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LOCAL EARTHQUAKES - GROUND MOTION MODELS FOR EPICENTRAL ZONE

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Abstract

Based on records on occurred shallow earthquakes obtained on soil type rock, epicentral distances of $R_e \leq 20km$, focal depths $h \leq 10\,km$ and local magnitude $M = 3.9 - 6.1$, ground motion models GMMs for an epicentral zone were developed. Investigated were horizontal acceleration response spectrum *SA* for *5%* of the critical damping and for *221* models of a single-degree-of-freedom system with a natural period ranging from *0.01* to *5.0* seconds.

Two mathematical physical models were selected. In the first one, the horizontal acceleration response spectrum *SA* was dependent on magnitude only, whereas in the second one, it depended on both magnitude and hypocentral distance. For an assumed normal distribution of the natural logarithm of *SA*, a multi-linear regression analysis was carried out. The results were regression coefficients and standard deviations. These are practically applicable for prediction of the expected *SA* in an epicentral zone by deterministic and probabilistic methods.

Keywords: ground motion models, spectral acceleration, epicentral zone, magnitude, epicentral distance

1. Ground motion models – GMMs

GMMs predict the expected level of ground motion depending on magnitude, distance, type of fault structure, local soil layers, azimuth, etc. They are empirical since they are developed by use of data from records of occurred earthquakes and using the regression analysis method. The selected mathematical form will fit in an available or formed databank of records of occurred earthquakes for an assumed normal or log-normal distribution of parameters on which earthquake ground motion depends. The result are regression coefficients and standard deviations. Such GMMs are called conventional /or traditional [1, 7, 8, 12]. Today, GMMs are also developed by use of machine learning approaches ML [6], which cannot be a replacement for the conventional ones. Therefore, the presented conventional GMMs in this paper are important for prediction of the seismic effect in an epicentral zone.

According to summary reviews of a large number of published GMMs [2, 3], it is evident that the number of GMMs for local earthquakes is very small [1, 6, 7, 12].

2. GMMs for Local Earthquakes as a Necessity

As a long year researcher [8, 10, 12] and user of GMMs [9, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23], the author has understood their great importance when probabilistic PSHA [9, 11, 13, 14, 19, 22, 23], and deterministic DSHA [9, 11, 13] methods are used for definition of seismic design parameters. Therefore, the development of GMMs for local earthquake effects is a necessity according to the author. This particularly holds for an epicentral zone and existence of shallow soil layers of weak characteristics that are great amplifiers of local and regional seismic effects upon seismic rock. The dynamic response of their characteristic soil model, upon the ground surface or at the foundation level, known as specific site spectrum SSS, very often surpasses the design spectra recommended and given in the valid standards.

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SSS is particularly important in design of seismically resistant structures of the first class of importance, located in the immediate vicinity of active fault structures with the potential to generate local earthquakes with $M > 6.5$ according to Richter and Eurocode 8 [4, 5], moment magnitudes $M_w > 6.5$, according to UBC 2000 [24], and defined characteristic of local soils. Therefore, the regulations for design of seismically resistant structures [4, 5, 24] also contain defined principles and rules for its determination as well as criteria for its selection as a design spectrum of a site.

2.1. GMMs for Epicentral Zone

GMMs for an epicentral zone were investigated within the frames of the scientific-research project: Ground Motion Models [10]. The created databank of recorded accelerogrammes of occurred earthquakes obtained by SMA- instruments, Kinemetrics, from the strong motion instrument network of former Yugoslavia [8] and the Italian databank ENEA-ENEL (ENEA-ENEL: File ENEAUN TUTTO C VM/HPO 4.2 CMSL–SIAM– 8.4.87) were used. The recorded accelerograms contained in both banks were available as corrected time histories of acceleration.

These were used to create two separate datasets with different distribution of time histories of acceleration per earthquake parameters like magnitude M, epicentral distance R_e, focal depth h and local soil conditions. All this for the purpose of investigating the effect of the distribution of data upon the size of the expected SA in an epicentral zone.

Two sets of data were investigated:

I set ***59*** **data**: $h \le 10\,km.,\ R_e \le 20km.\ (M = 3.9\text{-}6.1,\ R_h = 7.-30km.,\ h = 5\text{-}10km.)$

II set ***101*****data** $h \le 20\,km.,\ R_e \le 35km.\ (M = 3.9\text{-}6.5,\ R_h = 7-40km.,\ h = 5\text{-}17km.)$

Computed were the horizontal acceleration response spectra for *5%* of the critical damping $SA(T;\xi = 0.05)$ for *221* models of a single-degree-of-freedom system with periods ranging from *0.01* second to *5.0* seconds for each of the two data sets.

Two mathematical models (equations 1 and 2) were selected and fitted into each of the two created data sets.

ΓMM1: $$lnSA(T;\xi = 0.05) = b_1 + b_2 M + \sigma_{lnSA} P \quad (1)$$

ΓMM2 : $$lnSA(T;\xi = 0.05) = b_1 + b_2 M + b_3 lnR_h + \sigma_{lnSA} P \quad (2)$$

$$R_h = \sqrt{(R_e)^2 + h^2} \quad (3)$$

where: $SA(T;\xi = 0.05)$ is the amplitude of the horizontal acceleration response spectrum for 5% of the critical damping in (cm / s^2), M is local magnitude according to Richter, R_h is hypocentral distnce in *km.*, R_e is epicentral distance in *km.*, h is focal depth in *km.*, b_1, b_2, b_3 are regression coefficients, σ_{lnSA} is standard deviation, and P is random variable, with a value of zero for median and *1* for median plus one standard deviation.

The first GMM1 (Equation 1) is a function of magnitude M, i.e., of the earthquake energy, whereas the second GMM2 is a function of magnitude M and hypocentral distance R_h (Equation 2). In both equations, the term depending on the local soil conditions is omitted since the selected time histories of acceleration are obtained for the same type of soil, i.e., rock.

The size of SA amplutudes is directly proportional to the size of magnitude M and inverseley proportional to the size of distance R_h. Therefore, in the first GMM1, SA depends on M only, whereas in the second GMM2, SA depends on both M and R_h. With the application of both models, the assessment of the seismic effect in the epicentral zone is much more realistic.

A multi linear regression analysis was carried out for an assumed normal distribution for $lnSA$. In it, the dependent parameter was $lnSA$. Independent parameters were M for GMM1, and M and R_h for

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GMM2. For each of both GMMs, *221* regression analyses were performed. Regression coefficients and standard deviations were obtained.

