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ORIGINAL RESEARCH PAPER

2D equivalent linear site effect simulation: example applications to two deep valleys

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Abstract In the framework of the Sismovalp European project, an equivalent linear 2D code was developed to compute the response of a valley to SH waves, using the discrete wave-number method proposed by Aki and Larner (Aki K, Larner KL (1970) J Geophys Res 75:5). To overcome the frequency upper bound limitation, the Aki and Larner's method is combined with a one-dimensional computation using a classical multi-layer method (Aki K, Richards PG (1980) Quantitative Seismology: Theory and Methods, vols. 1 & 2. W.H. Freeman & Co, San Francisco). The so-called "Aki–Larner extended method" is associated to an iterative algorithm, as proposed by Seed and Idriss (Seed HB, Idriss IM (1969) Report No. EERC 70–10, Earthquake Research Center, University of California, Berkeley, California) which accounts for the modulus and damping degradation using a linear visco-elastic model. A comparison of the results in the linear and the equivalent linear cases, for a magnitude 6.0 earthquake, shows that the account for the equivalent linear behaviour of the soil significantly reduces the amplification level, especially at frequencies higher than the fundamental resonance frequency of the site. In the case of site effects or microzonation studies devoted to produce design spectra for engineering structures, this can have a major impact on the associated results and costs, depending on the frequency of interest for the considered structure. As a first application of the developed technique, 2D equivalent linear Aki–Larner computations are used to perform the seismic microzonation study of the upper Rhone valley, in the Visp area (Switzerland), a typical 2D alpine valley. These investigations

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made it possible to determine site specific spectra, associated with different zones, to be used instead of the code spectra that do not take into account the local 2D amplification.

Keywords Site effects · 2D simulation · Equivalent linear · Microzonation

1 Introduction

In the framework of the Sismovalp European project, an equivalent linear 2D code was developed to compute the response of a valley to plane SH waves, using the discrete wavenumber method proposed by Aki and Larner (1970). To overcome the frequency upper bound limitation, the Aki and Larner's method is combined with a one-dimensional (1D) computation using a classical multi-layer method (Aki and Richards 1980; Bard and Gariel 1986). The so-called "Aki–Larner extended method" is associated to an iterative algorithm, as proposed by Seed and Idriss (1969) which accounts for the modulus and damping degradation using a linear visco-elastic model. The present paper is devoted to the presentation of several example applications. It focuses on the response of alpine valleys for which the 2D behaviour cannot be ignored, and the plasticity index values also suggest that non-linear effects should be taken into account.

In the framework of the ESG 2006 ground motion simulation benchmark in the Grenoble basin, this 2D equivalent linear approach was applied. A comparison was done between results obtained with the linear and equivalent linear approaches.

As a first application of the methodology developed here, equivalent linear 2D Aki–Larner computations were used to perform the seismic microzonation study of the upper Rhone valley, in the Visp area (Switzerland), a typical 2D alpine valley. These investigations made it possible to determine site specific spectra, associated with different zones, to be used instead of the code spectra that do not take into account the local 2D amplification.

2 Methodology

The code that is used in this study (especially the equivalent linear module) was developed in the framework of the SISMOVALP European project (http://www-lgit.obs.ujf-grenoble.fr/sismovalp/).

2.1 The extended Aki–Larner model

The computation of the 2D response of alluvial basins is based on the discrete wavenumber method proposed by Aki and Larner (1970). The basis of this method lies on the transposition of the direct problem in space and time domain to the horizontal wavenumber and frequency domain, achieved by a double Fourier transform. To solve the problem numerically, a discretization in both space and time, and thus in wavenumber and frequency, is operated.

Some of the simplifying assumptions on which this method is based impose a frequency limitation which is approximately in the range between 4 × f_0 and 8 × f_0, f_0 being the resonance frequency of the considered basin. The iterative linear equivalent formulation forces to estimate the time domain response and associated peak and effective strains for each iteration. Thus, the response is needed over the whole frequency range covered by the input motion, which very often exceeds this 8 × f_0 upper bound. To overcome this frequency limitation,

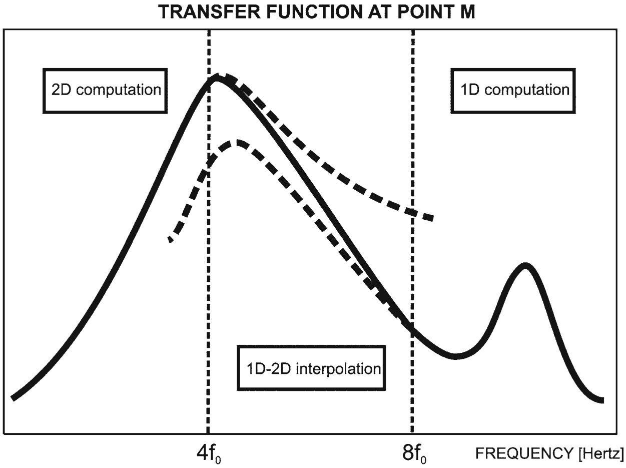

Fig. 1 Approximation of the 2D basin response by the extended Aki and Larner's method

the computation is combined with a classical 1D computation, for frequencies higher than $4 \times f_0$. Between $4 \times f_0$ and $8 \times f_0$, a hybrid solution if linearly interpolated between the 1D and the 2D solutions, as shown on Fig. 1. The hybrid transfer function can be written as:

$$\mathrm{TF}_{\mathrm{hybrid}} = \alpha\ \mathrm{TF}_{\mathrm{2D}} + (1 - \alpha)\ \mathrm{TF}_{\mathrm{1D}},\ \text{with:}$$

