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CLASSIFICATION OF SOIL PROFILES WITH CORRESPONDING EARTHQUAKE DESIGN SPECTRA FOR SPECIFIC CONDITIONS IN SWITZERLAND

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SUMMARY

Local soil conditions are often critical for earthquake resistant design. For economic reasons, the most effective tool, microzonation with zone specific design spectra, can not be carried out for all relevant industrial and residential areas. Site-specific investigations are only done in special cases. Therefore in most buildings codes, like the current Swiss Code SIA 261, the influence of local site conditions is taken into account by design spectra for different soil classes. These soil classes for the geological conditions of Switzerland and their corresponding amplification functions have been re-evaluated in a national research project, presented in this paper.

INTRODUCTION

This study aimed at producing soil profile classes to be incorporated in a future seismic design code for Switzerland. It is foreseen to specify at first the regional hazard on the base rock, and subsequently to provide the transfer functions depending on the specific soil profile classes, which allows to take the amplification of the earthquake motion caused by the alluvium deposits into account.

The study discussed here deals only with the transfer functions from the base rock to the surface. The results should significantly enhance the hazard definition for earthquake resistant design in the Swiss Midland, where about 90% of the population and the industry is located. The Swiss geological situation is very complex, so that the reduction to few profile classes needs a significant simplification to provide practical results. Therefore, for important structures, the local geotechnical conditions should still be investigated by individual site studies.

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GEOLOGICAL CONDITIONS AND GENERAL METHODOLOGY

Near Surface Geological Conditions in Switzerland

The morphology of Switzerland has been shaped to a large extent by the Pleistocene glaciers, and a large part of the country, especially of the Molasse Basin of Northern Switzerland, is covered by Pleistocene deposits composed of moraine (glacial till), alluvial gravels and sands and lacustrine silts and clays. During this period Alpine glaciers advanced probably more than 15 times into the Molasse Basin. Due to the strong erosions intervening during most glaciations, few geologically complete sections are preserved.

Bedrock topography and total thickness of Quaternary deposits in the northern Alpine foreland has been studied mainly by Wildi [1], Pugin [2] and Pugin & Wildi [3]. In western Switzerland, the deepest glacial erosion surfaces in the bedrock (Tertiary Molasse rocks) occur along the Rhone and Aar valleys with maximum depths of 400 m and 200 m below sea level (mbsl), respectively. For a mean surface elevation of the Rhone valley of 400 m above sea level (masl) and for the Aar valley of 550 masl, this results in total thicknesses of the corresponding soil deposits of about 800 m. In central and eastern Switzerland the deepest bedrock surfaces occur in the lakes (and valleys) along the border of the Alps (the piedmont zone): Lake Constance (400 masl), Walensee (420 masl), Lake of Zug (410 masl) and Vierwaldstättersee (430 masl). Their level normally ranges between 100 mbsl and 100 masl, with the deepest surface (190 mbsl) found in a borehole southeast of Lake Constance. The Ticino valley in southern Switzerland has been eroded even deeper into the crystalline bedrocks. This erosion is mainly fluvial and related to the "Messinian Crisis", when the Mediterrenean sea dried out and created a much deeper erosion base level. Therefore also the infilling of this valley is partially older than Quaternary and not always composed of un-lithified soils.

As the deposition and erosion history in the Alpine valleys, the piedmont zone and northern Alpine foreland is strongly variable, the corresponding soil profiles are far from being uniform or homogeneous. In the major valleys the geometry and structures of Quaternary deposits are complex, and highly variable over short distances. Along the ancient margins of the glaciers, lateral and vertical changes of sedimentary facies are relatively abrupt, but in the centers of the valleys and basins the facies are rather continuous (Pugin & Wildi [3]). The Quaternary sediments on the hills and plateaus between these valleys are mostly relatively uniform and mainly composed of moraines and old, often cemented gravels ("Deckenschotter" or "Hochterrassen-Schotter").

From a geotechnical point of view, two glacial events are especially important: the Most Extensive Glaciation (MEG, formerly called "Riss"), which extended over the Jura Mountains into the Rhine valley east of Basel, and the Last Glacial Maximum (LGM, formerly called "Würm"). The borders of the LGM are important because they outline the areas where Quaternary sediments older (and deeper) than the LGM-moraines, must be over-consolidated. Whereas the age of MEG is not well constrained (about 800,000 years), the age of the LGM in northern Switzerland is 18-20'000 years.

The profiles investigated in this study have been selected based on a systematic scanning and review of about 80, mostly published geological cross-sections through all major valleys in Switzerland. Based on this preview of profiles and the assessment of major events in the Quaternary history of northern Switzerland typical geological profile patterns were recognized and allocated to five different regions (Figure 1):

- Region A (Folded and Tabular Jura): Valleys mainly filled with coarse alluvial sediments (gravels). No glaciation during LGM.
- Region B (Molasse Basin, outside areas of the LGM): Valleys mainly filled with pro-glacial sediments (loose sediments from silt to gravel size with different types of grain size

distributions), lacustrine sediments (homogeneous clays, silts and sands) and alluvial sediments (mainly heterogeneous, but well sorted gravels). Most of the units are normally consolidated, but pre-LGM deposits may occur and be over-consolidated.

- Region C (Molasse Basin, inside areas of the LGM): Valleys filled with moraines (heterogeneous, poorly sorted gravels with lots of fines), proglacial, lacustrine and alluvial sediments. Deeper units are over-consolidated.
- Region D (Piedmont Region, north of the Alps): Mainly normally consolidated post- and late-glacial sediments in deeply incised (overdeepened) valleys. Lacustrine and alluvial sediments in the center of the valley. Alluvial fans, landslide deposits and remnants of moraines on valley sides.
- Region E (Inner Alpine Valleys: Rhone and Ticino): Deeply incised valley (>500 m). Boreholes are available only in upper layers, which are composed of relatively flat laying young alluvial sediments. Indirect information about deep valley infill mainly from geophysical invesigations (seismics and gravimetry).