It was for the first time that GMMs obtained with the first set of data (Tables 1 and 2) were published. The results obtained with the second data set (containing also the data from the first set) or a total of *101* horizontal acceleration components, were published in 2008 [12], but are not presented for all *221* models of a single-degree-of-freedom system, but only for selected *43* (Note: equations 1 and 2 of these investigations also hold for the GMMs published in 2008. In these, there is a typing error. Specifically, in the mathematical equations, regression coefficient b_1 without *ln* before it, or the same as in eq. 1 and 2 herein, should be used). GMMs defined with the two sets of data refer to an epicentral zone. The difference is that some of these are for very shallow earthquakes with focal depth of down *to 10 km*, epicentral distances of up to *20 km* and magnitudes between *3.9* and *6.1*, whereas the others are for shallow local earthquakes with focal depths of down to *20 km*, epicentral distances of up to *35 km* and magnitudes between *3.9* and *6.5.*

Using the results shown in Table 1 (GMM1, equation 1), horizontal acceleration response spectra *SA* for an expected earthquake with $M = 6.5$ were computed as median and median + one standard deviation (Figure 1, above). The comparison between these and those computed with GMM2 (Table 2, equation 2) for $M = 6.5$ and $R_h = 7\ km$, as median and median + *1* standard deviation, is presented type A (Figure 1, above and below). Such a direct comparison between a deterministic spectrum and a probabilistic spectrum, given according to the European standard /or other valid standard, can be made for all cases when such comparison is required by regulations or recommendations. Namely, during definition of maximum possible earthquake on locations of structures of capital importance, particularly when no regulations are elaborated for them, as are large dams [13, 15]. In other cases, it is necessary to compute a probabilistic spectrum by seismic hazard analyses PSHA, for a defined return period, applying GMMs developed for an epicentral zone. If used as alternative in PSHA, they should be given a corresponding weight factor. The results from the PSHA should be compared to the design ones given in Eurocode 8, for corresponding return periods.

In completely the same way as in Figure 1 (above and below), Figure 2 (above and below) shows the horizontal acceleration response spectra *SA* for GMM1 and GMM2, for the same values of magnitude and hypocentral distance ($M = 6.5,\ R_h = 7km$), as median and median + *1* standard deviation, for earthquakes with hypocentral depth of down to *20 km* [12].
The effect of *M* and R_h for deeper local earthquakes ($h \leq 20\,km.$) is given in Figure 3 (above and below). GMMs defined with the two equations and with the second data set, or *101* data [12], were used. The acceleration spectra *SA* for a single value of magnitude, ($M = 6.5$), and varied values of $R_h = 5, 7, 10, 20, 40\ km$ are shown in Figure 3 (above), while for a single value of $R_h = 10\ km$ and varied values of $M = 4.5$ to *6.5*, by a step of 0.5, they are given in Figure 3 (below). Figure 3 (above) shows that *SA*, for the range of periods $T > 0.4$ seconds, are decreased with the increase of R_h, whereas for $T < 0.4$ seconds, they are increased (the red line). For the same hypocentral distance, $R_h = 10\ km$, and increase of magnitude *M*, *SA* are increased for the range of $T > 0.3$ seconds, while they are negligibly reduced for the range $T < 0.3$ seconds (black line).

3. Conclusions

The presented regression coefficients and standard deviations, for two mathematical models of ground motion, for soil type - rock, are practically applicable in defining the seismic design parameters by deterministic and probabilistic methods. While using them, care should be taken for the values of the boundaries of magnitude, epicentral distance and focal depth for which they are used, for the purpose of avoiding the extrapolation effect or making a mathematical error. While using very small hypocentral depths that are smaller than the least included in the data, it is recommended to use a mathematical model in function of magnitude.

The investigations presented herein are a contribution to better inclusion of the effect of local earthquakes in providing seismic resistance of structures.

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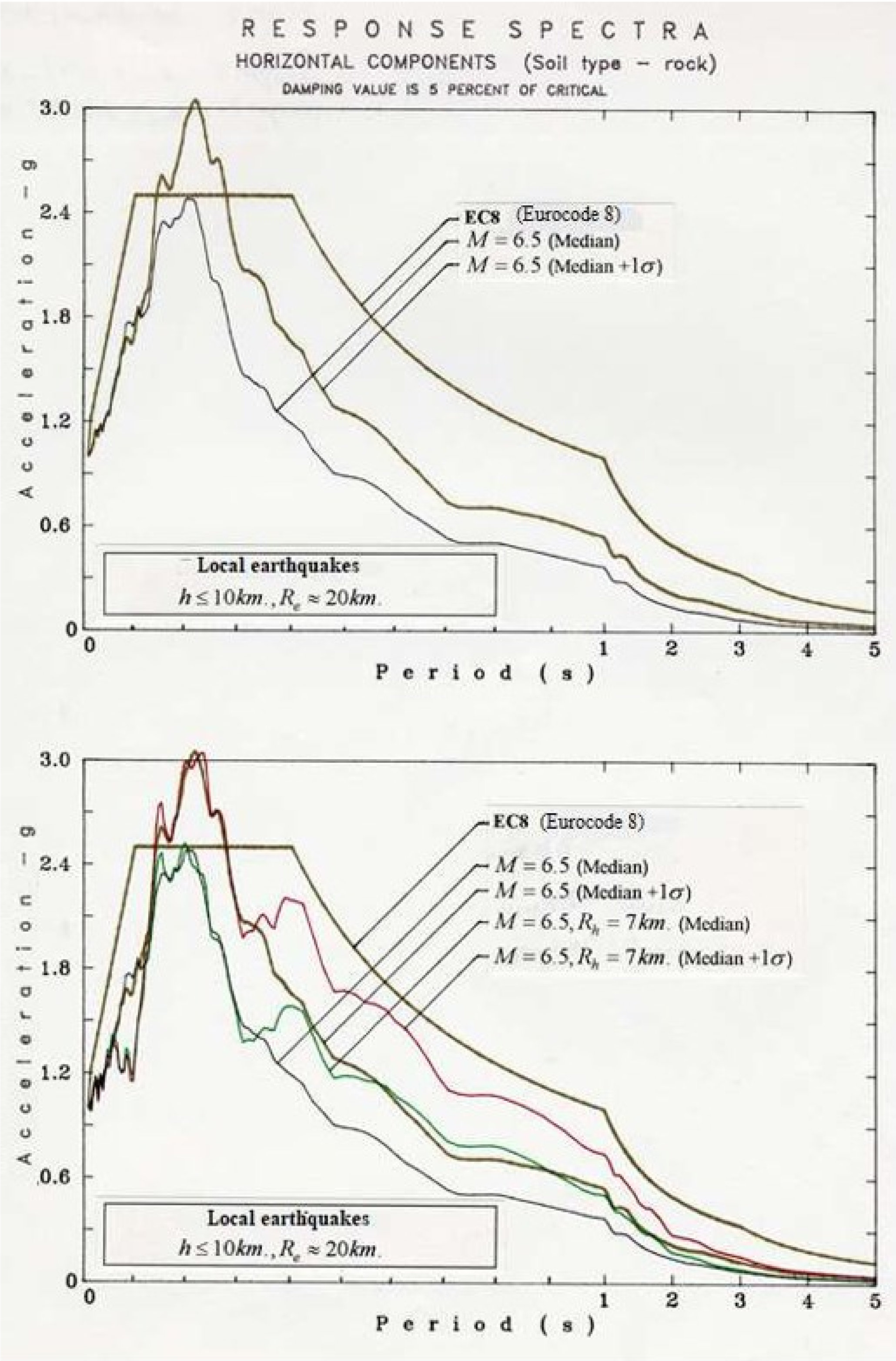

Figure 1. Comparison between expected *SA* (*g*) for an epicentral zone, for GMM1 (the figure above) and GMM2 (the figure below) and Eurocode 8.