- $\alpha = 1$ for $\mathrm{f} \leq 4\mathrm{f}_0$,
- $\alpha = 2 - \mathrm{f}/4\mathrm{f}_0$ for $4\mathrm{f}_0 < \mathrm{f} \leq 8\mathrm{f}_0$,
- $\alpha = 0$ for $\mathrm{f} > 8\mathrm{f}_0$

2.2 The equivalent linear model

Since an equivalent linear model accounts for the soil non-linear behaviour, it can be easily introduced in the linear method of Aki and Larner. First proposed by Seed and Idriss (1969), the original equivalent linear method states the modulus and damping degradation in the soil submitted to large strains. It can be modelled by the response of a linear visco-elastic model. The equivalence between linear and non-linear behaviour is ensured in terms of energy dissipation, represented by the internal area of the hysteresis loop in the stress-strain plane. As a matter of fact, an elliptical area in the stress-strain plane can represent the energy dissipated by the linear visco-elastic model, equal to that of a simple resonating oscillator. Therefore, the energy dissipated by the non-linear material is adequately approximated by the linear model by fitting the ellipse area (equivalent linear) to the area of the hysteresis loop (non-linear).

This is practically achieved by fitting the modulus and damping of the linear visco-elastic model to the effective modulus and damping of the non-linear material under loading. Experimental modulus and damping degradation curves obtained by laboratory tests generally give these effective values. In Seed and Idriss' visco-elastic model, modulus and damping values are computed from these degradation curves by an iterative algorithm. At each iteration, the effective strain is determined. This is done until a convergence limit is reached, between the effective strain at two consecutive iterations. Seed and Idriss' equivalent linear model, widely used in the well-known 1D SHAKE program (Schnabel et al. 1972), was implemented in the extended Aki and Larner method. In the 2D computation, it is assumed that the shear

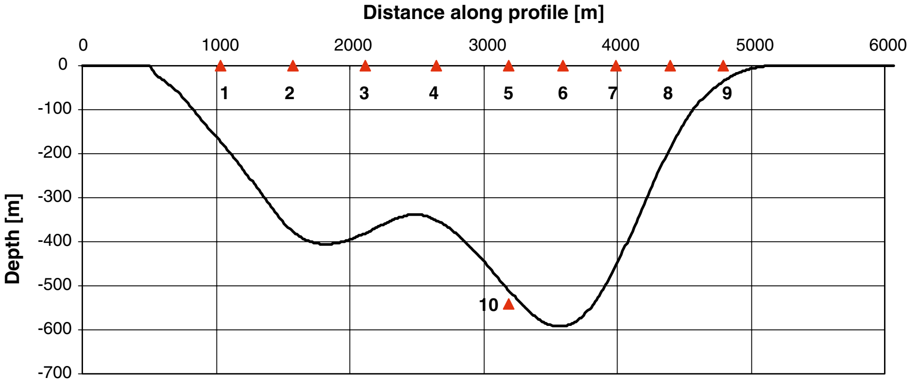

Fig. 2 Bedrock geometry along the 2D profile. The triangles indicate the position of the 10 receivers used for the computation. The vertical scale exaggeration is about a factor 3

modulus and damping are constant inside each layer, with the strain amplitude being variable (2D computation). In the 2D equivalent linear frame, the mean strain amplitude, computed at several points across the valley within each horizontal layer, is used to compute the new shear modulus and damping at each iteration step. One must be aware that this latter assumption is a very strong one that certainly puts severe limitations on the applicability of this hybrid technique. It is, however, a simple tool that allows to somewhat capture the modification brought in 2D response by non-linear phenomena.

3 Comparison of the linear and equivalent linear frames

The 2D response of the Grenoble valley is calculated, and compared, using the 2D linear and equivalent linear approaches (Lacave and Hollender 2006).

Figure 2 shows the shape of the 2D profile and the position of the ten receivers.

The selected input motion used for the present study is a record obtained in Albania in 1988 at an epicentral distance of 7 km from a Mw = 5.9 earthquake.

An incidence angle of 30° has been chosen to account for the fact that sources in the Grenoble area are shallow sources on the lateral bank of the valley.

The sediments in the Grenoble basin are characterised by the presence of thick clay deposits. It is excepted that such material does not have a purely linear behaviour under strong seismic loading. For this reason, the Aki–Larner method combined with an equivalent linear model was used to perform computations on the 2D profile. The Grenoble clay has been studied through samples coming from intermediate depth (40–50 m) boreholes in Crolles and cuttings from the deep Montbonnot borehole, by the 3 s laboratory “Soils Solids Structures”. Following these investigations, the most suitable material curves suggested for these clays (J. Jerram, pers. comm., 2006; Jerram et al. 2006) are the one proposed by Vucetic and Dobry (1991), for a plasticity index of 15%. Figure 3 shows the shear modulus (left) and the damping (right) as a function of strain, respectively.

The amplification is here regarded in terms of the so-called “amplification function”: ratio between the response spectrum (for 5% damping) of the resulting motion at the surface receiver and the response spectrum of the outcropping rock (twice the incoming wave field, as would occur at a free surface of the same rock).

