

The Significance of Site Effect Studies for Seismic Design and Assessment of Industrial Facilities

Corinne Lacave¹, Martin G. Koller¹ Pierino Lestuzzi^{1,2} and Christelle Salameh³

¹ Résonance Ingénieurs-Conseils SA
21 rue Jacques Gosselin, 1227 Carouge, Switzerland
corinne.lacave@resonance.ch, martin.koller@resonance.ch

² Ecole Polytechnique Fédérale de Lausanne
EPFL Station 18, 1015 Lausanne, Switzerland
pierino.lestuzzi@epfl.ch

³ Institut des Sciences de la Terre ISTerre
BP 53, 38041 Grenoble Cedex 9, France
salamehc@ujf-grenoble.fr

ABSTRACT:

Site effects can significantly modify the seismic motion in certain frequency domains, due to the resonance of soft deposits and subsequent amplification of the motion and / or due to the shape of the bedrock surface under soft deposits. Consequently, the shape of an appropriate elastic response spectrum might significantly differ from those proposed in building codes like EC8 based on a few soil classes. A site specific elastic response spectrum can either be lower or higher than the corresponding code spectrum or even both together, depending on the considered frequency band. Especially in the framework of assessment and reinforcement of existing industrial facilities, it might be of great importance to determine a site specific spectrum, much more adapted to account for local site effects. In some cases, such a specific spectrum makes it possible to save millions of unnecessary reinforcements. Some brief methodological aspects are presented, followed by real case examples, showing the importance of specific site effect studies and their consequences in terms of elastic response spectra for a more appropriate assessment or design of industrial facilities. In particular, the soil classification in EC8 is essentially based on Vs30 whereas site specific studies also account for the velocity contrast between the bottom of loose soil deposits and the bedrock, a parameter that can have a great influence on the amplitude of the resulting response spectrum.

Keywords: site effects, site specific spectra, seismic action, seismic design, seismic assessment of existing structures

1 Introduction

It is now well known, and widely accepted amongst the earthquake engineering community, that the effects of surface geology on seismic motion exist and can be large. It has been recognised for a very long time that earthquake damage is generally larger over soft sediments than on firm rock outcrops. This is particularly important because most of modern urban and industrial settlements have occurred along river valleys over such young, soft surface deposits. Older settlements were indeed often built on firm soils on the side of the valleys because of frequent inundations; before the rivers were corrected, people rarely settled within the valleys.

The fundamental phenomenon responsible for the amplification of motion over soft sediments is the trapping of seismic waves due to the impedance contrast between sediments and the underlying bedrock. When the structure is horizontally layered (which will be referred to in the following as 1-D structures), this trapping affects only body waves travelling up and down in the surface layers. When the surface sediments form a 2-D or 3-D structure, i.e., when lateral heterogeneities such as thickness variations are present, this trapping also affects the surface waves which develop on these heterogeneities and reverberate back and forth.

The interference between these trapped waves leads to resonance patterns, the shape and the frequency of which are related to the geometrical and mechanical characteristics of the structure. While these resonance patterns are very simple in the case of 1-D media (vertical resonance of body waves), they become more complex in the case of 2-D and a fortiori 3-D structures. An illustration of 2-D effects is given in Figure 1.

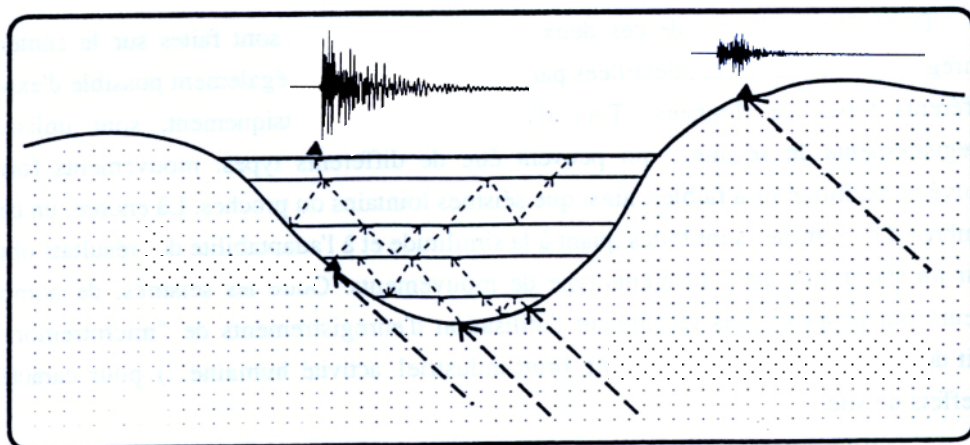


Figure 1: Illustration of site effects due to trapped waves in a sedimentary basin; ground motion within the basin is significantly stronger than on an adjacent rock site

More physical insight, together with a general overview on key factors controlling seismic hazard, is given by Bard [1], and a more detailed presentation on 2D site effects can be found in Makra et al. [2].

