SEISMIC RESPONSE ANALYSIS OF LA SALLE FLUVIAL FAN, VALLE D’AOSTA, ITALY

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ABSTRACT - In the framework of the EC-funded Sismovalp project, dealing with the evaluation of seismic risk in Alpine valleys, the seismic response of La Salle fluvial fan, located in North-Western Italy, Valle d’Aosta, has been analyzed. Amplification phenomena are first investigated using the HVSR and RSM techniques on noise data and local earthquake data recorded by a temporary dense velocimetric and accelerometric network, operated from May 2005 to September 2005 in the municipal area of La Salle, formed by 4 velocimetric stations and 3 accelerometric stations. Even if the HVSR results for the stations installed on the alluvial fan do not indicate any clear amplification frequency, the RSM technique application shows considerable site amplification phenomena for frequencies higher than 1 Hz. Considering the results coming from a hybrid seismic survey and a geotechnical investigation campaign, a 2D cross-section of the fan has been reconstructed. The seismic response has been analyzed by a semi-analytical method for SH wave propagation inside triangular-shaped geological irregularities, which allowed us to perform fast parametric analyses.

1. Introduction

In this study we analyze the seismic response of La Salle fluvial fan, located in North-Western Italy, Valle d’Aosta. The analysis is carried out in the framework of the EC-funded Sismovalp project and is based, on one side, on the application of spectral techniques on the records of a small temporary network and, on the other side, on the numerical simulation of the seismic response of a cross-section of the fluvial fan.

Fluvial fan seismic response characterisation can be a very important issue in defining alpine earthquake scenarios: as observed for example during the Friuli (Italy) earthquake sequence in 1976, especially in the town of Gemona, heavy damages may occur to buildings located on fluvial fan deposits, due to amplification effects in the presence of highly consolidated fluvial fan materials. The main objectives of the Sismovalp project (Seismic Hazard and Alpine Valley Response Analysis) are: 1) the construction of transnational databases which can be used in the alpine space for seismic hazard studies; 2) the definition of representative alpine valleys shapes and earthquake scenarios; 3) the numerical simulation of the associated earthquake-induced ground motion; 4) the proposition of spectral shapes and accelerograms suitable for the Alpine environment and comparison with the level of protection pursued at a national or European (EC8) scale. The final task of the project is the dissemination of the previous results to civil engineers and local authorities in order to reduce seismic vulnerability in the alpine space.

Site effects related to geological and geo-morphological setting and topography actually represent one of the main factors responsible for building damage; in recent
years, their evaluation by experimental methods and/or numerical simulations has attracted growing attention. Among methods based on instrumental recordings we mention reference site [Borcherdt, 1970; Bonilla et al., 1997; Parolai et al., 2000] and non-reference site [Lermo and Chavez-Garcia, 1993] approaches. The standard HVSR (horizontal to vertical spectral ratio) technique can be applied to ambient seismic noise records [Nakamura, 1989] and/or to earthquake data. Nevertheless, the assessment of site amplification effects by means of microtremor measurements alone often lead to unreliable results as demonstrated in many studies [Lermo and Chavez-Garcia, 1993; Lachet and Bard, 1994; Bard et al., 1998; Bindi et al., 2000, Parolai et al., 2001, Parolai et al., 2004], so that the collection of a suitable data set of seismic events is needed to ensure accurate site response estimation. Reference site methods (RSM) assume that records from the reference site (generally a station installed on outcropping hard rock) contain the same source and propagation effects as records from sedimentary sites providing a frequency amplification function of the site. Also the generalized inversion technique (GIT) can be used to calculate site response separating the contribution of path, source and site by means of an inversion scheme.

In addition to experimental studies based on the previous spectral amplification techniques, an effort has been made to analyze the seismic response of the fan by a simple but physically sound 2D numerical model, for which a fast computation procedure has been devised to allow one to perform fast parametric numerical simulations.

2. Geological framework and seismic network

La Salle is a village located in North – Western Italy, Valle d’ Aosta. It is built on a well-steady fluvial fan composed by marsh palustrine deposits with different thickness, superimposed on a crystalline substratum belonging to Brianzonese lithotype (Figure 1).