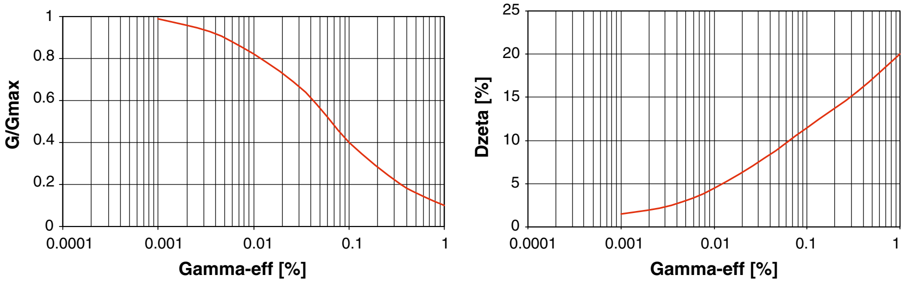

Fig. 3 Material behaviour curves used for the clay deposits, PI = 15% (Vucetic and Dobry 1991). Left: shear modulus as a function of strain; right: damping as a function of strain

Figures 4 and 5 show the amplification functions obtained both in the linear and the equivalent linear cases, at different surface receivers along the 2D profile, for input motions S1-X and S1-Y, respectively.

This comparison shows that the account for the non-linear behaviour of the soil—even in an approximate way with an equivalent linear approach—significantly reduces the amplification level, especially at frequencies higher than the fundamental resonance frequency of the site. In the case of site effects or microzonation studies devoted to produce design spectra for engineering structures, this can have a major impact on the associated results and costs, depending on the frequency of interest for the considered structure.

4 Application to the microzonation of Visp (upper Rhone valley, Switzerland)

The Swiss Rhone river valley in Valais region is characterised by a typical 2D alpine valley configuration (Lacave and Lemeille 2006). For this reason, the design spectra proposed in the seismic code are not sufficient to account for specific 2D amplification effects expected in this region. The city of Visp, located in the upper valley, is furthermore characterised by the presence of a large chemical plant, built in the middle of the valley. In 1855, a magnitude 6.4 earthquake hit Visp, leading to intensity VIII. But at that time, the village was built only on the lateral slope. The valley itself was only used for agriculture, because of the frequent Rhone river floods. The same earthquake today could lead to considerable damages due to a complete expansion of the city and industry on the central valley deposits. These are the reasons why a spectral seismic microzonation study was conducted in the Visp area.

A bedrock and S wave velocity profile is estimated through the city of Visp and computations are carried out, using the above described equivalent linear 2D approach, for different points along the profile. Results are given in terms of amplification functions (ratio of the response spectra at the surface deposits and at the hypothetical outcropping hard rock). Based on these results and the 2D geological characterisation of the valley, zones of similar site response are determined, and associated design response spectra are given, to be used by engineers instead of the code spectra. The final microzonation map gathers this information. The present paper does not enter into details concerning all the geological and geotechnical aspects of the study, which are detailed in the corresponding report (Résonance et al. 2005). It focuses only on the seismological aspects, especially the site effects estimation.

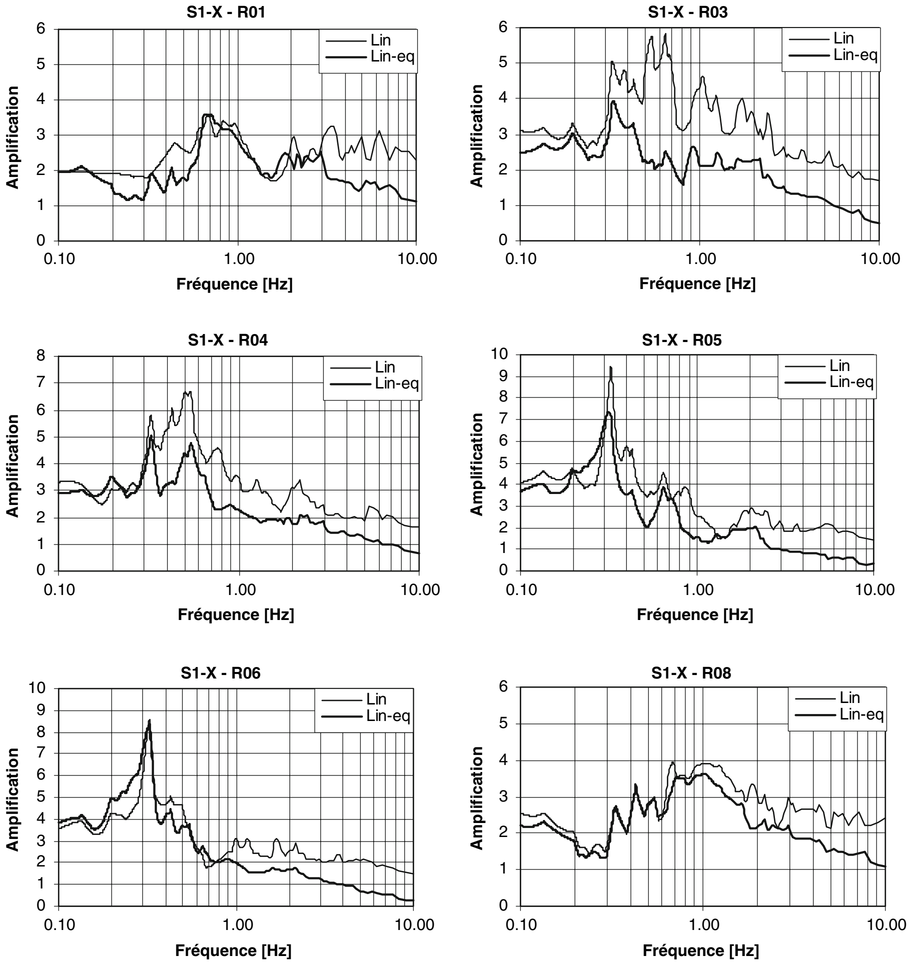

Fig. 4 Amplification functions along the 2D profile (receivers R01, R03, R04, R05, R06 and R08, as examples), for S1-X input motion, for the linear and the equivalent linear computations