2 Site effect study

In order to take site effects into account, the shape of the response spectrum used to design or evaluate structures can be adapted to reflect the characteristics of the amplification of the ground motion. The first way to do this was to introduce different soil classes into the building codes. Most of the building codes include five or six different soil classes with an associated spectral shape.

Of course, these shapes are supposed to be compatible with a kind of mean behaviour of all soils belonging to one class. Looking to the shapes of real recordings, it appears that there is a great variability between sites belonging to the same class. Most of the soil classes' definitions (Eurocode 8, ASCE 7-10, etc.) do account for the mean V_s over the first 30 m of deposits; no account is taken for the total thickness of the deposits, nor for the velocity contrast at top bedrock, etc.

In order to take into account the influence of the ground structure on the resulting seismic behaviour of a site in more details, it is possible to conduct a site effect study. The goal of such a study is to define a site specific spectrum, to be used instead of the mean code spectrum.

First, an S-wave velocity profile has to be defined, based on all available geological and geotechnical information, as well as some geophysical measurements such as MASW or H/V measurements, for example. If necessary, the shape of the bedrock has to be defined also, for a 2D account of site effects. Then, some computations (1D or 2D) are conducted in order to get the seismic motion at the surface, given a regional input rock motion at the bottom of the profile (as shown on Figure 2). The account for the non linear behaviour of the soil can also be included, as well as for the uncertainties in the V_s determination, in the incidence angle in case of 2D computations, and so on.

Finally, using all resulting spectra at a given site, a site specific spectrum is defined, characterizing the soil response at this site much better than the mean spectrum of the corresponding code soil class. For example, it can be seen on Figure 2 that the shape of the resulting spectrum for the lateral shallow part of the valley is very different from the one for the deep central part.

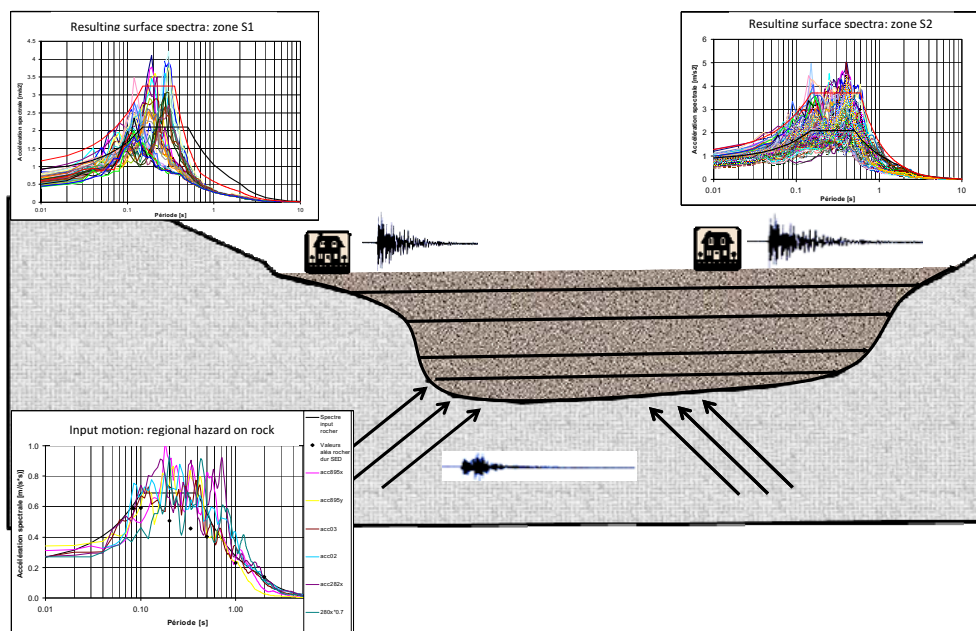


Figure 2: 2D computation of site effects with different input motions and the account for different incidence angles and uncertainties on the V_s profile

3 Influence of the velocity contrast at top bedrock

The influence of the velocity contrast at top bedrock on the response spectrum is illustrated for a simple, but realistic example. Three velocity profiles are considered; all correspond to the soil class E according to Eurocode 8 (Figure 3). All three profiles have a strictly identical gravelly sand layer of 18 m thickness, with a shear wave velocity V_s growing from 200 m/s at the surface to 400 m/s at 18 m depth. The only difference is in the underlying rock profile. In profile 1, V_s jumps to 800 m/s at 20 m depth (top bedrock), then grows smoothly, attaining 2400 m/s in about 350 m depth and remaining constant below. In profile 2, V_s jumps to 1400 m/s at 20 m depth (top bedrock), then grows smoothly, attaining 2400 m/s in 250 m depth and remaining constant below. Finally, in profile 3, V_s immediately jumps to 2400 m/s at 20 m depth and remains constant below. From 18 m to 20 m depth, in all profiles, there is a layer of weathered rock with a value for V_s that is in-between those at 18 m and 20 m depth.