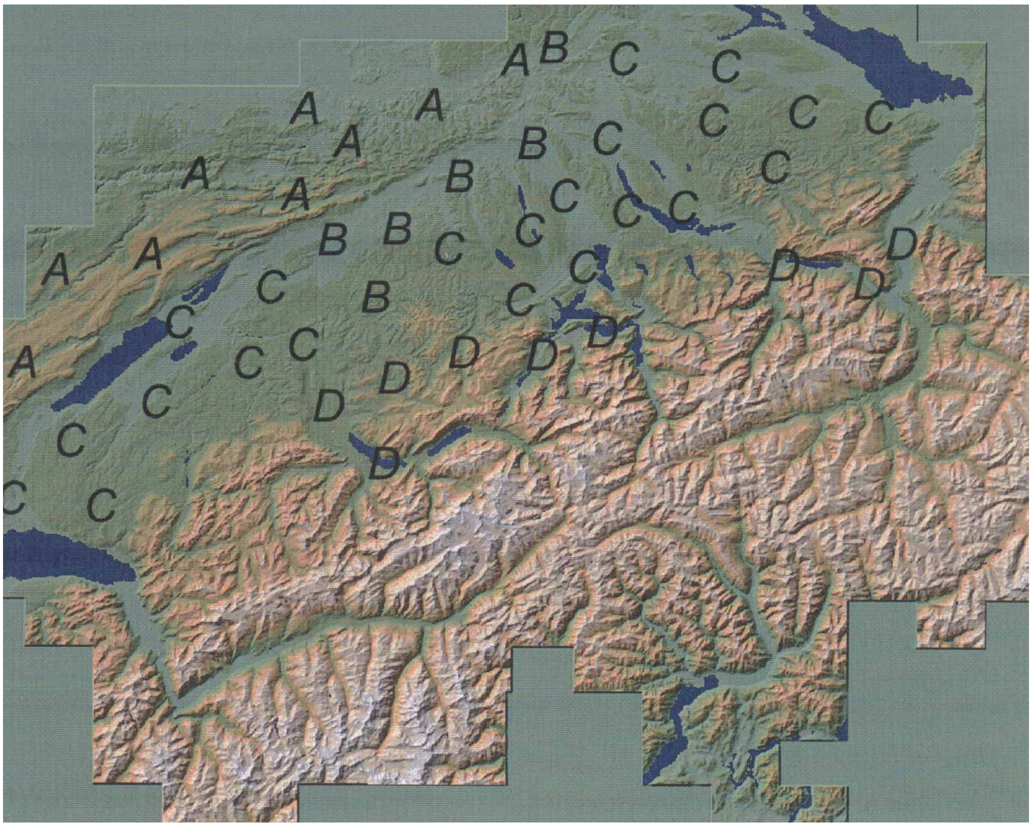

Figure 1: Geomorphologic regions in northern Switzerland

Based on this analysis, 23 profiles were selected , which represent the variability of geological conditions in all 5 different regions. Most of the profiles document geological situations in the densely populated areas of northern Switzerland. The profiles are described in detail in Pasotti and Loew [4]. The location of the profiles is shown in Figure 2.

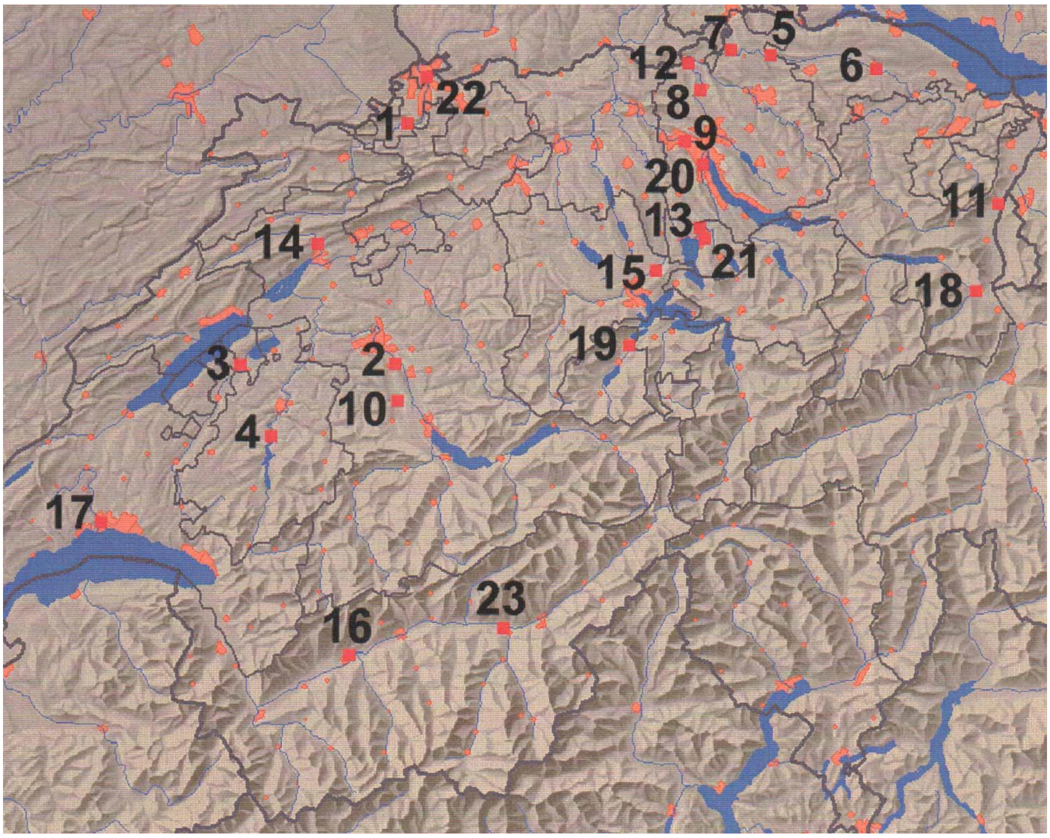

Figure 2: Location of the profiles

Most profiles were collected from publications; few unpublished profiles were provided by experts and private companies. Though the profiles display important information (for instance the valley shapes and the Quaternary units geometry), they have a low degree of resolution and geotechnical soil parameters are often not reported at all. Thus, geotechnical information was compiled by contacting private companies and federal offices in order to collect results from borehole and laboratory tests.

For each of the selected 23 profiles, a soil model for a representative location within the profile was defined, with corresponding geotechnical material properties. In view of the few basic soil profile types expected as resulting from the calculations, only significant changes in layering and material properties were taken into account. Nevertheless, the material properties were very carefully evaluated, to provide an accurate input for the amplification calculations. To check the accuracy of the geotechnical model, the fundamental frequency was assessed by ambient noise measurements (Nakamura [5]). At a few selected locations, additional SASW measurements (Spectral Analysis of Surface Waves) and/or array measurements of the ambient noise were carried out. Where needed, the soil model parameters were adjusted to provide the same fundamental frequency in the zero-strain range as determined by the Nakamura measurements. Details of the geotechnical properties assigned to the individual profiles are reported in Loew et al. [6].

Amplification calculations

To compute the amplification functions, three different computer programs were used:

- ProShake [7] and CyberQuake [8] for 1D and
- Aki-Larner SH according to Bard and Gariel [9] for 2D calculations.

As input motion on the bedrock, time histories following as closely as possible the shape of the elastic response spectra of the national application document of Eurocode 8 [10] (version ENV-1998-1-1) for rock and zone 1 were taken. Zone 1 of the Swiss design code represents the largest part of the highly populated area in Switzerland. The selected time histories had to fulfil the following criteria:

- Occurrence in similar tectonic conditions as Switzerland and
- Covering the target response spectra (split into the period ranges of 0.02-0.2s and 0.2-4s).

Table 1 contains the selected earthquakes. Figures 3 and 4 show the response spectra of the selected time histories in comparison to the target spectra.