4.1 Input motion

4.1.1 Regional hazard on rock

The Swiss Seismological Service has re-evaluated the seismic hazard for Switzerland (SED 2004). For any point in Switzerland, the values of spectral acceleration are available for five periods between 0.1 and 2 s (shown by the black diamonds in Fig. 6). These values are valid for a “hard rock” type with Vs around 1500 m/s. In analogy with what was determined for the new Swiss building code SIA 261, we propose to use, for the “hard rock” with Vs = 1500 m/s, a spectrum with the class A shape (similar to EC8 type 1 shape) and the following design horizontal spectral acceleration value, a_0:

$$a_0 = \frac{S_a\,(5\,\mathrm{Hz}) + S'_a\,(10\,\mathrm{Hz})}{2} \cdot \frac{1}{2.5} \tag{1}$$

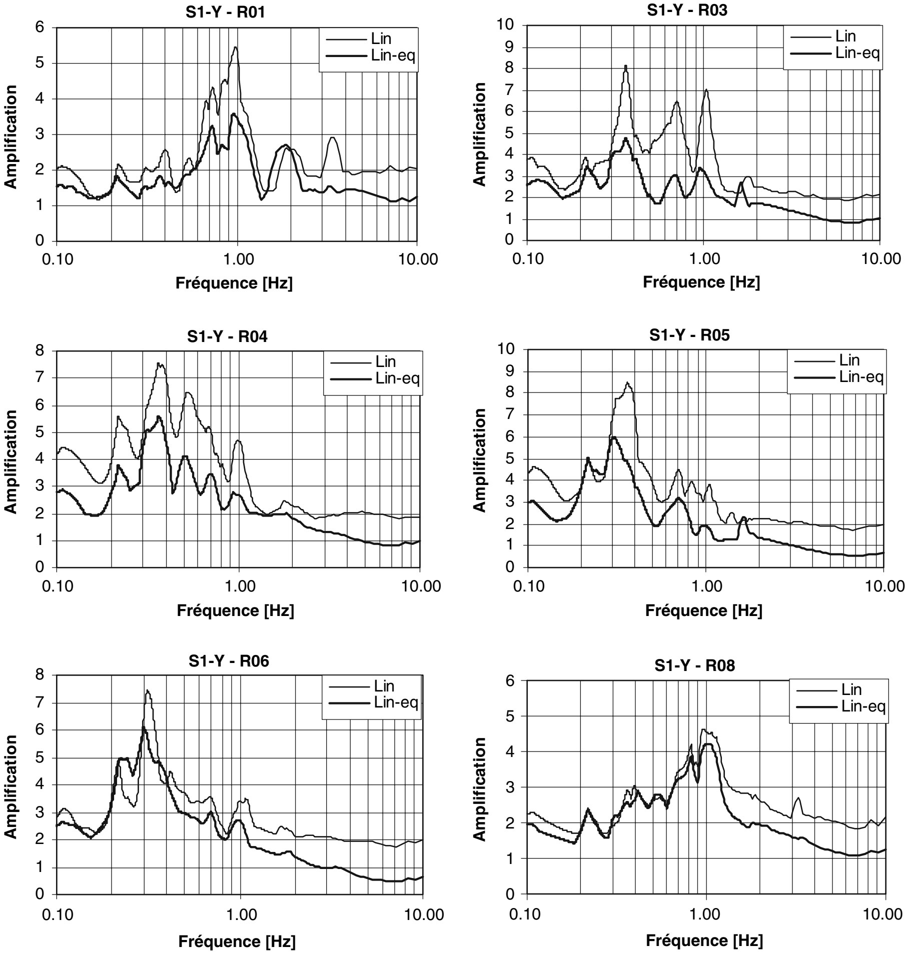

Fig. 5 Amplification functions along the 2D profile (receivers R01, R03, R04, R05, R06 and R08, as examples), for S1-Y input motion, for the linear and the equivalent linear computations

where S_a and S'_a are the spectral acceleration values for "hard rock" at 5 and 10 Hz respectively. In the case of the Visp area, $a_0 = 0.68\,m/s^2$. The corresponding "rock input spectrum", shown in Fig. 6 (thick line), is valid for the motion at an hypothetical outcropping hard rock.

4.1.2 Selection of input motions

For site effect computations, a set of five acceleration time histories was selected, that all together cover the input rock spectrum. These accelerograms were either found in the European Strong Motion Database (Ambraseys et al. 2001) and scaled by a factor if necessary, or they are semi-artifical accelerograms, created using the Sabetta and Pugliese (1996) program. The characteristics of the selected accelerograms are given in Table 1. It is reminded here that, in 1885, Visp was hit by a magnitude 6.4 earthquake, at an epicentral distance of about 10 km for a depth of about 5 km.