Figure 4 compares the resulting response spectra, assuming that the site is located somewhere near Berne (Switzerland). All response spectra show a pronounced peak around a period of 0.2 s, corresponding to the natural period of the sandy deposit. However, the height of this peak depends on the velocity contrast below the sandy deposit: the stronger the velocity contrast, the higher the resulting amplification of the spectral acceleration around the natural period. In the opposite,

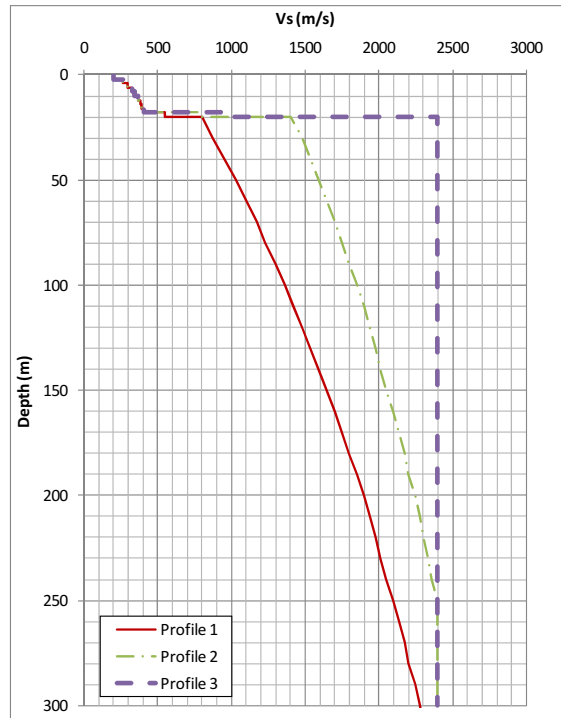


Figure 3: Three different velocity profiles, all belonging to the Eurocode 8 soil class E; the Vs profile for the first 18 m (gravelly sand) is always identical

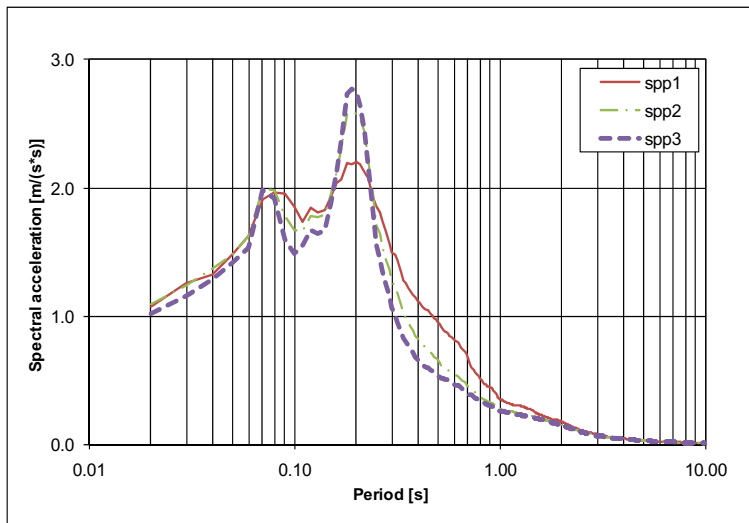


Figure 4: Resulting site specific response spectra for the soil profiles shown in Figure 3 for a regional rock hazard corresponding to Berne (Switzerland)

for a period around 0.5 s, profile 3 leads to a spectral acceleration which is only about half of the one resulting from profile 1, whereas according to Eurocode 8, the same response spectrum for soil class E would have to be used for both profiles. However, in reality, profile 3 is more unfavourable or, in the contrary, much more favourable than profile 1, depending on the (fundamental) natural period of the structure to be designed. Profile 2 is somewhere in-between the others.

4 Examples of site specific spectra

This section presents four examples of site specific spectra obtained in different areas in Switzerland, in order to illustrate the variation between the code spectra and the specific spectra, depending on the type of local geological conditions.