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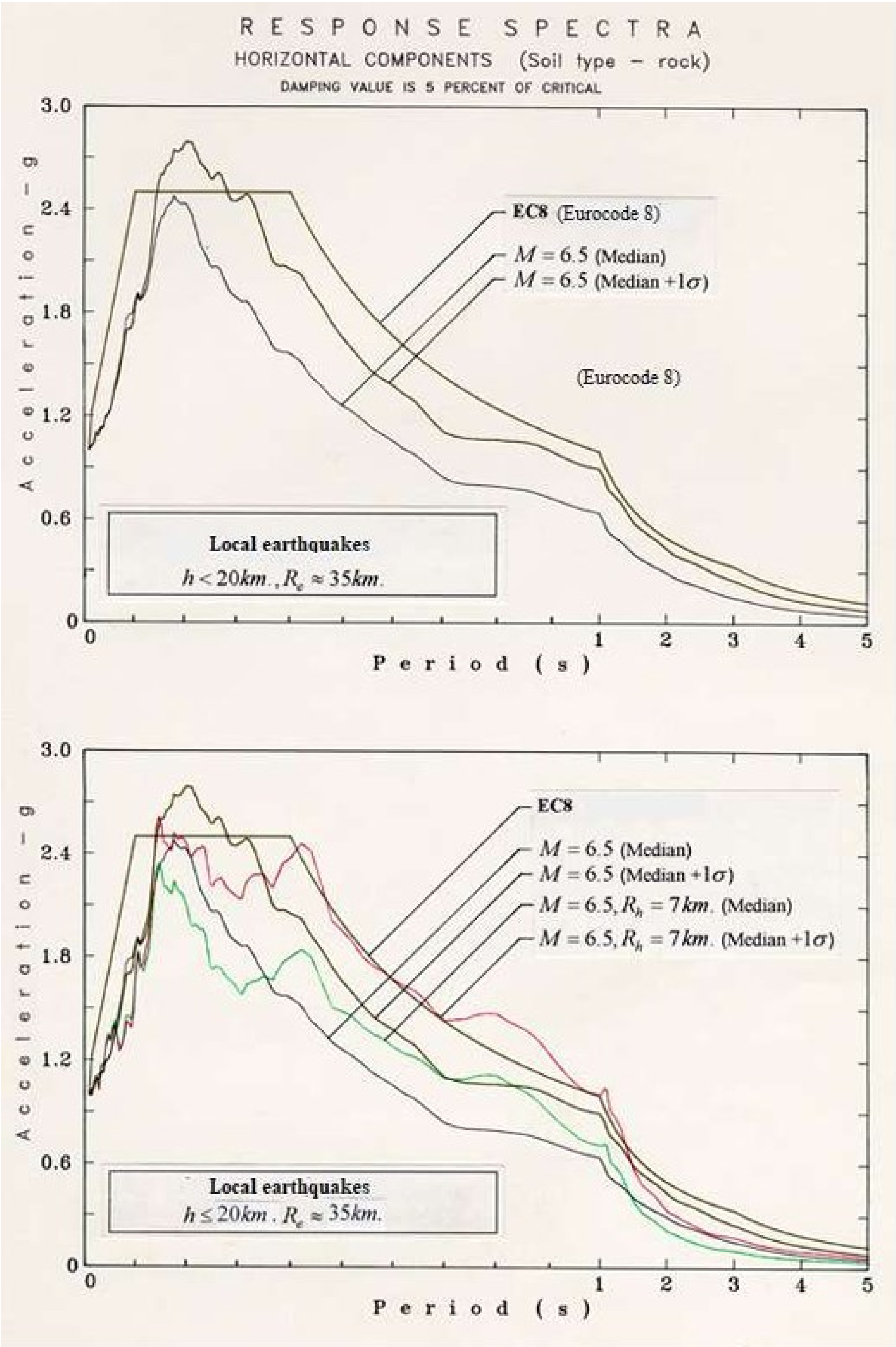

Figure 2. Expected *SA* (*g*) for an epicentral zone, for GMM1 (the figure above) and GMM2 (the figure below) and comparison with Eurocode 8.