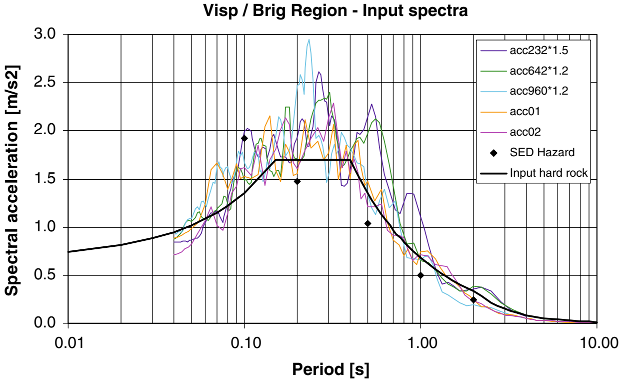

Fig. 6 Hard rock regional hazard values (black diamonds) and associated hard rock hazard spectrum (thick curve). Thin curves are the response spectra of the selected input motions

Table 1 Characteristics of the input motions

Name	Earthquake	Country	Date	M_S	Epicentral distance (km)	Scaling factor
acc232	Montenegro	Yugoslavia	05/24/79	6.3	21	* 1.5
acc642	Umbro-Marchigiana	Italy	10/14/97	5.6	23	* 1.2
acc960	Sicilia-Orientale	Italy	12/13/90	5.2	75	* 1.2
acc01	Semi-artificial Sabetta & Pugliese			6.5	50	–
acc02	Semi-artificial Sabetta & Pugliese			6.5	50	–

The response spectra of the selected input motions, for 5% of critical damping, are shown on Fig. 6, in comparison with the rock input spectrum (thick curve). The final surface spectra will be obtained by multiplying the computed amplification functions by the spectrum valid for "hard rock" (thick curve on Fig. 6). For this reason, it does not matter if the individual input signal spectra are not exactly following the "hard rock" regional hazard spectrum.

4.2 Valley and deposit properties

4.2.1 Bedrock profile

A bedrock profile was drawn across the valley, through the city of Visp, based on geological knowledge. In this part of the Valais region, the valley is about 2 km wide, for a maximum depth of 225 m. The valley is filled with lacustrine, fluvial and morainic deposits, overlaying a granite—gneiss and limestone bedrock (depending on the position along the profile). The loose soil deposits are made of fine silty sands and gravels. Figure 7 shows the shape of the valley profile. Several points were selected, were the surface motion is calculated using the 2D site effect numerical simulation.

4.2.2 Determination of the S-wave velocity profile

Some measurements of the ambient vibrations have been conducted on the whole Visp area, at 80 points. This made it possible to draw a resonance frequency map of the area.

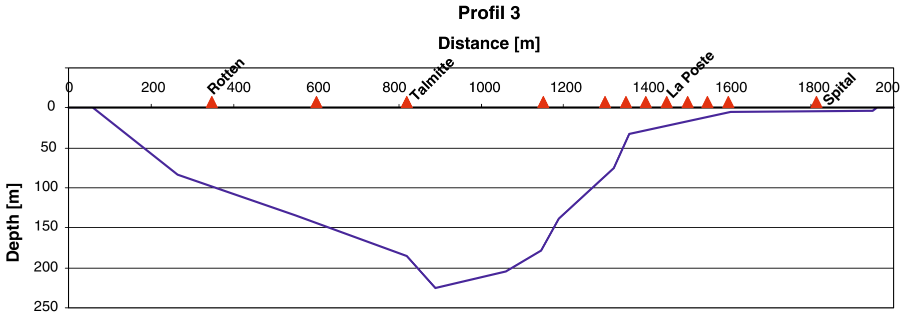

Fig. 7 Bedrock profile across the Rhone valley at Visp

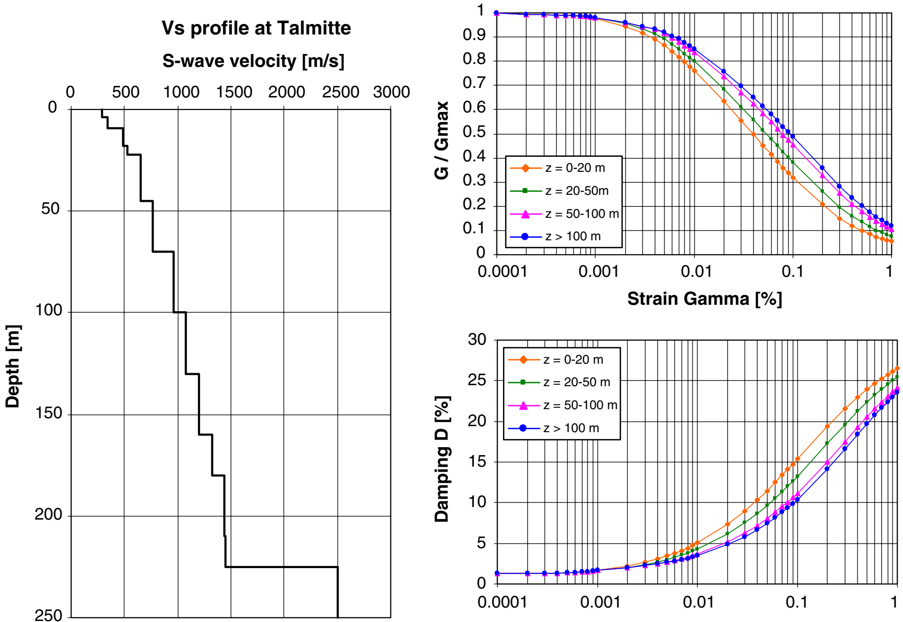

Fig. 8 Left: S-wave velocity profile in the centre of Rhone valley at Visp. Right: Shear modulus and damping as a function of strain and depth

Using available geotechnical and geological information, especially SPT values when possible, a best estimate S-wave velocity profile has been defined for the centre of the valley in Visp. A 2D computation has been conducted for very weak motion. Then the natural frequency of the obtained transfer function has been compared to the measured value at the centre of the profile. Finally, the Vs-profile has been adjusted so that the computed resonance frequency matches the measured one. The velocities in the sediments are ranging from 290 m/s, at the surface, in the silts and fine sands, to 1450 m/s at the base of the moraine (see Fig. 8). The bedrock velocity is estimated at 2500 m/s.