Within the scope of the Sismovalp project, a thorough subsoil exploration was undertaken with the aim of defining the physical – mechanical parameters of the superficial lithotypes as well as providing information about the geometry and the depth of bedrock structures. The investigation survey included a preliminary gravimetric investigation on the area and a hybrid seismic survey. The hybrid seismic investigation revealed for the fluvial fan a typical morenic deposit configuration in which three reflectors characterized by materials with a growing seismic velocity appears; the crystalline substratum seems to be cut by numerous faults. As regards the bedrock formation underlying the fluvial fan, the hybrid seismic survey revealed a simple geometry, which, as shown in the following, justifies the use of simple numerical modelling techniques.

For the optimal design of the temporary seismic network, a preliminary noise survey was carried out in the area of La Salle and, since May to September 2005, a temporary network composed by four velocimetric stations (Lennartz 3D – 5s/MarsHD) and three accelerometric stations (K2–Kinematics digital recorders coupled with Episensor FBA ES-T accelerometers) has been installed in the municipal area of La Salle.

As shown in Figure 2, the network was deployed to encompass regions inside the fan with different thickness, as indicated by seismic and gravimetric profiles, and one velocimetric station (used as the reference site in the following) was installed on outcropping rocks composed by arenaceous micaceous carbonic phylladic schists with antracite’s levels, in the area of Fenetre.
Figure 1. Geological setting of the area of La Salle. The reference site of Fenetre is also shown in the map.

Figure 2. Position of the two seismic profiles (orange thick lines) and the temporary seismic network stations. In red are represented the velocimetric stations and in blue the accelerometric ones.
3. HVRS and RSM results

From May to September 2005, more than 40 low energy seismic events ($2 < M_l < 3.5$) and some regional events have been recorded by the seismic temporary network installed in La Salle. All events were recognized and located by RSNI seismic network (Regional Seismic network of North-western Italy) managed by Dip.Te.Ris., University of Genoa (see Table I). Among micro-earthquakes showing an acceptable SNR (signal to noise ratio), records were selected focusing on:
- epicentral distance $< 60$ km;
- magnitude $> 2.5$.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Depth</th>
<th>$M_l$</th>
<th>Ipocentral coordination</th>
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Using all local events selected for each station, RSM (Reference Site Method) [Borcherdt, 1970; Parolai, 2004] and HVSR techniques were applied. For what concerns RSM method, it is important to underline that a good seismic response estimation is generally obtained if the distance between each station and the reference site is small if compared to epicentral distance of selected events. Moreover, no site effects must be present at the reference site. Being installed on outcropping schists, Lsv5 (figure 3) was used as a reference station.

RSM and HVSR techniques were also applied to regional events recorded by velocimetric stations in order to better investigate seismic response at low frequencies.

The HVSR results from all accelerometric and velocimetric stations, as reported in Figure 3, do no show particular amplification effect. Nevertheless the application of RSM techniques points out different seismic response between the reference station and the other ones located on the fan. In particular it is evident, as reported in Figure 4, that the stations installed on the alluvial fan (Lsa2, Lsv4, Lsa4, Lsv6), near La Salle village, show relevant site amplification effects in a wide frequency range starting from about 1 Hz.

The RSM results indicate that the seismic signal recorded in the alluvial fan is clearly amplified with respect to the reference station and the amplification level of the peaks at frequencies greater than 1 Hz increases from Lsv1 station towards Lsv6 station. The seismic response of the fan, as indicated by RSM technique application, seems to be dominated by a wide amplification band in which several amplification peaks appear for the frequencies 2, 4-5, 7-8 Hz.
Figure 3. HVSR results; mean value of the HVSR curves (red line) and $\pm 1\sigma$ area (in grey) computed considering the best quality data (local and regional events) for four representative sites. The accelerometric station Lsa4 and the velocimetric station Lsv4 are located at the same site and are characterized by very similar HVSR curves. Similar results have been obtained for Lsa2 accelerometric station.

Figure 4. RSM results; mean value of the RSM curves (red line) and $\pm 1\sigma$ area (grey) computed averaging NS and EW component, considering the best quality data (local and regional) and taking Lsv5 as reference site. The local seismic amplification, indicated by RSM technique application for the fan, is also investigated through the computation of response spectra and amplification factors.

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Taking into account the high quality recordings, response spectra (5% damping) and amplification factors ($F_a$), defined as the ratio between the acceleration spectrum intensity at the site and the acceleration spectrum intensity at the reference station (Lsv5) computed between different period ranges, have been estimated for each station. The mean $F_a$ values, obtained processing local and regional events, increases from Lsv1 to Lsv6 as reported in table II. The main amplification effects are bounded at period lower than 1s.
Table II: Fa values, obtained processing local and regional events and averaging the results, for each component of Lsv1, Lsv4 and Lsv6 stations. The reference acceleration spectrum intensity is computed at Lsv5 station (see text for detail).

