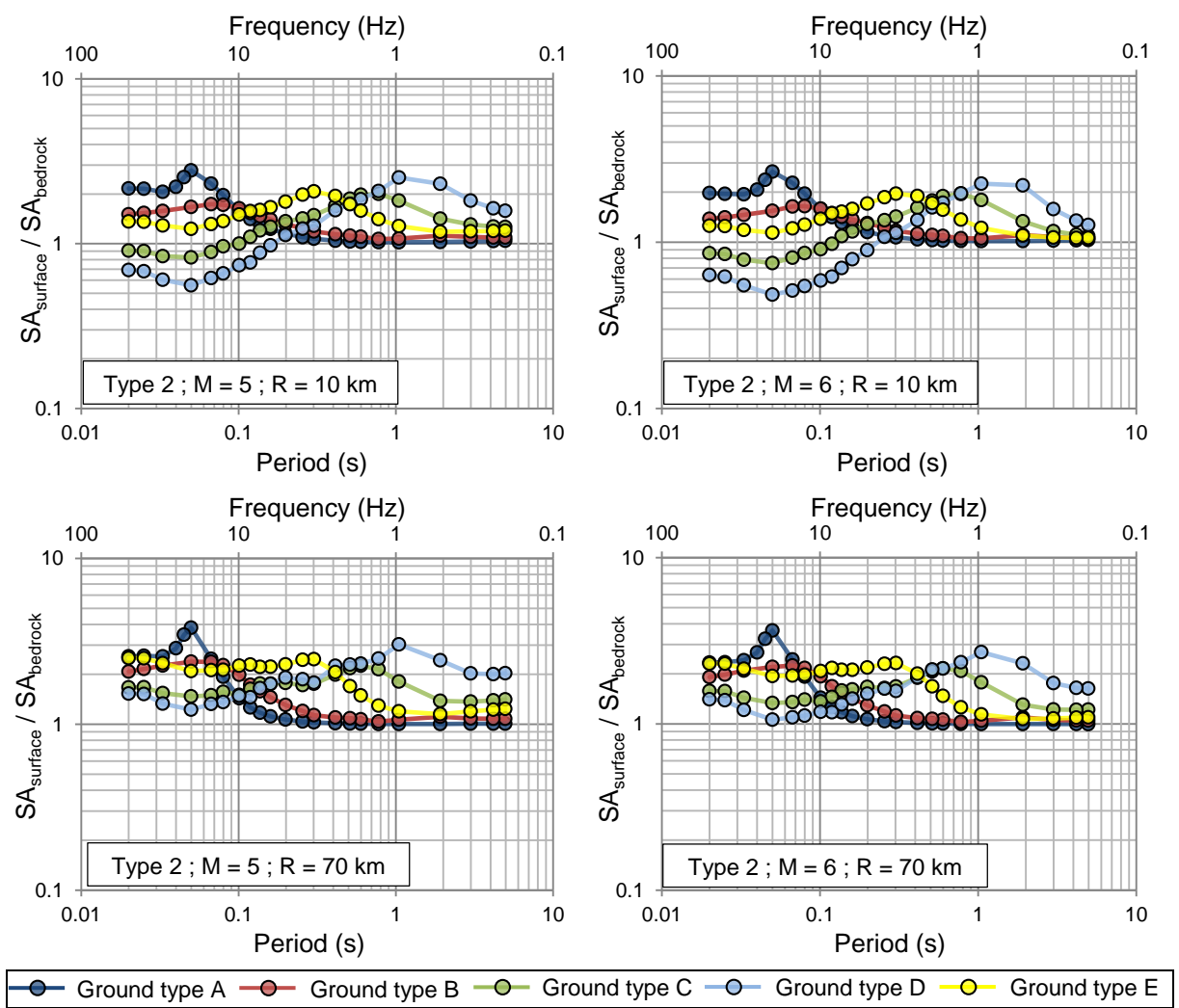


Figure 3 – Ratio between spectral acceleration at the surface and at the top of the bedrock, for Eurocode 8 ground types A to E, considering the GMPEs obtained for type 2 spectra, with $M = \{5; 6\}$ and $R = \{10; 70\}$ km

In the Figures 2 and 3 it can be observed that, for soft soils (ground types C and D), there is an amplification of the spectral acceleration at high periods and, for stiff soils (ground types A and B), the amplification is perceived at low periods. This can be explained by the difference of natural periods.