The first site is characterized by a 3 to 10 meter thick alluvial layer over the bedrock. The site is classified in A class where the deposits are less than 5 m thick, and in E class elsewhere. Figure 5 shows the resulting site specific spectrum, compared to the code spectra for A and E classes. It appears, in this case, that the code E spectrum can significantly be reduced, for periods longer than 0.2 s, due to the fact that the alluvial layer is not very thick (maximum 10 m).

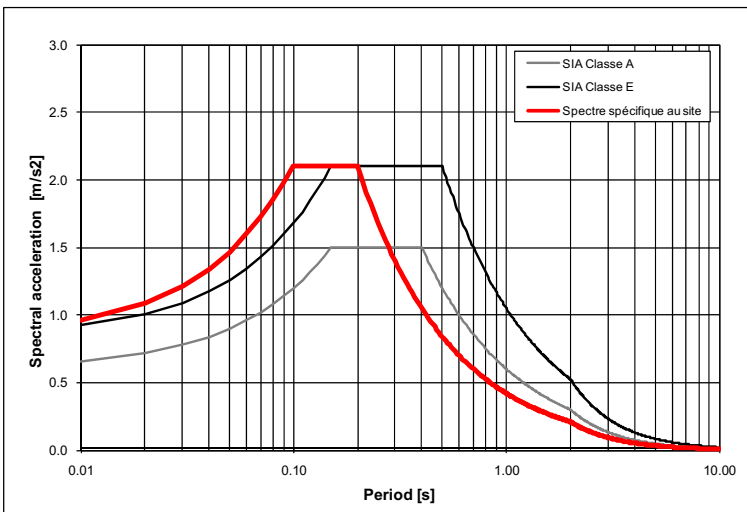


Figure 5: Site specific spectrum (in thick red), compared to A and E class spectra of the code (grey and black lines respectively)

The second example comes from a site characterized by a layer, about 40 to 50 m thick, of silty clay. Figure 6 shows the resulting proposed site specific spectrum, compared with the class C code spectrum that would have to be used without a site effect study. The plateau of the site specific spectrum is much higher than the one of the code spectrum, due to the very high velocity contrast between the clay layer

and the bedrock. However, the proposed spectrum could significantly be reduced for periods longer than 0.8 s, which can be of great interest for existing flexible buildings or structures.

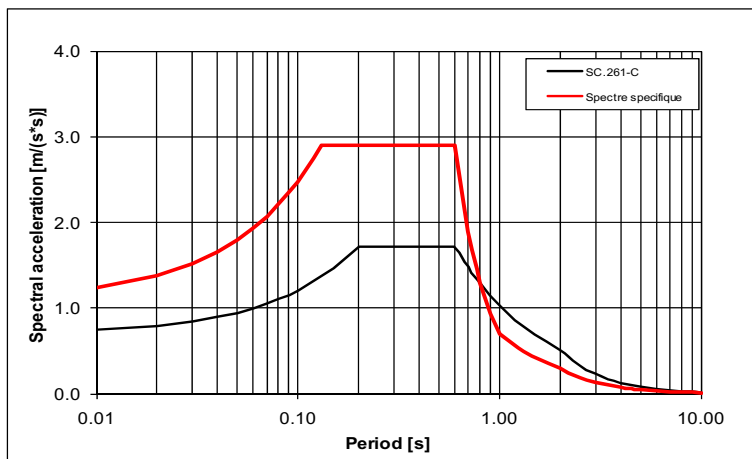


Figure 6: Site specific spectrum (in thick red), compared to C class spectrum of the code (black line)

A third example shows the case of a deep 2D sedimentary valley filled with 300 to 400 m of sedimentary deposits; the site would be class D. As shown on Figure 7, in this case, the resulting site specific spectrum is larger than the code class D spectrum over the whole frequency range.

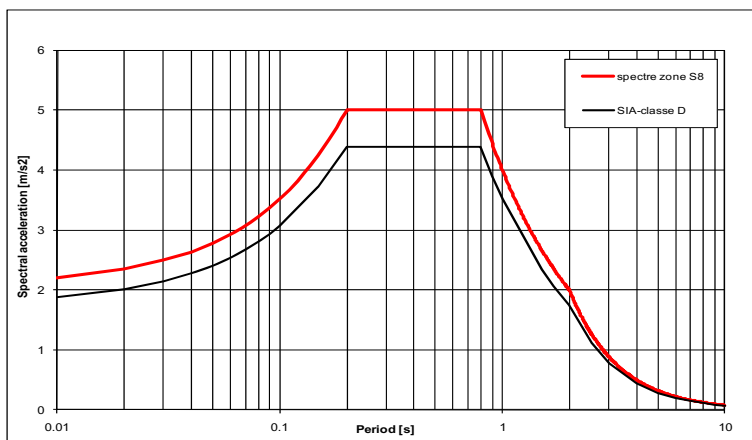


Figure 7: Site specific spectrum (in thick red), compared to D class spectrum of the code (black line)