Table 1: Selected earthquakes as input motion

Input	Name	Country	Date	Depth	m_b	M_L	M_s	Local intensity	Epicentral distance	PGA [m/s²]
1	Etolia	Greece	05/22/88	15 km	5	5	4.68	VI (MSK64)	21 km	0.527
2	Montenegro	Yugoslavia	05/24/79	5 km	5.7	6.2	6.34		21 km	0.543
3	Lazio Abruzzo	Italy	05/07/84	8 km	5.4	5.7	5.79	VII+ (MCS)	31 km	0.628
4	Lazio Abruzzo	Italy	05/11/84	12 km	4.7	4.5	4.27	VI (MCS)	5 km	0.932
5	Umbro-Marchigiana	Italy	10/14/97	7 km	5.3	5.5	5.6	VIII (MCS)	23 km	0.670
6	Umbro-Marchigiana	Italy	12/01/97	10 km		4.1			5 km	0.771
7	Sicilia-Orientale	Italy	12/13/90	5 km	5.3	5.2	5.2	VIII (MCS)	75 km	0.710
8	Sicilia-Orientale	Italy	12/13/90	5 km	5.3	5.2	5.2	VIII (MCS)	79 km	0.886

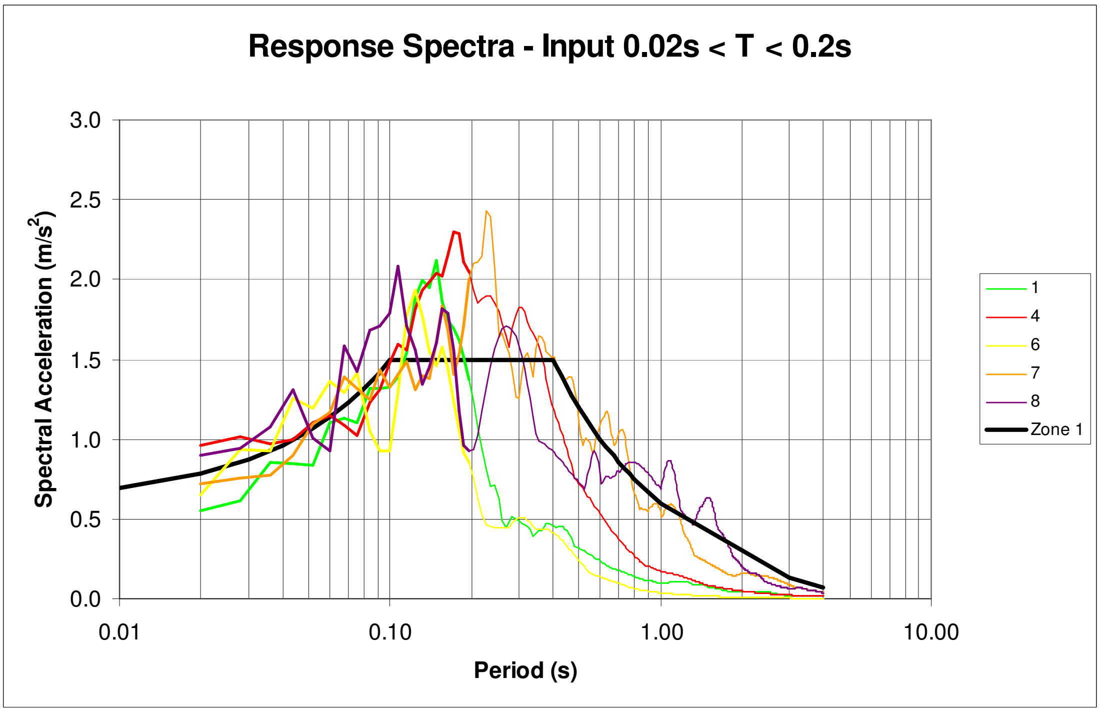

Figure 3: Selected response spectra in comparison to the target spectra, period range 0.02-0.2s

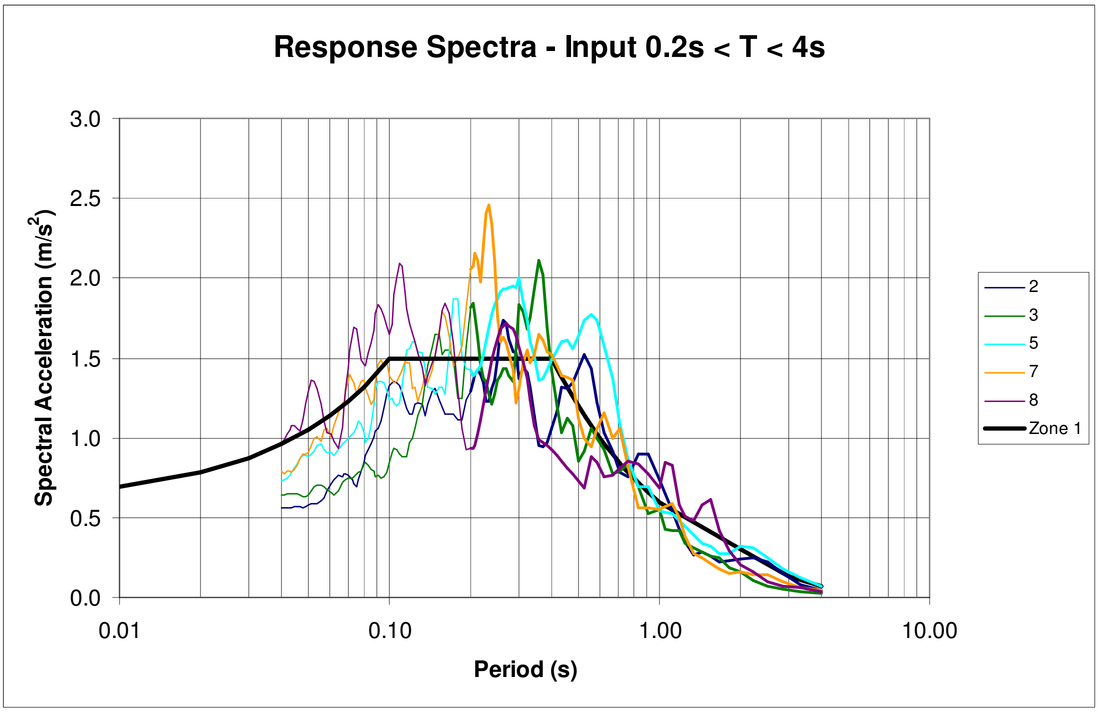

Figure 4: Selected response spectra in comparison to the target spectra, period range 0.2-4s

The most significant soil properties were the shear wave velocities as well as the G-modulus and damping versus shear strain based on Seed et al. [11] or Ishibashi/Zhang [12]. The shear wave velocity of the base rock was assessed based on measurements of similar formations. In general, these shear wave velocities were in the range of 1400-1600m/s, consistent with the shear wave velocity used for the recent hazard calculations by the Swiss Seismological Service (SED). For significantly different shear wave velocities, correction spectra with respect to a shear wave velocity of 1500m/s were derived from some generic rock velocity profiles. Figure 5 shows the used correction spectra (Résonance [13]).