4.2.3 Equivalent linear behaviour of material

The material curves for the account of the equivalent linear behaviour have been determined using typical curves for the same type of deposits. The curves correspond to the mean curve between the one from Seed and Idriss (1970) and the one from Ishibashi and Zhang (1993) for a plasticity index Ip = 0. As the curves from Ishibashi and Zhang (1993) are dependent on the vertical effective stress, they are dependent on the depth (see Fig. 8, right).

4.3 2D site effect computations

4.3.1 Procedure

The 2D response of the valley is computed for the five input time histories, using the 2D equivalent linear Aki–Larner code. The following procedure is adopted:

- Computation of the surface response at several receivers along the profile, for each input motion,
- Computation of the associated response spectra,
- Computation of the amplification functions: ratio between the response spectrum (for 5% damping) of the resulting motion at the surface receiver and the response spectrum of the outcropping rock (twice the incoming wave field, as would occur at a free surface of the same rock),
- Computation of the resulting site response spectrum: multiplication of the amplification function by the regional hard rock hazard spectrum.

Furthermore, using the same procedure, a sensitivity study is conducted in order to account for the uncertainties linked to the S-wave velocity estimation and to the input motion characteristics. For this purpose, the following is done:

- The input incidence angle is varied as to be vertical (0°), as well as oblique with values of −30 and +30°.
- The S-wave velocity profile is varied by multiplying the values by a factor of 1.4 and dividing them by a factor of 1.4 (corresponding to a factor of 2 in the shear modulus).

4.3.2 Amplification functions and resulting response spectra

Figure 9 shows, as an example, the amplification functions obtained for the five input motions, at the valley centre, for the mean Vs-profile and a vertical incidence. Figure 10 gives a comparison between the mean amplification functions obtained at the valley centre, considering equivalent linear 1D (using CyberQuake 2000) or 2D (Aki–Larner) computations.

For the two accelerograms giving the stronger values at high frequency, computations where done using a velocity profile multiplied by a factor of 1.4. On the contrary, for the two accelerograms resulting in stronger results in the low frequency domain, computations were performed using the velocity profile divided by a factor of 1.4. Figure 11 shows, for the location called "Rotten", the influence of the uncertainty on the S-wave profile on the resulting response spectra. Final spectra are chose accounting for this strong uncertainty on the S-wave velocity profile.

Figure 12 shows the variation, at one point located on the edge of the basin, for different incidence angles. The incidence angle has a particularly strong influence on this side of the basin, characterised by a bevel-edged shape (see Fig. 7).

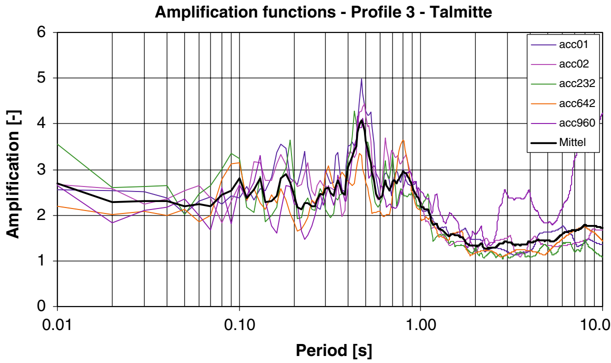

Fig. 9 Amplification functions obtained for the five input motions in the centre of the valley, and mean amplification function (thick curve)

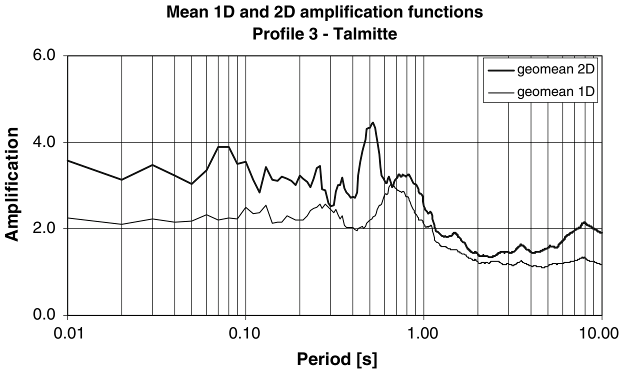

Fig. 10 Mean 1D and 2D amplification functions obtained for the five input motions in the centre of the valley

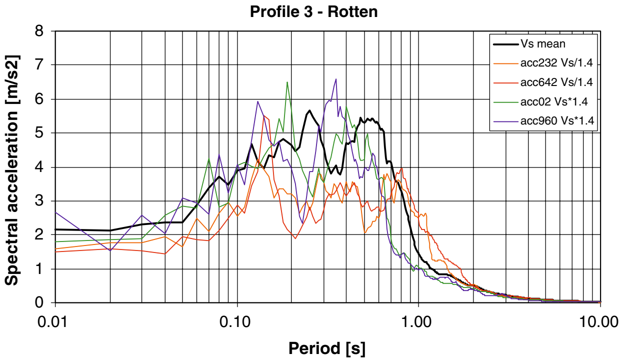

Fig. 11 Response spectra obtained with the mean velocity profile (thick curve) and the varied velocity profiles