Finally, a last example shows the case of a deep 2D sedimentary valley filled with 800 m of sedimentary deposits. As shown on Figure 8, in this case, the resulting site specific spectrum is lower or equal to the code class C spectrum over the whole frequency range, and of course then much lower than the class D spectrum. The site specific spectrum stems from a spectral microzonation study and is valid for an area that corresponds partly to soil class C, and partly to soil class D. In this case, the damping effect in the very thick sedimentary deposits is stronger than the amplification effect due to the trapping of waves in the 2D valley.

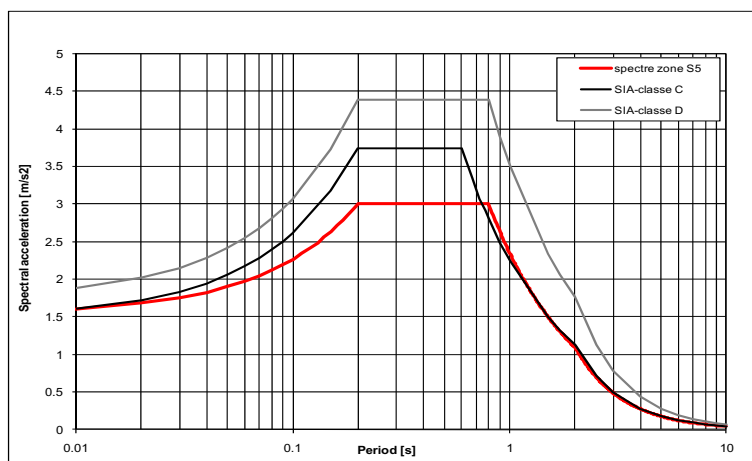


Figure 8: Site specific spectrum (in thick red), compared to C and D class spectra of the code (grey and black lines, respectively)

5 Consequences for structures

The impact of site effect studies on the seismic design or assessment depends on the dynamic characteristics of the considered structures. Generally speaking, the plateau of the site specific spectrum is significant for stiff structures such as low-rise buildings or typical industrial equipment, whereas the long period range is significant for more flexible structures such as high-rise buildings.

The consequence of the site specific spectrum of Figure 5 was that several relatively flexible buildings of a CIF did finally not need any seismic upgrade; a large amount of money could be economised.

A similar outcome was the consequence of the site specific spectrum of Figure 6. In fact, the site study had been carried out for a high-rise building with a natural period of about 2 s. For this period, the site specific spectrum turned out to be significantly lower than the corresponding code spectrum – although the site showed a particularly strong site amplification due to a strong velocity contrast at top bedrock. However, this amplification was limited to periods shorter than 0.8 s. Needless to say that for most types of industrial equipment, with natural periods

shorter than 0.8 s, this spectrum would have been particularly unfavourable. Or in other words: the simple use of the code spectrum would significantly underestimate the seismic risk associated with most types of industrial equipment and 'non-high-rise' buildings at that site.

The site specific spectrum of Figure 7 leads to the same consequences for all structures. Compared to soil class D, the seismic action is slightly increased by a factor of about 1.2.

Finally, the site specific spectrum of Figure 8 is favourable for stiff structures such as low-rise buildings or most types of industrial equipment, since the plateau is clearly lower than the plateaus of the spectra for soil classes C and D. The seismic action is reduced by a factor of about 0.8 in the short and medium period range. For flexible structures, such as high-rise buildings, however, this site specific spectrum is neutral with respect to the spectrum for soil class C.

6 Conclusions

Site effects can significantly modify seismic ground motion owing to the local resonance of soil deposits and subsequent amplification of ground motion and/or owing to the shape of the bedrock topography below the soil deposits. A site specific response spectrum can either be lower or higher than the corresponding code spectrum. Often, the modification is different and in an opposite way for the plateau and for the long period range.

Compared to code spectra, seismic action can sometimes be reduced by a factor of up to 2 or, in rare cases, even more, within a limited period range. Consequently, particularly in the framework of assessment of existing industrial facilities, it might be of great interest to determine a site specific spectrum. Sometimes, a seismic reinforcement that would be necessary according to the code spectrum can be shown to be superfluous thanks to a site specific study.

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