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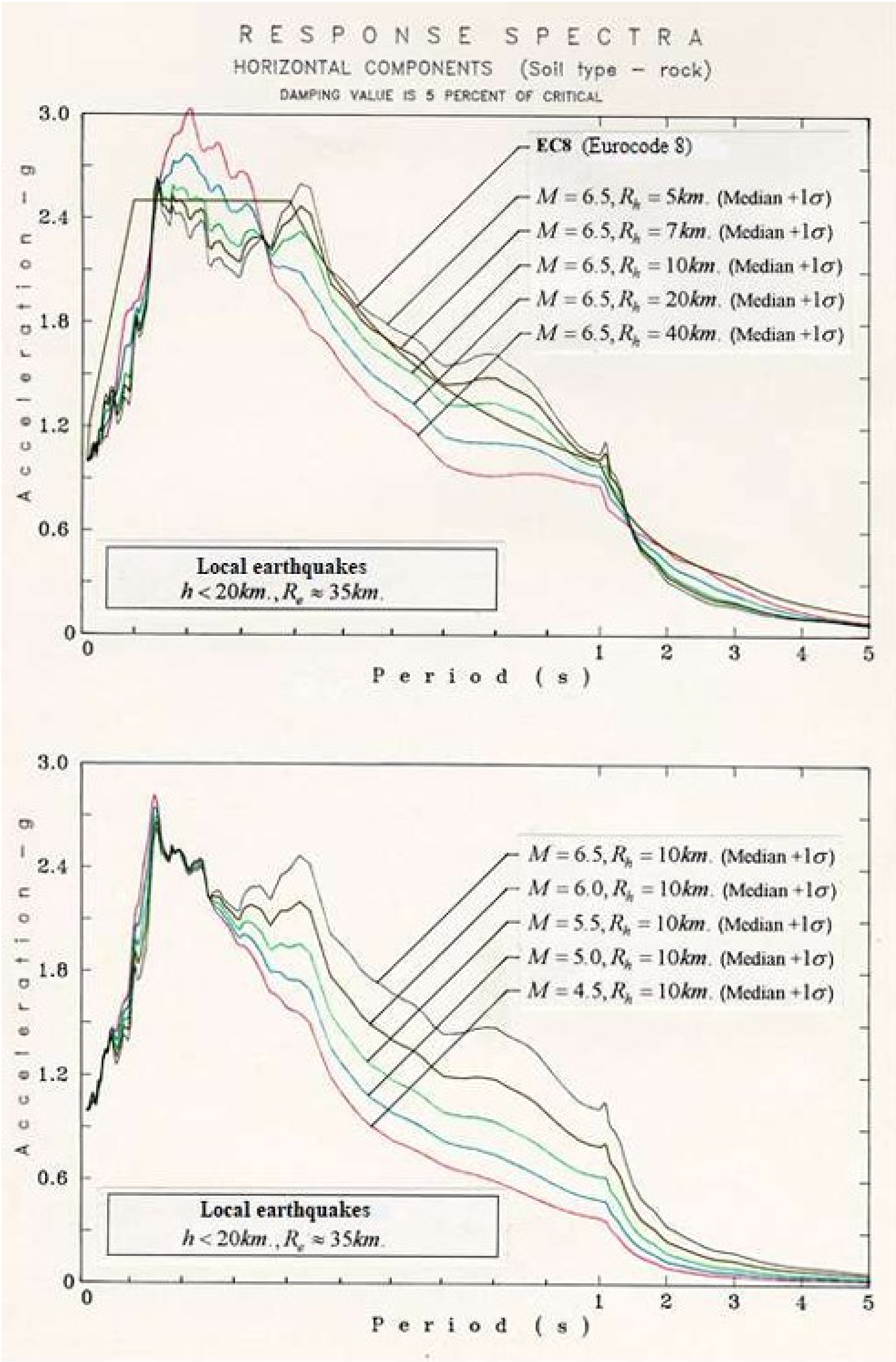

Figure 3. Distribution of expected *SA* (*g*) for an epicentral zone for GMM2 (the figure below) and comparison with Eurocode 8 (the figure above).

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Table 1. Regression coefficients and standard deviation
Mathematical model: $lnSA(T;\xi=0.05)=b_1+b_2M+\sigma_{lnSA}P$

No.	Period T (s)	b_1	b_2	σ_{lnSA}
1	0.0100	2.7280	.2865	.5958
2	0.0145	2.7310	.2908	.5847
3	0.0190	2.6465	.3092	.5920
4	0.0235	2.5599	.3343	.5898
5	0.0280	2.7046	.3101	.5711
6	0.0325	2.6892	.3186	.5766
7	0.0370	2.8587	.2894	.5792
8	0.0415	2.9389	.2839	.5896
9	0.0460	2.9838	.2820	.5797
10	0.0505	3.0690	.2697	.5759
11	0.0550	3.1238	.2725	.5791
12	0.0595	3.2308	.2640	.5633
13	0.0640	3.3098	.2576	.5739
14	0.0685	3.4338	.2414	.5728
15	0.0730	3.4811	.2436	.5830
16	0.0775	3.6054	.2289	.5626
17	0.0820	3.5816	.2419	.5504
18	0.0865	3.6808	.2278	.5407
19	0.0910	3.8249	.2052	.5257
20	0.0955	4.0689	.1656	.5435
21	0.100	4.1839	.1518	.5586
22	0.105	4.1673	.1605	.5794
23	0.110	4.2340	.1446	.6043
24	0.115	4.2185	.1483	.6361
25	0.120	4.2124	.1512	.6525
26	0.125	4.2442	.1486	.6460
27	0.130	4.1652	.1696	.6491
28	0.135	4.0044	.2044	.6777
29	0.140	3.7978	.2454	.6967
30	0.145	3.6550	.2711	.7086
31	0.150	3.5136	.2966	.7051
32	0.155	3.4297	.3099	.6965
33	0.160	3.3998	.3134	.6905
34	0.165	3.4233	.3085	.6858
35	0.170	3.4275	.3086	.6865
36	0.175	3.3737	.3198	.6991
37	0.180	3.3784	.3188	.7184
38	0.185	3.3700	.3207	.7373
39	0.190	3.2925	.3349	.7479
40	0.195	3.1564	.3598	.7583
41	0.200	3.0752	.3731	.7675
42	0.205	3.0150	.3819	.7810
43	0.210	2.9715	.3888	.7953
44	0.215	2.9635	.3887	.8113
45	0.220	2.9640	.3847	.8312
46	0.225	2.9688	.3795	.8427
47	0.230	2.9723	.3754	.8488
48	0.235	3.0277	.3608	.8568
49	0.240	3.0573	.3506	.8661
50	0.245	3.0717	.3424	.8777
51	0.250	3.0281	.3476	.8873
52	0.255	2.9637	.3574	.8959
53	0.260	2.9213	.3626	.9043
54	0.265	2.9259	.3580	.9102
55	0.270	2.9561	.3480	.9141
56	0.275	2.9992	.3359	.9135
57	0.280	3.0841	.3153	.9109
58	0.285	3.1183	.3051	.9095
59	0.290	3.1373	.2971	.9134
60	0.295	3.1592	.2885	.9179
61	0.300	3.1789	.2808	.9278
62	0.305	3.1890	.2755	.9366
63	0.310	3.1782	.2754	.9433
64	0.315	3.1531	.2792	.9452
65	0.320	3.1297	.2816	.9493
66	0.325	3.1090	.2830	.9541
67	0.330	3.0666	.2887	.9579
68	0.335	3.0258	.2935	.9611
69	0.340	2.9773	.3000	.9587
70	0.345	2.9209	.3083	.9516
71	0.350	2.8837	.3122	.9438
72	0.355	2.8660	.3118	.9360
73	0.360	2.8716	.3068	.9301
74	0.365	2.8798	.3012	.9260
75	0.370	2.8609	.3021	.9289
76	0.375	2.8288	.3056	.9299
77	0.380	2.7960	.3090	.9320
78	0.385	2.7676	.3117	.9337
79	0.390	2.7515	.3123	.9314
80	0.395	2.7382	.3129	.9276
81	0.400	2.7329	.3125	.9267
82	0.420	2.6917	.3125	.9386
83	0.440	2.7506	.2894	.9425
84	0.460	2.6613	.2932	.9465
85	0.480	2.5702	.2958	.9498
86	0.500	2.4156	.3173	.9435
87	0.520	2.2638	.3388	.9367
88	0.540	2.0909	.3626	.9277
89	0.560	1.9356	.3808	.9314
90	0.580	1.8709	.3826	.9353
91	0.600	1.8471	.3752	.9441
92	0.620	1.8563	.3628	.9519
93	0.640	1.8525	.3554	.9459
94	0.660	1.8504	.3464	.9364
95	0.680	1.8641	.3335	.9297
96	0.700	1.8539	.3240	.9262
97	0.720	1.8087	.3248	.9324
98	0.740	1.7404	.3340	.9329
99	0.760	1.6249	.3525	.9301
100	0.780	1.5004	.3722	.9273
101	0.800	1.3918	.3878	.9289
102	0.820	1.3242	.3937	.9369
103	0.840	1.2439	.4014	.9474
104	0.860	1.1514	.4123	.9558
105	0.880	1.0699	.4200	.9691
106	0.900	1.0085	.4245	.9770
107	0.920	.9593	.4272	.9816
108	0.940	.9285	.4270	.9815
109	0.960	.9127	.4234	.9826
110	0.980	.8697	.4251	.9817
111	1.000	.8053	.4308	.9806
112	1.020	.7627	.4330	.9815
113	1.040	.7198	.4353	.9857
114	1.060	.6922	.4345	.9891
115	1.080	.7137	.4242	.9922