<table>
<thead>
<tr>
<th>component</th>
<th>Z 0.1s ≤ T ≤ 0.5s</th>
<th>Fa 0.1s ≤ T ≤ 0.5s</th>
<th>Fa 0.1s ≤ T ≤ 1.0s</th>
<th>Fa 0.1s ≤ T ≤ 2.5s</th>
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<td>Lsv1/Lsv5</td>
<td>1.47 2.09 1.51</td>
<td>1.58 2.07 1.53</td>
<td>1.60 2.08 1.56</td>
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<tr>
<td>Lsv4/Lsv5</td>
<td>2.52 2.76 2.25</td>
<td>2.41 2.56 2.16</td>
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<tr>
<td>Lsv6/Lsv5</td>
<td>3.24 4.22 3.55</td>
<td>3.00 4.15 3.50</td>
<td>2.89 4.13 3.52</td>
<td></td>
</tr>
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</table>

Preliminary numerical studies for the interpretation of these experimental results and for their correlation with the geomorphologic and geotechnical characteristic of the alluvial fan will be shown in the sequel. It is worth noting now the increase of the amplification level of the peaks at frequencies greater than 4 Hz from the Lsv1 station, close to the lateral edge of the fan, towards the Lsv6 station where the fan presumably approaches its maximum thickness.

4. 2D numerical simulation

In this section the salient characteristics and results of 2D numerical analyses performed on a transverse cross-section of La Salle fluvial fan are presented. A schematic 2D profile of the fluvial fan is derived both from a hybrid seismic survey carried out in the municipal area of La Salle at the end of 2005, and from a geotechnical survey performed in 1989 (6 deep boreholes with N_{SPT} values). As regards the bedrock formation underlying the fluvial fan, the hybrid seismic survey revealed a simple geometry, which can be reasonably approximated by a triangular shape (Figure 5). For this simple configuration, 2D numerical simulations of SH seismic wave propagation can be performed using the fast computation method devised by Paolucci et al. [1992] for triangular valleys. Soil-behaviour is linear visco-elastic; non-linearity is not taken into account in the analyses. The underlying bedrock formation is homogeneous and characterised by $\rho_r$ and $\beta_r$. Input signal propagates vertically towards the monitoring receivers at the surface of the model.

The geometric features of the transverse cross-section of the fluvial fan for the 2D simulations are (Figure 5): $L=1156$ m, $\alpha_1=13^\circ$ and $\alpha_2=30^\circ$. Therefore, the maximum depth of the deposit is about 190 m; 24 equally spaced receivers are positioned at the surface of the model. Location points of velocimetric and accelerometric stations of the temporary seismic network were projected on the cross-section trace to locate the position of the receivers that may best represent the actual recording sites (Figure 5).

Concerning the bedrock formation, mechanical properties were set to $\rho_r=2.7$ t/m$^3$ and $\beta_r=3000$ m/s. Turning to the fluvial fan, a density value $\rho=2$ t/m$^3$ was used, while different simulations were performed for different ranges of shear wave velocity ($\beta=700 \div 1200$ m/s) and quality factor ($Q=40 \div 120$). In Figure 6, we show the comparison of the theoretical transfer functions, for $\beta = 800$ m/s and $Q = 40$, with the average RSM results from local and regional events computed for station Lsv1, Lsv4 and Lsv6 and for the observed spectral ratios computed for two relevant earthquakes recorded by the temporary seismic network: the Ml4.7 Vallorcine-Martigny (France-Switzerland border) earthquake of September 8, 2005 (epicentral distance $R=32$ km), and the Ml2.8 La Salle event occurred on July 28, 2005 (epicentral distance $R=2$ km). The observed spectral ratios were computed in the E-W direction, taking Fenetre as reference site (see Figure 2).

The following remarks can be made from the analysis of Figure 6:
the fundamental resonance frequency of the site from numerical simulations is at 2 Hz, in good agreement with the La Salle events but at variance with the Ml4.7 event and average RSM results;

from the parametric numerical simulations, it turns out that there is no way of reducing significantly the numerical fundamental frequency to get an improved agreement with the Ml4.7, unless with an enlargement of the dimensions of the fluvial fan or a significant reduction of the shear wave velocity, that are not supported by the available data;

at the edges of the fan, the role of the fundamental resonance frequency is less important, while that of the higher modes is more relevant;

the recording stations are not aligned, and their position on the numerical cross-section has been obtained by projection, as shown in Figure 6, so that the comparison of observed vs. simulated results should not be overemphasized.