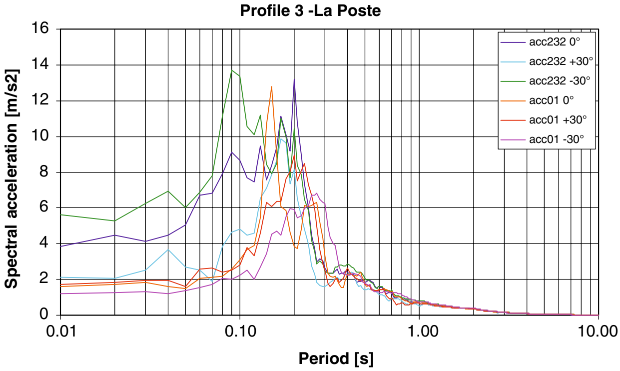

Fig. 12 Response spectra obtained for different incidence angles, at the same point on the edge of the basin

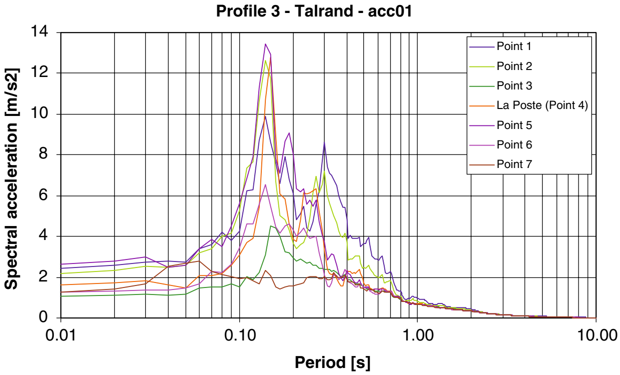

Fig. 13 Strong basin edge effect observed at different points along the edge of the valley

Strong "high frequency" amplification was obtained for the point located at the edge of the valley, called "La Poste" on the profile of Fig. 8. In order to better constrain the lateral extension of this phenomenon, the amplification functions have been computed for a dense series of points around "La Poste". Figure 13 shows the resulting response spectra, exhibiting a strong basin edge effect—or, at least, the effect of the waves trapped into the thin soft layer overlaying the bedrock, that constitutes the edge of the basin (see Fig. 7)—on this side of the valley.

As described earlier in the "Procedure" section, the final response spectra have been computed for each point, each input motion, and with the different varied parameters. Then, these spectra are shown together, for each zone where they have a similar shape. In the case of the area of Visp, three zones are distinguished, based on the results, within the valley:

- the valley centre, called "Rhonetal" (Rhone valley),
- the edge of the valley, called "Talrand" (edge of the valley),
- and the lateral torrential cone area, called "Schuttkegel" (alluvial fan).

Figure 15 shows these spectra for zone Rhonetal, as an example. On this figure, all spectra are presented, including the account for the uncertainty on the velocity profile, input motion, incidence angle, and for several positions within each zone. The aim of a microzonation study is to define site specific spectra, that better account for the local site effects than the average

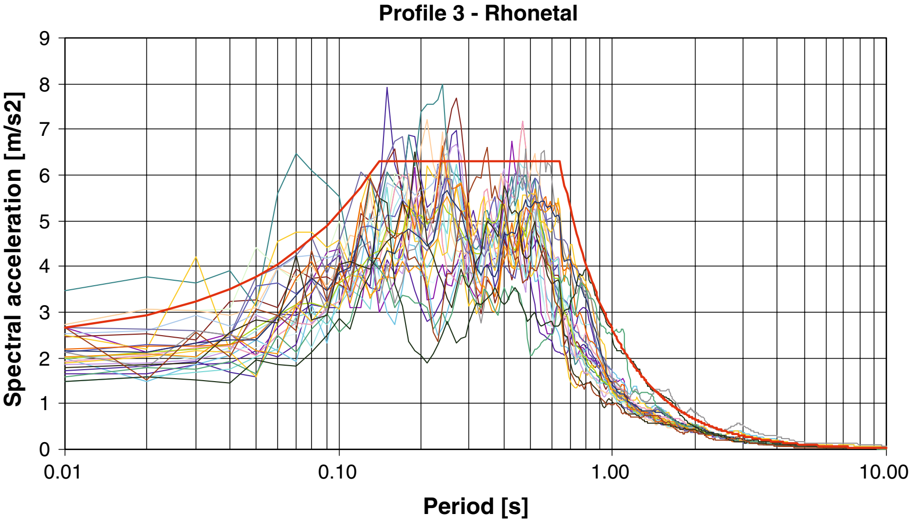

Fig. 14 Response spectra resulting from the computations in the valley centre. The thick curve is the proposed elastic design spectra for the corresponding zone