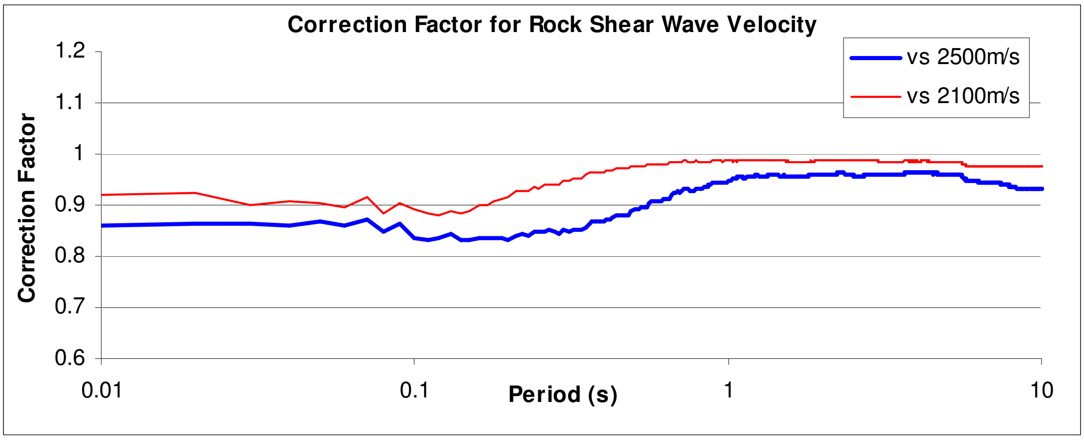

Figure 5: Correction spectra with respect to a rock shear wave velocity of 1500m/s

MAIN RESULTS

Definition of soil classes according to Swiss Code SIA 261 (2003)

In Table 2, the current definition of soil classes according to Swiss Code SIA 261 (2003) is summarized. The definition of the parameters S, T_B, T_C and T_D is the same as in Eurocode 8 [10].

Table 2: Definition of soil classes according to Swiss Code 261 (2003)

Soil Class	Description	S	T_B [s]	T_C [s]	T_D [s]
Class A	Stiff or soft rock, covered by at most 5m soil layer	1	0.15	0.4	2.0
Class B	Cemented gravel and sand and/or preloaded soils (including moraines) with a thickness above 30m	1.2	0.15	0.5	2.0
Class C	Normal consolidated and not cemented gravels and sands and/or moraines with a thickness above 30m	1.15	0.2	0.6	2.0
Class D	Normal consolidated fine sands and silts with a thickness above 30m	1.35	0.2	0.8	2.0
Class E	Surface layer of Soil Classes C or D with a thickness between 5 and 30m, over soil deposits of class A or B	1.4	0.15	0.5	2.0

Comparison with soil classes according to Swiss Code SIA 261 (2003)

Extensive calculations were performed and compared with several existing design response spectra (Loew et al. [14]). In this paper, we concentrate on the comparison of the calculation results with the Swiss Code 261 (2003). The spectra in the Swiss Code are the same as in Eurocode 8 (Type 1).

The comparison is shown in Figures 6 to 9. In Figure 6, continuous lines represent the results from the calculations with "best estimate" soil parameters (mean shear wave velocities) and are labelled with "vsm". Dashed lines represent results from parametric studies, where the shear wave velocity was increased or decreased by a factor of the square root of two. These results are labelled with "1.4 vsm". These parametric studies were particularly helpful for Soil Class B, since actually only two of the selected profiles match the definition of Soil Class B according to Code SIA 261. By virtually increasing the shear wave velocity of the selected profiles, more data could be obtained for the comparison with Soil Class B.

In Figures 7 to 9, only results from the calculations with "best estimate" soil parameters are shown. Dashed lines represent "second choice" classifications, in cases where the corresponding profiles could be differently classified, by engineering judgement.