The non-linear behaviour of the soil can also be observed on the Figures 2 and 3. On soft soils, there is attenuation of the spectral acceleration on the low periods and this attenuation is more noticeable at high magnitudes, for the same hypocentral distance. Stiff soils tend to maintain the behaviour, amplifying at low periods, for any magnitude or hypocentral distance.

A comparison between the obtained spectra and defined by the Portuguese National Annex to Eurocode 8 was made. The results show that, for ground types C (see example at Figure 4), D and E, the Eurocode 8's spectra have higher values than the ones obtained. For ground types B, the type 1 spectrum for a seismic event with $M = 7,5$ and $R = 70$ km has higher values of spectral acceleration than the Eurocode 8, therefore a revision of this spectra is suggested.

For ground types A, the spectrum obtained for lower hypocentral distances has also higher values than the Eurocode 8. However, there should be accounted that there is a low number of borehole data classified as ground type A.

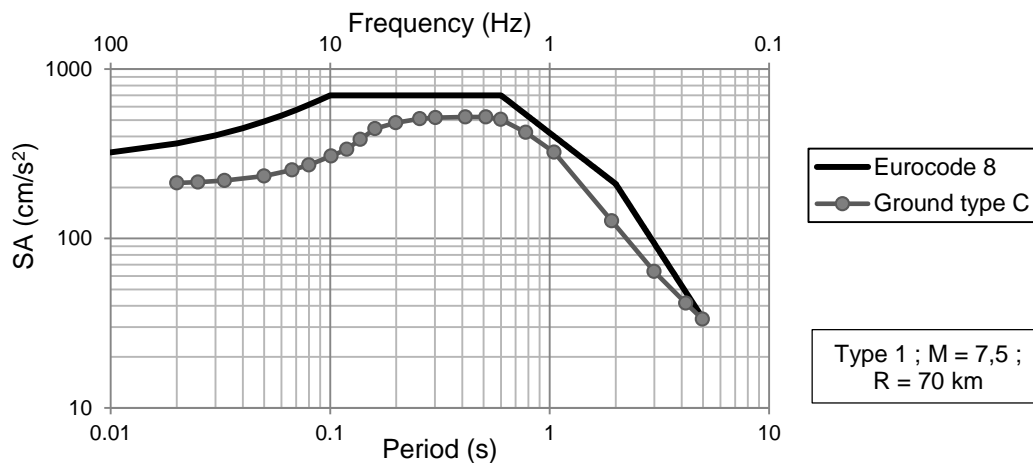


Figure 4 – Comparison between type 1 spectrum obtained and defined by the Eurocode 8, for a seismic scenario of $M = 7,5$ and $R = 70$ km

4) Conclusions and further developments

The North-American Recommendations for Probabilistic Seismic Hazard Analysis [10] indicates that, for medium seismicity areas, the spectral accelerations should be acquired from seismic base models. The usage of this methodology, for Mainland Portugal, is essential to obtain spectral content that is relevant for structural engineering (with return periods between 475 and 10 000 years) and is lacking in the recorded data.

Therefore, with simulated response spectra obtained from various scenarios in terms of magnitude, distance and frequency, it was possible to obtain ground motion prediction equations for Mainland Portugal, from the source to the surface.

The results obtained show that soft soils amplify the spectral acceleration at high periods and stiff soils amplify at low periods. For the studied scenarios, it is observed that there is attenuation in soft soils, at low periods.

The obtained spectra display good approximation to the ones defined in the Portuguese National Annex to Eurocode 8, though it is suggested a revision of the type 1 spectrum for ground type B, at high magnitudes and low hypocentral distances.

As further developments, it is proposed to: i) calculate or estimate natural periods of each ground type and propose a new classification method that includes this property, given its importance in the present study; ii) apply a different methodology that includes other wave propagation, such as surface waves; iii) conduct a geotechnical prospection campaign, to increase data sampling; iv) apply ground motion prediction equations to a given ground profile, to obtain a response spectrum that is useful for a dynamical approach while designing a certain structure; v) perform seismic hazard and seismic risk studies with the ground motion prevision equations obtained in the present study.

5) References

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