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Table 1. Regression coefficients and standard deviation (continued)
Mathematical model: $lnSA(T;\xi = 0.05) = b_1 + b_2 M + \sigma_{lnSA} P$

No.	Period *T (s)*	b_1	b_2	σ_{lnSA}
116	1.100	.7185	.4168	.9936
117	1.120	.6945	.4154	.9950
118	1.140	.6432	.4188	.9977
119	1.160	.5621	.4289	1.0044
120	1.180	.4509	.4457	1.0102
121	1.200	.3473	.4615	1.0132
122	1.220	.2417	.4781	1.0146
123	1.240	.1555	.4908	1.0163
124	1.260	.0765	.5026	1.0172
125	1.280	.0067	.5126	1.0159
126	1.300	-.0708	.5240	1.0119
127	1.320	-.1489	.5354	1.0088
128	1.340	-.2185	.5444	1.0063
129	1.360	-.2647	.5483	1.0036
130	1.380	-.2964	.5489	1.0029
131	1.400	-.3206	.5483	1.0027
132	1.420	-.3414	.5469	1.0014
133	1.440	-.3578	.5454	1.0007
134	1.460	-.3698	.5437	.9982
135	1.480	-.3742	.5400	.9975
136	1.500	-.3852	.5377	.9978
137	1.520	-.3935	.5348	1.0003
138	1.540	-.4067	.5334	1.0022
139	1.560	-.4196	.5323	1.0037
140	1.580	-.4366	.5317	1.0061
141	1.600	-.4587	.5319	1.0091
142	1.620	-.4823	.5324	1.0126
143	1.640	-.5046	.5326	1.0171
144	1.660	-.5295	.5338	1.0212
145	1.680	-.5525	.5344	1.0242
146	1.700	-.5683	.5338	1.0248
147	1.720	-.5975	.5360	1.0254
148	1.740	-.6287	.5383	1.0267
149	1.760	-.6594	.5403	1.0282
150	1.780	-.6846	.5412	1.0297
151	1.800	-.7036	.5408	1.0313
152	1.820	-.7215	.5405	1.0317
153	1.840	-.7630	.5452	1.0305
154	1.860	-.8017	.5489	1.0305
155	1.880	-.8405	.5527	1.0301
156	1.900	-.8718	.5550	1.0290
157	1.920	-.8930	.5554	1.0272
158	1.940	-.9144	.5561	1.0271
159	1.960	-.9402	.5579	1.0271
160	1.980	-.9728	.5609	1.0275
161	2.000	-.9969	.5621	1.0287
162	2.020	-1.0195	.5628	1.0301
163	2.040	-1.0407	.5631	1.0326
164	2.060	-1.0608	.5630	1.0357
165	2.080	-1.0843	.5637	1.0395
166	2.100	-1.1171	.5663	1.0435
167	2.120	-1.1532	.5699	1.0476
168	2.140	-1.1833	.5723	1.0519
169	2.160	-1.2098	.5741	1.0565

No.	Period *T(s)*	b_1	b_2	σ_{lnSA}
170	2.18	-1.2319	.5751	1.0616
171	2.20	-1.2606	.5776	1.0660
172	2.22	-1.2887	.5800	1.0705
173	2.24	-1.3159	.5822	1.0748
174	2.26	-1.3459	.5851	1.0786
175	2.28	-1.3889	.5910	1.0813
176	2.30	-1.4276	.5962	1.0843
177	2.32	-1.4577	.5997	1.0869
178	2.34	-1.4842	.6027	1.0885
179	2.36	-1.5098	.6054	1.0906
180	2.38	-1.5399	.6091	1.0926
181	2.40	-1.5654	.6119	1.0948
182	2.42	-1.5891	.6142	1.0969
183	2.44	-1.6144	.6169	1.0988
184	2.46	-1.6383	.6192	1.1007
185	2.48	-1.6509	.6190	1.1029
186	2.50	-1.6598	.6181	1.1053
187	2.52	-1.6682	.6170	1.1077
188	2.54	-1.6760	.6158	1.1102
189	2.56	-1.6840	.6149	1.1130
190	2.58	-1.6921	.6139	1.1158
191	2.60	-1.6999	.6128	1.1181
192	2.62	-1.7102	.6123	1.1198
193	2.64	-1.7167	.6111	1.1218
194	2.66	-1.7214	.6094	1.1240
195	2.68	-1.7237	.6072	1.1265
196	2.70	-1.7256	.6051	1.1293
197	2.72	-1.7267	.6027	1.1313
198	2.74	-1.7341	.6017	1.1340
199	2.76	-1.7380	.5999	1.1366
200	2.78	-1.7359	.5970	1.1395
201	2.80	-1.7288	.5930	1.1425
202	2.82	-1.7194	.5886	1.1444
203	2.84	-1.7062	.5837	1.1466
204	2.86	-1.6903	.5782	1.1482
205	2.88	-1.6726	.5723	1.1495
206	2.90	-1.6593	.5674	1.1507
207	2.92	-1.6449	.5625	1.1523
208	2.94	-1.6423	.5600	1.1531
209	2.96	-1.6424	.5580	1.1533
210	2.98	-1.6424	.5559	1.1533
211	3.00	-1.6453	.5546	1.1537
212	3.20	-1.6850	.5418	1.1463
213	3.40	-1.6284	.5058	1.1332
214	3.60	-1.5659	.4731	1.1201
215	3.80	-1.4483	.4317	1.1219
216	4.00	-1.4885	.4250	1.1260
217	4.20	-1.4741	.4068	1.1189
218	4.40	-1.5439	.4077	1.1092
219	4.60	-1.5134	.3894	1.1086
220	4.80	-1.4543	.3646	1.1133
221	5.00	-1.3966	.3383	1.1119