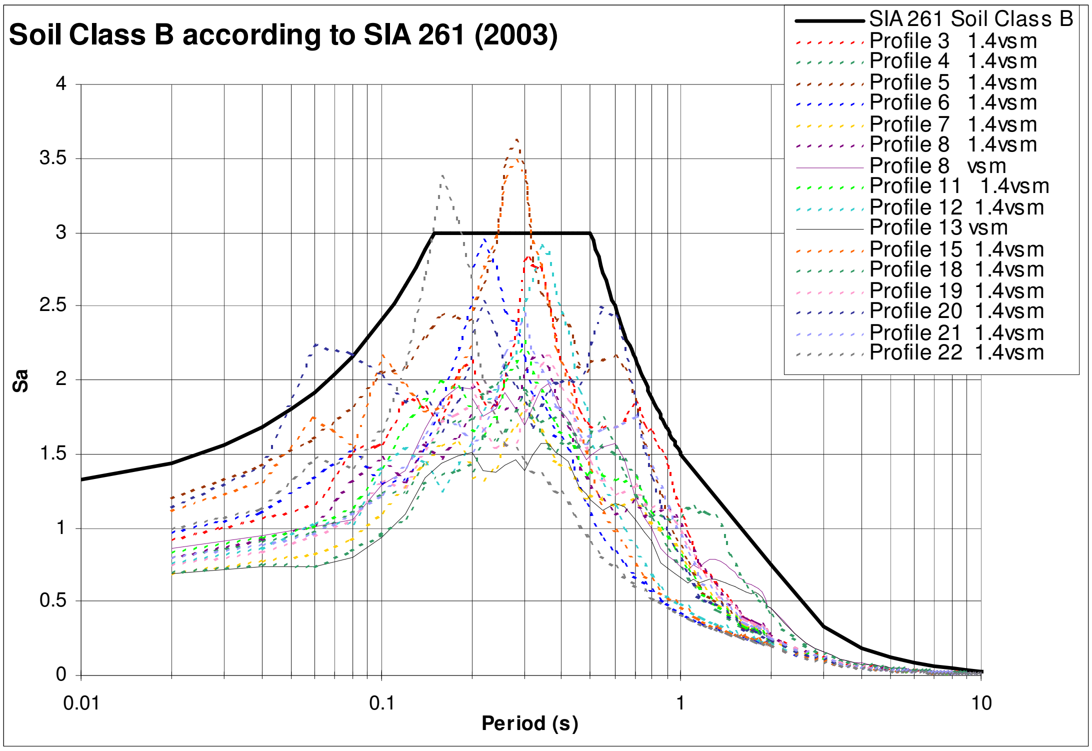

Figure 6: Comparison of computed spectra with design spectra, Soil Class B

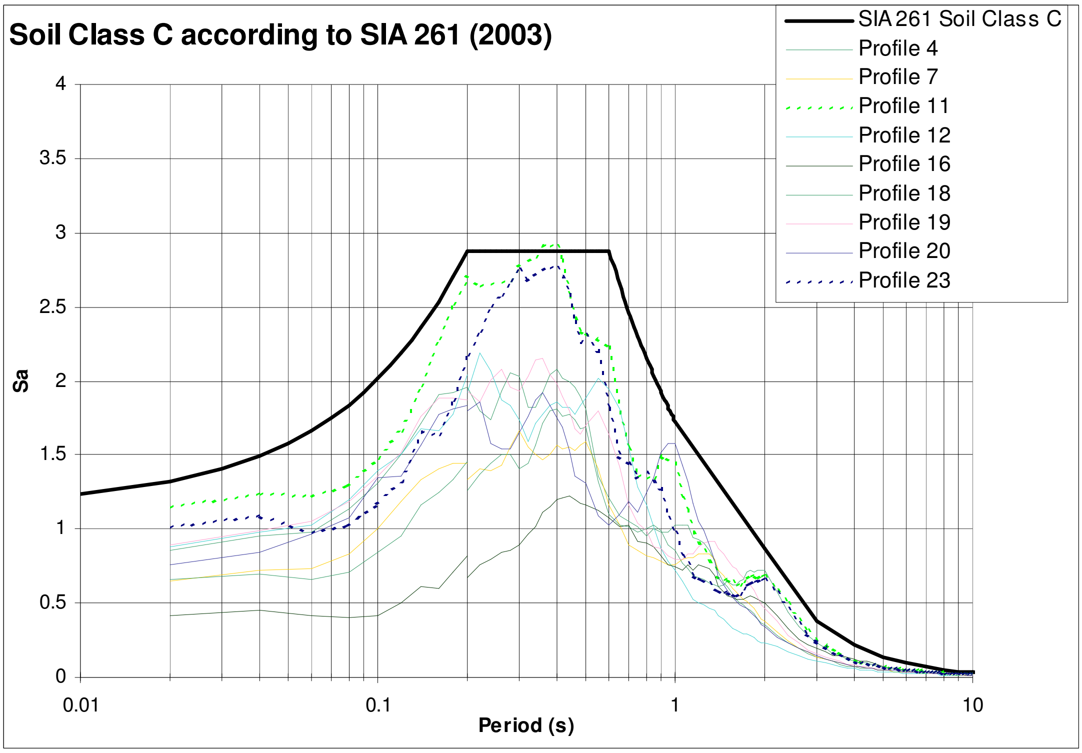

Figure 7: Comparison of computed spectra with design spectra, Soil Class C

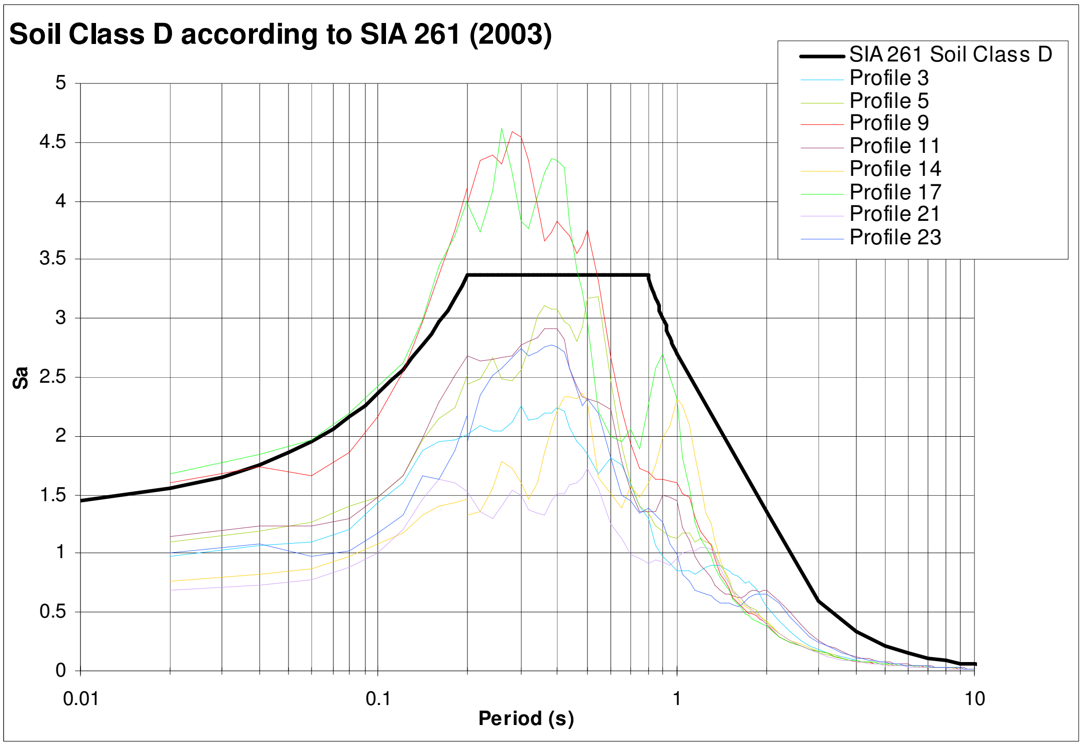

Figure 8: Comparison of computed spectra with design spectra, Soil Class D

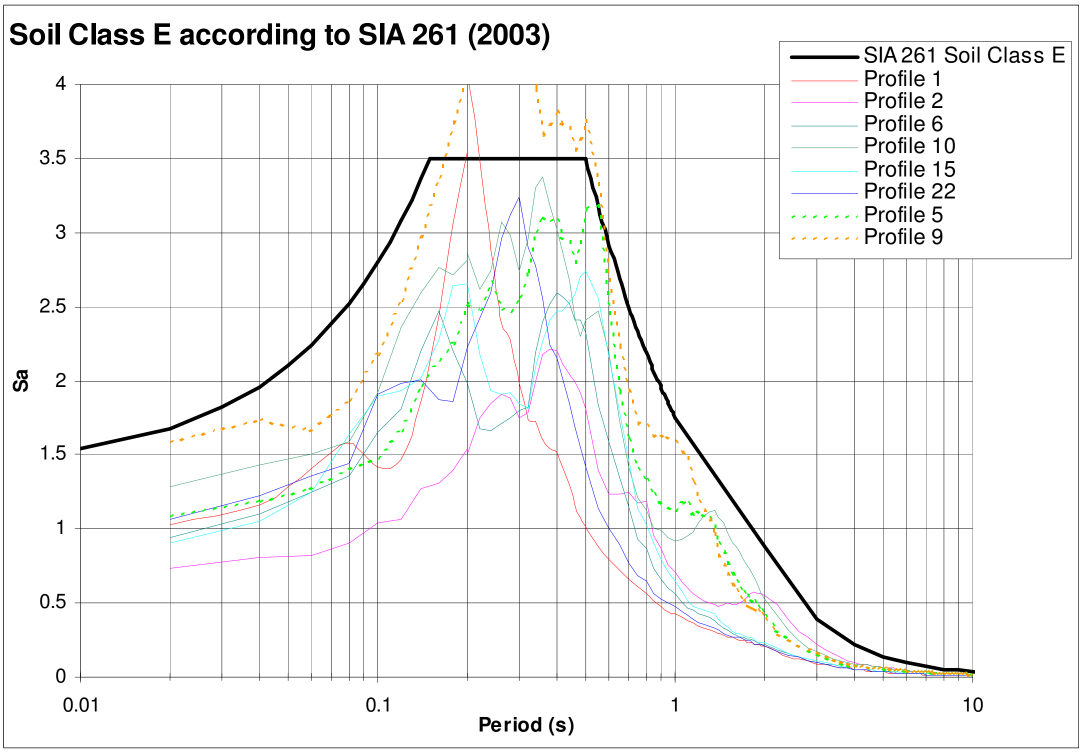

Figure 9: Comparison of computed spectra with design spectra, Soil Class E

The comparisons in Figures 6 to 9 show that the calculated spectra are compatible with the design spectra from SIA 261, but generally the latter are very conservative, since they mostly represent the envelope of the calculated spectra. For many profiles, the differences are significantly high.