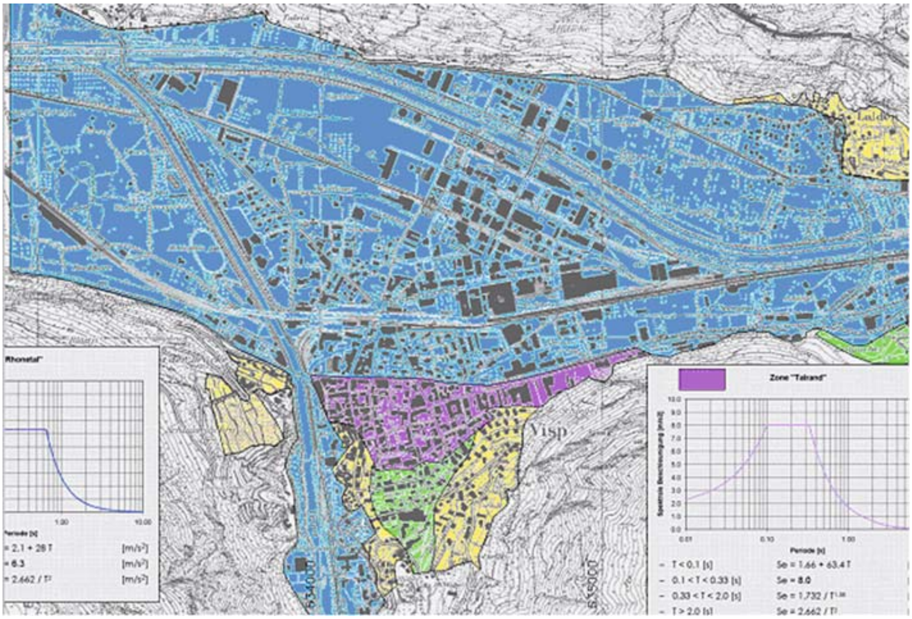

Fig. 15 Extract of the seismic microzonation map of Visp

spectra proposed in the building codes. The next step is then to use the results obtained in order to draw simple "code type shaped" response spectra, for each zone. Out of the computed spectra, a unique design spectrum is chosen for each zone (thick curve on Fig. 14), rather in a conservative manner, to cover all the above mentioned uncertainties.

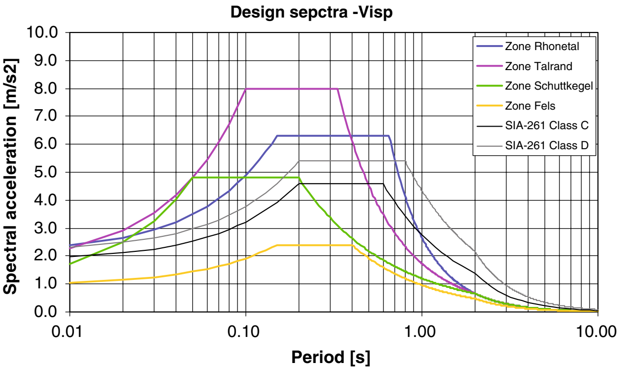

Fig. 16 Proposed elastic design spectra in each zone, compared to the code spectra, that would be used without accounting for the specific 2D site effects (thin curves)

For the surface rock areas, the proposed spectrum has the shape of a class A code spectrum, but anchored to the value of the regional hazard on hard rock at the frequency of 10 Hz.

4.4 Seismic microzonation of Visp

The zones to which the above spectra are attributed have to be delimited on a map. To do this, several aspects are taken into account, such as:

- the shape of the bedrock,
- the geology of the deposits,
- the resonance frequency distribution,
- the surface topography,
- the parcels or roads for the fine drawing of the limits.

Figure 15 shows an extract of the seismic microzonation map of Visp. The shape of the spectra associated to each zone is directly given on the map. Figure 16 shows the elastic design spectra proposed for each zone. These spectra are compared to the code spectra, that should have been used without accounting for the specific 2D site effects. This shows that for periods shorter that 1 s, the code spectra underestimate the local site amplification, whereas for longer periods the code spectra are rather too conservative.

5 Conclusions

A new computation tool has been developed, in the framework of the Sismovalp European project, in order to model the site effects in 2D valley areas, such as alpine valleys for example. A comparison is done between amplification functions obtained in the linear and equivalent linear cases, for the same input motion. This comparison shows that the account for the equivalent linear behaviour of the soil significantly reduces the amplification level, especially at frequencies higher than the fundamental resonance frequency of the site (see Figs. 4 and 5). In the case of site effects or microzonation studies devoted to produce design spectra for engineering structures, this can have a major impact on the associated results and costs, depending on the frequency of interest for the considered structure.

On the other hand, the account for 2D effects (compared to 1D only) are rather detrimental on a wide frequency band, as shown in the case of the centre of the valley in Visp area

(Fig. 10). This shows that in case of 2D configurations, as for alpine valleys for example, it is mandatory to perform 2D computations for a reliable investigation of site effects.

This equivalent linear 2D Aki–Larner code has been applied to the seismic microzonation of the area of Visp (upper Rhone valley, Switzerland). The final objective of such a study is to develop site specific spectra that account for the local site effects and that are used instead of the code spectra. The seismic microzonation map, showing the zones where these spectra have to be used, is then a tool that can be used directly by engineers for the seismic evaluation or design of structures in the corresponding region. The results of this study are daily used now, as it has become mandatory to use the site specific spectra instead of the building code spectra.

Acknowledgements The equivalent linear 2D Aki–Larner code was developed in the framework of the European Interreg IIIB Alpine Space project SISMOVALP, number F/1-2/3.3/25. The Swiss contribution was financed by the Swiss Confederation, CREALP and Canton Valais. The simulations on the Grenoble basin were carried out in the framework of the ESG 2006 Grenoble benchmark and were supported by the Institut Laue Langevin (ILL, France) and the Commissariat à l'Energie Atomique (CEA, France), through the "Cashima" research program on site effects. We are grateful to J. Jerram, A. Pecker and P. Sollogoub for their advises. We also would like to thank the organisers of the ESG 2006 Grenoble benchmark. We are grateful to H. Rovina and P. Tissières for the geological and geotechnical aspects in the microzonation of Visp and to J.-D. Rouiller for his continuous effort for seismic risk reduction in the Valais (Switzerland).

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