With regard to the Ml4.7 Vallorcine earthquake of 2005 September 8, a comparison between observed and predicted acceleration time histories and response spectra is presented in the following. The simulated accelerograms are computed through the inverse DFFT algorithm after a convolution procedure, in the frequency domain, between the Fourier spectrum of the E-W horizontal component recorded at Lsv5 Fenetre reference site and the numerical transfer functions at Lsv1, Lsa2, Lsa-v4 and Lsv6. To obtain acceleration time histories, the velocimetric records have previously been differentiated and resampled, if necessary, at 100 Hz. Results are plotted in Figure 7, in terms of acceleration time histories, and Figure 8, in terms of elastic acceleration response spectra.

A satisfactory agreement is found, especially for Lsa2 station, showing that, although the comparison in terms of spectral ratios may not be satisfactory enough, the response spectra tend to smoothen the fluctuations inherent to the Fourier spectra. As expected, the most remarkable difference is for the simulated response spectra at Lsa-v4 site, where, for structural periods ranging between 0.4 s and 0.7 s, the numerical response is strongly amplified at the resonance frequency of the system (2 Hz). This discrepancy can be justified looking again at Figure 6: while the simplified triangular model allows us to fit reasonably well the spectral ratios of the local events, there is no evidence of spectral amplification at 2 Hz during the Ml4.7 earthquake.

Figure 5. (Left) Schematic representation of the fluvial fan as a triangular deposit. Fluvial fan transverse profile geometry is fully described by three of the following four parameters: the total length $L$, the maximum depth $h$ and the slope of each side, $\alpha_1$ and $\alpha_2$. The deposit is assumed to be homogeneous with density $\rho$, shear wave velocity $\beta$ and quality factor $Q$. (Right) Location of the transverse cross-section of La Salle fluvial fan (orange thick line). Accelerometric (blue points) and velocimetric stations (red points) are indicated on the map, along with their projection on the trace of the cross section.
Figure 6. Comparison between numerical and experimental transfer functions. Red lines represent the RSM results for the event of MI4.7, while blue lines refer to a MI2.8 earthquake. Black lines denote numerical transfer functions. Average RSM results from local events (green lines) are also shown for station Lsv1, Lsv4 and Lsv6. Green dashed lines represent the triangular approximation of the fluvial fan cross-section.

Figure 7: Comparison between simulated (in black) and recorded (in blue) acceleration time histories for the M4.5 Vallorcine-Martigny (France-Switzerland border) earthquake of 2005 September 8.
5. Conclusions

The seismic response of La Salle fluvial fan has been analysed coupling spectral analyses on seismic records and 2D modelling techniques. Impedance contrast between the fluvial fan and the underlying bedrock is probably too small to obtain unbiased HVSR results, from which no local amplification phenomena were highlighted. However, as suggested by RSM results, amplification factor calculation and by 2D numerical simulations as well, the seismic response of the fan is characterised by relevant amplification effects, mainly for frequency greater than 1 Hz. It seems interesting to note that similar results have been obtained analysing the (smaller) alluvial fan of Torre Pellice (Piemonte, Italy) within the framework of the Sismovalp project (Cauzzi et al., 2006).

RSM results obtained from the most relevant records collected during the temporary seismic survey are found to be strongly dependent on the type of excitation, so that the frequency range in which the largest amplification levels occur is not clearly discernible.

The support of 2D numerical simulations has been useful to highlight that the fundamental resonance frequency of the fan is expected to be around 2 Hz, in reasonable agreement with the observations during the local events in La Salle, but at variance with a stronger M4.7 event.

While more complicated and detailed modelling assumptions can be adopted, assuming for example a 3D geometry for the fluvial fan deposit in order to investigate source-site azimuth dependence of the seismic response, we believe that the results presented here can be a useful starting point to address from a quantitative point of view an issue that is often disregarded in seismic hazard studies. Indeed, the amplification effects in the presence of highly consolidated fluvial fan materials, overlying a very rigid bedrock, may be relevant from an engineering point of view, because they typically occur in soils for which site amplification factors are generally not applied.
6. Acknowledgements

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7. References