An important exception is shown in Figure 8 (Soil Class D), where for profiles 9 and 17 the calculated values are higher than those of the design spectra given in the code. These two profiles are characterized by thick deposits (35m and 65m) of normally consolidated clays over the underlying bedrock. Also for Soil Class E, some profiles exceed the values given in the code.

Attempt for a definition of new soil classes

An attempt to cover the deficiencies explained above, due to the definitions of soil classes given in the code SIA 261, was made. These investigations show that at least three or four groups can be (visually) distinguished. The grouping in four value ranges is shown in Figure 10.

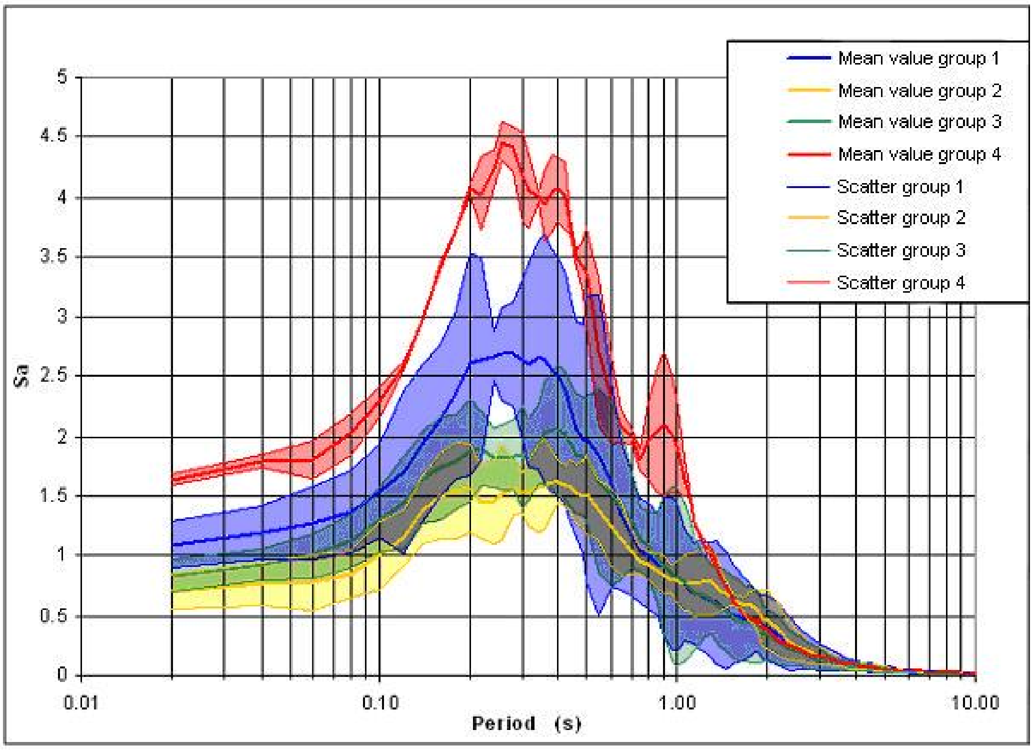

Figure 10: Mean values and scatter of the new grouping, four groups are distinguished

A closer interpretation of this grouping showed that three ranges can be identified by geotechnical characteristics:

- Range I (Group 4 in Figure 10) represents soil profiles with deep clay deposits
- Range II (Group 1 in Figure 10) represents fine grained soils, silts and sands with shear wave velocities around 200-300m/s
- Range III (Groups 2 and 3 in Figure 10) represents gravelly soils.

In view of the above findings, a proposal for new soil classes was made, which seem more appropriate for the investigated representative profiles. This proposal of a new soil classification is shown in Table 3, with corresponding spectra in Figure 11. To avoid confusion with the actual code classes, double characters have been introduced. The definition of the parameters S, T_B, T_C and T_D is the same as in Eurocode 8 [10].

Table 3: Proposal for new soil classification of the investigated profiles

Soil Class	Description	S	T_B [s]	T_C [s]	T_D [s]
Class BB	Cemented gravel and sand and/or preloaded soils (including moraines) with a thickness above 30m	0.8	0.15	0.5	2.0
Class CC	Normal consolidated and not cemented gravels and sands and/or preloaded moraines with a thickness above 30m	0.9	0.2	0.7	2.0
Class DD	Normal consolidated fine sands and silts with a thickness above 30m or normal consolidated clays with a thickness above 30m, over soil deposits of class CC	1.2	0.2	0.7	2.0
Class EE	Normal consolidated clays with a thickness above 30m or surface layer of Soil Classes CC or DD with a thickness between 5 and 30m, over soil deposits of class A or BB	1.6	0.2	0.5	2.0

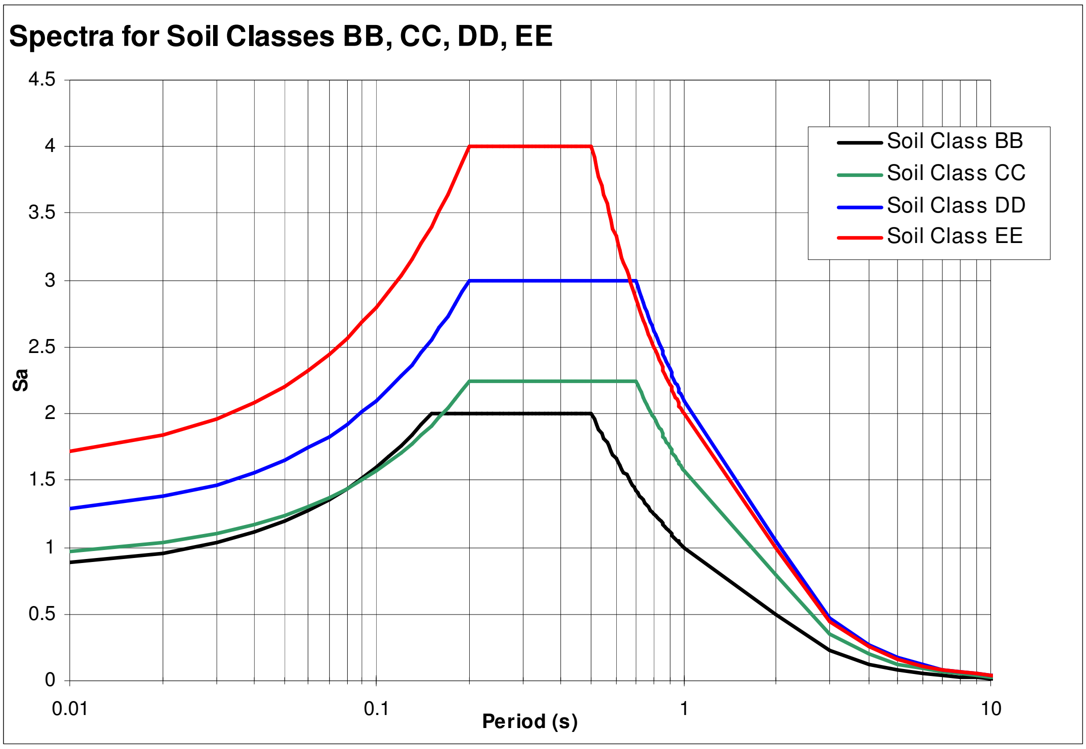

Figure 11: Spectra for proposed soil classes according to Table 1

Verification

To verify the appropriateness of the proposed classification and of the spectral values, the investigated profiles were first re-classified according to Table 3. The comparison of the calculated spectra with the proposed spectra for the respective classes is shown in Figures 12 to 15 below.