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Table 2. Regression coefficients and standard deviation
Mathematical model: $lnSA(T;\xi=0.05)=b_1+b_2M+b_3lnR_h+\sigma_{lnSA}P$

No	Period T (s)	b_1	b_2	b_3	σ_{lnSA}
1	0.0100	3.7204	.4090	-.5851	.5708
2	0.0145	3.6740	.4073	-.5560	.5621
3	0.0190	3.7231	.4421	-.6348	.5612
4	0.0235	3.5984	.4625	-.6123	.5614
5	0.0280	3.5934	.4198	-.5241	.5510
6	0.0325	3.7016	.4436	-.5969	.5491
7	0.0370	3.7999	.4056	-.5549	.5564
8	0.0415	3.9480	.4084	-.5950	.5631
9	0.0460	4.0799	.4173	-.6462	.5467
10	0.0505	4.1313	.4008	-.6263	.5449
11	0.0550	4.1950	.4047	-.6316	.5477
12	0.0595	4.1988	.3835	-.5708	.5378
13	0.0640	4.1840	.3655	-.5154	.5547
14	0.0685	4.1325	.3276	-.4119	.5624
15	0.0730	4.0372	.3123	-.3279	.5787
16	0.0775	4.1435	.2953	-.3173	.5583
17	0.0820	4.1716	.3147	-.3478	.5439
18	0.0865	4.2335	.2960	-.3259	.5353
19	0.0910	4.2510	.2578	-.2512	.5241
20	0.0955	4.4854	.2171	-.2456	.5426
21	0.10	4.7439	.2210	-.3302	.5534
22	0.105	4.8393	.2435	-.3962	.5705
23	0.11	5.0188	.2415	-.4628	.5911
24	0.115	5.0740	.2540	-.5044	.6209
25	0.12	5.2457	.2788	-.6092	.6284
26	0.125	5.2854	.2772	-.6139	.6210
27	0.13	5.2426	.3027	-.6353	.6221
28	0.135	5.0579	.3344	-.6212	.6539
29	0.14	4.8822	.3792	-.6394	.6721
30	0.145	4.7554	.4069	-.6489	.6837
31	0.15	4.5899	.4295	-.6346	.6814
32	0.155	4.4436	.4351	-.5978	.6758
33	0.16	4.4014	.4371	-.5905	.6702
34	0.165	4.4134	.4308	-.5838	.6659
35	0.17	4.4161	.4307	-.5829	.6667
36	0.175	4.3809	.4442	-.5939	.6789
37	0.18	4.3734	.4417	-.5867	.6997
38	0.185	4.4082	.4489	-.6121	.7173
39	0.19	4.3462	.4650	-.6212	.7275
40	0.195	4.1859	.4869	-.6070	.7396
41	0.20	4.0802	.4972	-.5926	.7505
42	0.205	3.9833	.5014	-.5709	.7662
43	0.21	3.9132	.5050	-.5552	.7822
44	0.215	3.9139	.5060	-.5604	.7983
45	0.22	3.9324	.5043	-.5710	.8182
46	0.225	3.9789	.5042	-.5956	.8283
47	0.23	4.0118	.5038	-.6129	.8333
48	0.235	4.0855	.4914	-.6237	.8407
49	0.24	4.0720	.4759	-.5983	.8523
50	0.245	4.0418	.4622	-.5720	.8661
51	0.25	3.9997	.4676	-.5730	.8760
52	0.255	3.9366	.4775	-.5736	.8848
53	0.26	3.8973	.4830	-.5754	.8933
54	0.265	3.9178	.4804	-.5848	.8988
55	0.27	3.9558	.4714	-.5894	.9025
56	0.275	3.9786	.4568	-.5774	.9027
57	0.28	4.0643	.4363	-.5779	.9000
58	0.285	4.0948	.4257	-.5757	.8987

No	Period T (s)	b_1	b_2	b_3	σ_{lnSA}
59	0.29	4.1080	.4170	-.5724	.9029
60	0.295	4.1121	.4061	-.5618	.9082
61	0.30	4.1000	.3945	-.5431	.9196
62	0.305	4.0876	.3864	-.5298	.9295
63	0.31	4.1066	.3900	-.5474	.9352
64	0.315	4.0853	.3943	-.5497	.9370
65	0.32	4.0721	.3979	-.5557	.9409
66	0.325	4.0628	.4007	-.5624	.9454
67	0.33	4.0502	.4102	-.5799	.9482
68	0.335	4.0445	.4192	-.6007	.9502
69	0.34	4.0270	.4296	-.6189	.9465
70	0.345	3.9883	.4401	-.6293	.9385
71	0.35	3.9691	.4462	-.6400	.9296
72	0.355	3.9764	.4489	-.6547	.9205
73	0.36	4.0185	.4484	-.6762	.9127
74	0.365	4.0733	.4485	-.7037	.9064
75	0.37	4.1194	.4575	-.7420	.9062
76	0.375	4.1403	.4675	-.7733	.9045
77	0.38	4.1515	.4763	-.7992	.9044
78	0.385	4.1564	.4832	-.8188	.9039
79	0.39	4.1646	.4867	-.8331	.9006
80	0.395	4.1641	.4890	-.8407	.8959
81	0.40	4.1729	.4903	-.8491	.8941
82	0.42	4.1658	.4945	-.8691	.9046
83	0.44	4.2230	.4712	-.8681	.9089
84	0.46	4.0701	.4671	-.8306	.9167
85	0.48	3.9697	.4686	-.8251	.9207
86	0.50	3.8556	.4951	-.8491	.9118
87	0.52	3.7150	.5180	-.8556	.9040
88	0.54	3.5437	.5419	-.8566	.8944
89	0.56	3.4334	.5657	-.8831	.8957
90	0.58	3.4177	.5735	-.9120	.8968
91	0.60	3.4229	.5697	-.9291	.9043
92	0.62	3.4875	.5642	-.9618	.9091
93	0.64	3.4904	.5576	-.9657	.9022
94	0.66	3.4955	.5495	-.9699	.8916
95	0.68	3.5027	.5358	-.9661	.8849
96	0.70	3.5081	.5282	-.9753	.8801
97	0.72	3.4841	.5316	-.9878	.8853
98	0.74	3.4192	.5412	-.9898	.8856
99	0.76	3.3057	.5600	-.9910	.8824
100	0.78	3.1797	.5795	-.9901	.8796
101	0.80	3.0627	.5941	-.9852	.8818
102	0.82	2.9928	.5997	-.9838	.8906
103	0.84	2.9076	.6067	-.9810	.9021
104	0.86	2.7893	.6145	-.9657	.9128
105	0.88	2.6843	.6192	-.9518	.9285
106	0.90	2.5900	.6197	-.9324	.9389
107	0.92	2.5120	.6189	-.9155	.9454
108	0.94	2.4430	.6140	-.8930	.9476
109	0.96	2.3961	.6065	-.8746	.9505
110	0.98	2.3424	.6070	-.8683	.9501
111	1.00	2.2930	.6145	-.8772	.9481
112	1.02	2.2642	.6183	-.8852	.9483
113	1.04	2.2348	.6224	-.8932	.9520
114	1.06	2.2306	.6245	-.9071	.9542
115	1.08	2.2809	.6176	-.9240	.9558