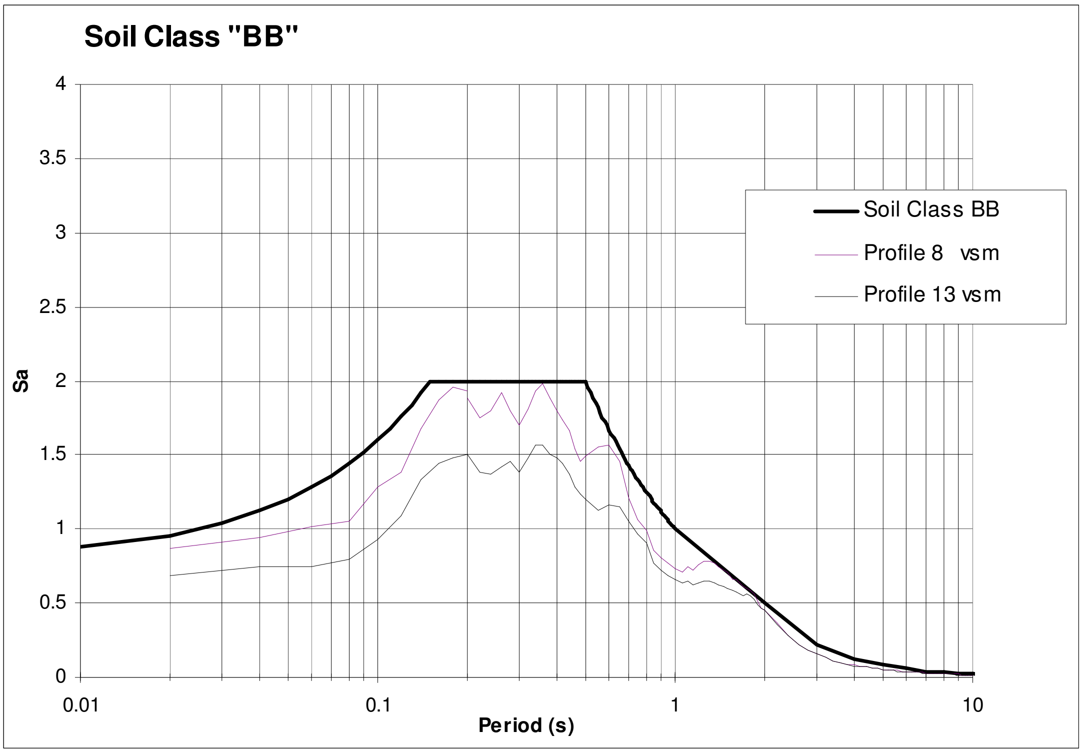

Figure 12: Proposed Soil Class "BB"

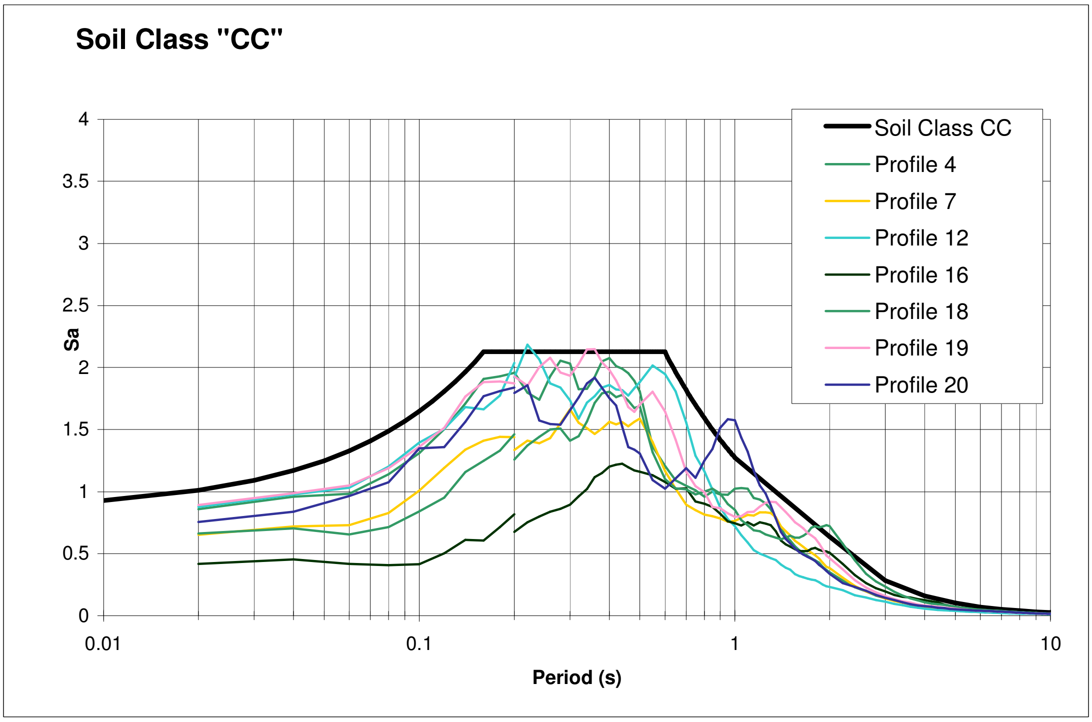

Figure 13: Proposed Soil Class "CC"