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Table 2. Regression coefficients and standard deviation (continued)
Mathematical model: $lnSA(T;\xi = 0.05) = b_1 + b_2 M + b_3 lnR_h + \sigma_{lnSA} P$

No	Period *T (s)*	b_1	b_2	b_3	σ_{lnSA}
116	1.10	2.3080	.6130	-.9372	.9559
117	1.12	2.2819	.6114	-.9359	.9576
118	1.14	2.2241	.6140	-.9321	.9608
119	1.16	2.1449	.6243	-.9332	.9677
120	1.18	2.0273	.6403	-.9295	.9743
121	1.20	1.9223	.6560	-.9286	.9775
122	1.22	1.8041	.6710	-.9212	.9797
123	1.24	1.7032	.6819	-.9125	.9824
124	1.26	1.6077	.6916	-.9028	.9843
125	1.28	1.5136	.6986	-.8885	.9842
126	1.30	1.4219	.7083	-.8801	.9808
127	1.32	1.3340	.7184	-.8743	.9781
128	1.34	1.2590	.7268	-.8711	.9758
129	1.36	1.2206	.7317	-.8757	.9725
130	1.38	1.2051	.7343	-.8852	.9708
131	1.40	1.1966	.7356	-.8946	.9697
132	1.42	1.1959	.7367	-.9064	.9673
133	1.44	1.1933	.7369	-.9145	.9657
134	1.46	1.1741	.7343	-.9103	.9635
135	1.48	1.1659	.7302	-.9080	.9630
136	1.50	1.1490	.7271	-.9046	.9636
137	1.52	1.1462	.7249	-.9078	.9660
138	1.54	1.1424	.7246	-.9133	.9675
139	1.56	1.1374	.7245	-.9180	.9686
140	1.58	1.1304	.7252	-.9239	.9705
141	1.60	1.1178	.7265	-.9295	.9731
142	1.62	1.1110	.7291	-.9394	.9758
143	1.64	1.1098	.7320	-.9519	.9793
144	1.66	1.1065	.7357	-.9646	.9823
145	1.68	1.1035	.7389	-.9764	.9843
146	1.70	1.0976	.7395	-.9822	.9844
147	1.72	1.0592	.7405	-.9768	.9856
148	1.74	1.0171	.7415	-.9703	.9877
149	1.76	.9811	.7428	-.9672	.9895
150	1.78	.9537	.7434	-.9659	.9912
151	1.80	.9339	.7429	-.9655	.9930
152	1.82	.9040	.7412	-.9584	.9941
153	1.84	.8288	.7417	-.9385	.9948
154	1.86	.7631	.7421	-.9226	.9961
155	1.88	.6965	.7424	-.9062	.9975
156	1.90	.6310	.7405	-.8860	.9982
157	1.92	.5729	.7364	-.8643	.9983
158	1.94	.5284	.7343	-.8507	.9993
159	1.96	.4790	.7331	-.8368	1.0006
160	1.98	.4279	.7338	-.8258	1.0020
161	2.00	.3951	.7339	-.8207	1.0037
162	2.02	.3772	.7353	-.8235	1.0049
163	2.04	.3699	.7373	-.8317	1.0068
164	2.06	.3677	.7394	-.8423	1.0092
165	2.08	.3620	.7422	-.8527	1.0122
166	2.10	.3404	.7463	-.8594	1.0158
167	2.12	.3072	.7501	-.8610	1.0199
168	2.14	.2787	.7527	-.8620	1.0244
169	2.16	.2585	.7553	-.8657	1.0288

No	Period *T (s)*	b_1	b_2	b_3	σ_{lnSA}
170	2.18	.2453	.7574	-.8710	1.0337
171	2.20	.2215	.7605	-.8738	1.0381
172	2.22	.2003	.7639	-.8779	1.0424
173	2.24	.1810	.7670	-.8825	1.0465
174	2.26	.1527	.7701	-.8836	1.0504
175	2.28	.0926	.7739	-.8735	1.0541
176	2.30	.0425	.7777	-.8668	1.0577
177	2.32	.0046	.7803	-.8622	1.0609
178	2.34	-.0277	.7825	-.8587	1.0628
179	2.36	-.0578	.7847	-.8561	1.0652
180	2.38	-.1021	.7866	-.8477	1.0681
181	2.40	-.1466	.7871	-.8365	1.0712
182	2.42	-.1872	.7873	-.8266	1.0742
183	2.44	-.2291	.7879	-.8168	1.0770
184	2.46	-.2686	.7883	-.8076	1.0797
185	2.48	-.2933	.7866	-.8004	1.0825
186	2.50	-.3146	.7842	-.7932	1.0855
187	2.52	-.3346	.7817	-.7863	1.0885
188	2.54	-.3532	.7791	-.7799	1.0915
189	2.56	-.3723	.7768	-.7734	1.0950
190	2.58	-.3887	.7748	-.7685	1.0982
191	2.60	-.4058	.7725	-.7630	1.1009
192	2.62	-.4261	.7708	-.7571	1.1032
193	2.64	-.4349	.7693	-.7557	1.1053
194	2.66	-.4374	.7680	-.7570	1.1075
195	2.68	-.4353	.7663	-.7596	1.1099
196	2.70	-.4322	.7648	-.7626	1.1126
197	2.72	-.4291	.7629	-.7650	1.1145
198	2.74	-.4403	.7614	-.7628	1.1174
199	2.76	-.4432	.7598	-.7634	1.1201
200	2.78	-.4350	.7576	-.7670	1.1228
201	2.80	-.4182	.7548	-.7728	1.1255
202	2.82	-.3993	.7516	-.7783	1.1271
203	2.84	-.3711	.7486	-.7872	1.1287
204	2.86	-.3426	.7446	-.7946	1.1298
205	2.88	-.3148	.7400	-.8006	1.1307
206	2.90	-.2917	.7362	-.8064	1.1315
207	2.92	-.2599	.7335	-.8166	1.1324
208	2.94	-.2528	.7315	-.8193	1.1331
209	2.96	-.2509	.7298	-.8204	1.1332
210	2.98	-.2503	.7277	-.8208	1.1331
211	3.00	-.2567	.7260	-.8187	1.1337
212	3.20	-.3686	.7043	-.7761	1.1292
213	3.40	-.2705	.6734	-.8006	1.1138
214	3.60	-.2057	.6410	-.8020	1.1002
215	3.80	-.0447	.6049	-.8275	1.1001
216	4.00	-.1111	.5950	-.8121	1.1055
217	4.20	-.0850	.5783	-.8190	1.0977
218	4.40	-.2000	.5736	-.7923	1.0896
219	4.60	-.1900	.5528	-.7802	1.0899
220	4.80	-.1139	.5301	-.7903	1.0940
221	5.00	-.0591	.5034	-.7886	1.0927