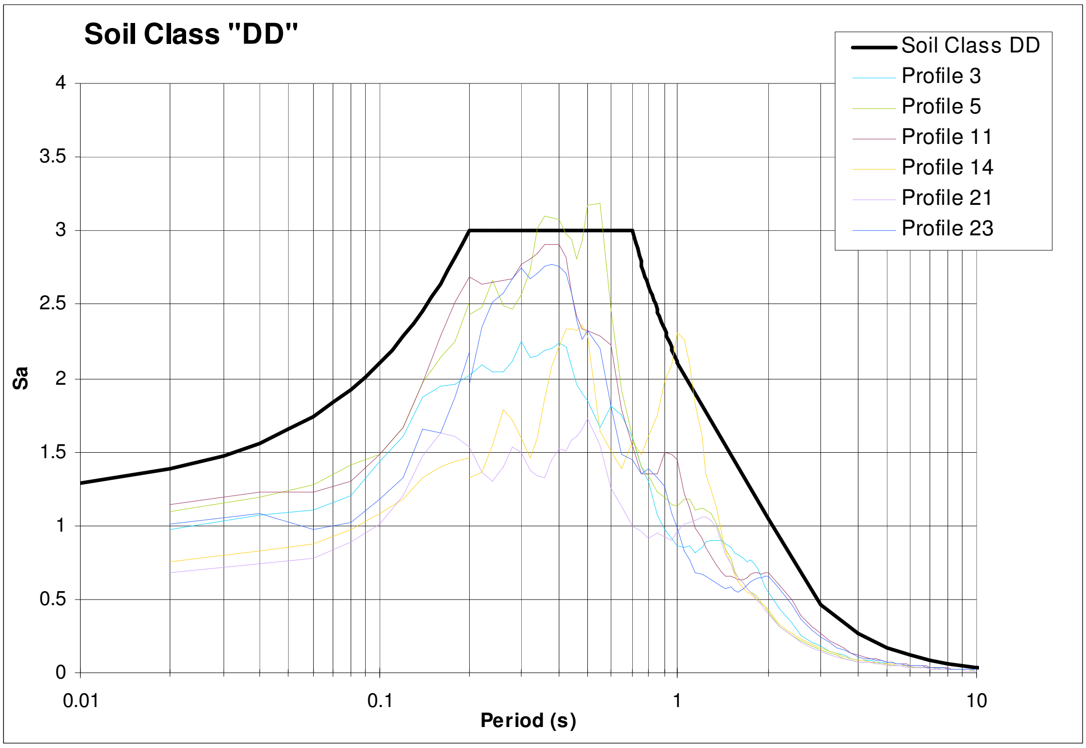

Figure 14: Proposed Soil Class "DD"

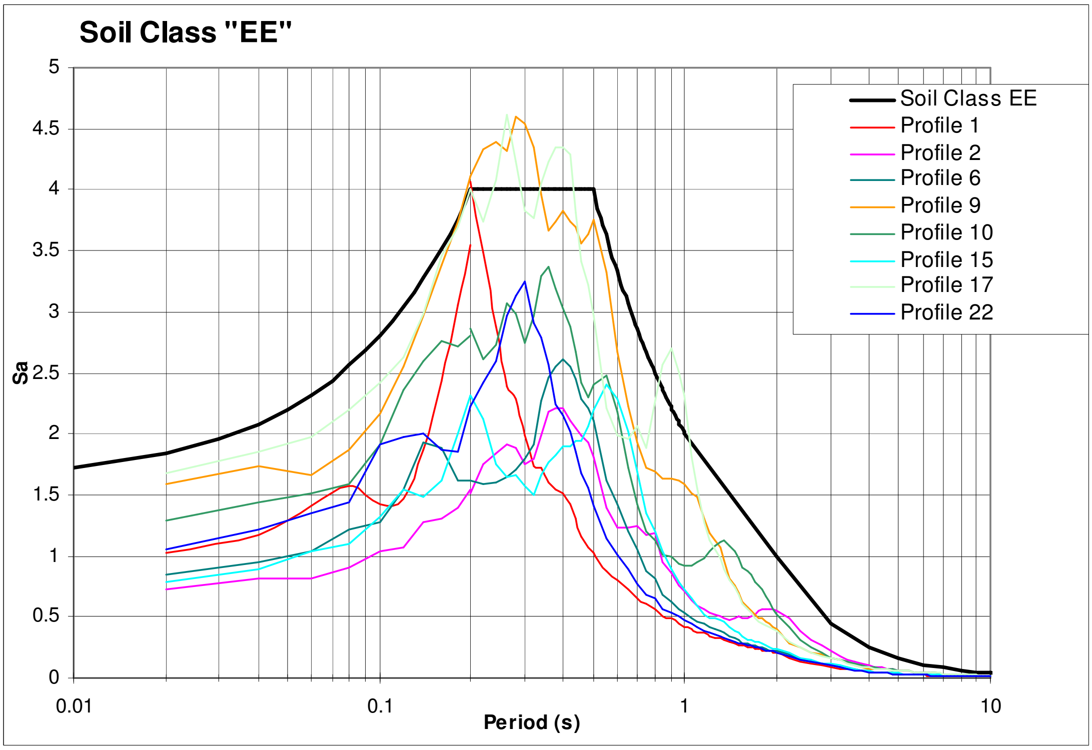

Figure 15: Proposed Soil Class "EE"

Investigation of 2D effects

The 2D-effect on three profiles (number 10, 14, 18) has been investigated and compared with the results of 1D calculations. These profiles have been selected due to their low valley shape ratio (defined as the ratio between the half valley width and the depth of soil deposits).

For profile 10, no significant 2D effect resulted from the calculations. This could be explained because of the rather high valley shape ratio of 6.6 in comparison with the other two investigated profiles with shape ratios if 2.8 and 2.0. For the latter profiles, a significant 2D effect could be observed, leading to values 1.5 times higher than those obtained with 1D calculations.

In a recent study by Chavez-Garcia and Faccioli [15], an attempt is made to relate the decision to take into account 2D effects based on the soil class. The present study could not support nor deny this proposal, for more calculations would be necessary.

DISCUSSION AND CONCLUSIONS

It should be pointed out that EC 8 spectra are mostly based on strong motion recording analysis, which inherently contains “non 1-D” effects that are not considered in this paper. This could explain part of the seemingly overconservatism of the EC 8 spectra.

Figures 6 to 9 show that today's definitions of soil classes with corresponding design spectra in the Swiss design code SIA 261 often lead to very conservative values in comparison with the actual spectra resulting from computations. In contrast, the definition of class D includes deep clay deposits, for which the calculated spectra show substantially higher values than those defined in the code.

A new classification with corresponding spectra is therefore proposed in Table 3 and Figure 11, which is believed to better represent the actual conditions at Swiss sites.

A comparison of the calculated spectra with the proposed spectra resulting from the new classification is shown in Figures 12 to 15. The new classification leads to a better agreement between calculated and proposed spectra.

The investigation of 2D effects showed mainly the high influence of the valley shape ratio on the results. A factor of 1.5 in comparison to the results of 1D calculations could be taken into account, in simple cases where the valley shape ratio does not exceed a value of 4 or 5. It has to be pointed out that this value represents only a mean amplification value over the whole frequency range and can be underestimated or overestimated for certain frequency ranges. In cases with very low valley shape ratios, an explicit evaluation of 2D effects by means of explicit calculations is recommended.

The above findings are exclusively based on numerical simulations. These simulations were carried out using carefully chosen published data as input or, where this input was not available, using well founded correlations to assess the geological/geotechnical characteristics of the profiles. Nevertheless, experience shows that one cannot rely on numerical simulations alone (nor on measurements alone). Both extremes have to be used complementarily. For the present work, this should be done by checking published strong motion databases for measurements at sites corresponding to the geologic/geotechnical situation at the selected profiles. However, the soil profiles of most strong motion recording stations in the world are still badly constrained. The only extensive data base where the corresponding soil profiles are sufficiently well known seems to be the recent Japanese KNET data. A systematic comparison with the KNET data would therefore correspond to an independent verification of the presented findings by measurements.

Such a verification is mandatory before any new soil classification is introduced in the Swiss building code.

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