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4. References

[1] Akkar S., Cagnan Z. (2010): A Local Ground-Motion Predictive Model for Turkey and Its Comparison with Regional and Global Ground Motion-Models. *BSSA, Vol. 100, No.6. pp. 2978-2995, December 2010. doi: 10.1785/0120090367*

[2] Douglas et al. (2011): Ground Motion Prediction Equations 1964-2010 (and its upgrading up to 2018). *PEER Report 2011/102* Pacific Earthquake Engineering Research Center, Collage of Engineering, Berkeley, California.

[3] Douglas J. (2019): Ground Motion Prediction Equations (1964-2019). Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK.

[4] EUROCODE 8: Design Provisions for Earthquake Resistance of Structures, Seismic Actions and General Requirements for Structures, [2004] EN 1998-1:2004, Stage 51, May 2004.

[5] EUROCODE 8: Design Provisions for Earthquake Resistance of Structures, Part 2-Bridges, [2005] EN 1998-2:2005, December 2005.

[6] Sedaghati, F., M.EERI[1] and Shahram P., M. EERI[2], sagepub.com/journals-permisssions DOI: 10.1177/87552930231191759 journals.sagepub.com/home/eqs (2023). Machine Learning – Based Ground Motion Models for Shallow Crustal Earthquakes in Active Tectonic Regions.

[7] Pacor F., Spallarossa D., Oth A., Luzi A., Puglisa R., Cantore L., Mecuri A., D'Amico M., Bindi D. (2016): Spectral Models for Ground Motion Prediction in the L'Aquila Region. *Geophysical Journal International,* Volume 204, Issue 2, February 2016, Pages 697-718, http://doi.org/10.1093/gji/ggv448

[8] Stamatovska S. (1988): Probability Response of SDFS Exposed to Seismic Loads. Master Thesis (in Macedonian), Institute of Earthquake Engineering and Engineering Seismology, "Ss. Cyril and Methodious" University, Skopje, R. of Macedonia, 1988.

[9] Stamatovska S. (2001): Design Response Spectra–Deterministic and Probabilistic Approach. *Albanian Journal of Natural &Technical Science (AJNTS),* No.10/2001, pp. 113-123.

[10] Stamatovska S., Paskalov A., Petrovski D., Hadzievski D. (2003). *Ground Motion Models*, Institute of Earthquake Engineering and Engineering Seismology, "Ss. Cyril and Methodius" University, Skopje, Republic of Macedonia, *Report IZIIS-2003-19*, March 2003 (in Macedonian).

[11] Stamatovska S. (2003): Design Response Spectra for a Rock Site in the City of Skopje. *International Conference on Earthquake Engineering to Mark 40 Years from Catastrophic 1963 Skopje Earthquake and Successful City Reconstruction*, Skopje-Ohrid, R. of Macedonia, 26-29 August 2003. Reference: CD: SE-40EEE, 0155.pdf.

[12] Stamatovska S. (2008): Ground Motion Models for Local Earthquakes. Proceedings, Volume 1, *Second International Meeting Civil Engineering - Science and Practice (GNP2008)*, Zabljak, 03-07 March 2008, pp.469-474 (In Serbian)

[13] Stamatovska S. (2008): Evaluation of Seismic Design Parameters of Structures of the HPP Kozjak - ICOLD Method, IZIIS Report 2008 - 67/2, November 2008, Skopje, R. Macedonia (in Macedonian)

[14] Stamatovska S. (2010): Gas Power Plant 'Skopje-East" – Seismic Design Parameters. *3rd International Conference - GNP2010*. Zabljak, 15-19 February, 2010. Proceedings, Volume 1, pp.553–558.

[15] Stamatovska S. (2010): Seismic Design Parameters for Large Dams –ICOLD Method. *14th ECEE*, Ohrid, August 30-September 3, 2010, Republic of Macedonia. Paper No.1826.

[16] Stamatovska S. (2010): Local Soil Response to Seismic Input Compatible to Uniform Hazard Spectra at Bedrock. *Journal of Acta Geodaetica et Geophisica Hungarica*, Volume 45, Number 3, September 2010, pp.273-283. (DOI: 10.1556 /AGeog.45.2010.3.2).

[17] Sesov V., Stamatovska S., Aleksovski D., Zafirova I., Gadza V., Gjorgjeska I. (2010). Evaluation of Seismic Potential of a Site for Preliminary Project on the Ohrid Airport. UKIM-IZIIS, *Report IZIIS 2010-33*, Skopje, May 2010.

[18] Stamatovska S., Sesov V. (2011): "St. Paul the Apostle" Airport in Ohrid - Assessment of Seismic Potential of the Site. *15th International Symposium of MASE (MASE -15)***.** Struga, Macedonia 18-21 September 2013.

[19] Mirakovski G., Stamatovska S., Micajkov S., Aleksovski D., Mircevska V., Zafirova I., Gadza V., Filipovski D., Markovski I. (2011): Geological and Seismogeological Bases for the General Urban Plan of the Wider Urban Area of Skopje City. UKIM-IZIIS, *Report IZIIS 2011-31*, June 2011.

[20] Mirakovski G., Stamatovska S. (2012): Seismic Zoning of the Skopje City Urban Area Using Tomographic Concept. *15th WCEE*, Lisboa, Portugal, 2012. Paper: WCEE2012_1889.pdf

[21] Stamatovska S. (2012): Urban Area Microzonation as Prevention in Managing Earthquake Risk. *Journal of Frontiers in Geotechnical Engineering (FGE),* Volume 1 Issue 1, December 2012. (Online 2012-12), pp. 9-18. www.seipub.org/fge/

[22] Stamatovska S. (2012): Seismic Parameters of Seismic Base of the Location of Antenna Tower on Vodno Mountain. UKIM-IZIIS, *Report IZIIS 2012-44*, October 2012.

[23] Sesov V., Stamatovska S., Gjorgjeska I., Jovanovski Gj. (2012): Definition of Seismic Design Parameters – Structure – State institutions ELEM, Makedonija Str. bb Skopje. UKIM-IZIIS, *Report IZIIS 2012-46*, August 2012.

[24] Uniform Building Code, Volume 2, Division IV, Earthquake Design, 1997. Published regulation of design, A WORLD List -1996, Supplement 2000.

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