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Analysis of the local seismic hazard for the stability tests of the main bank of the Po River (northern Italy)

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ABSTRACT This paper presents the methodology and the results of the local seismic analyses, performed in the bank areas of the Po River (Lombardia and Emilia-Romagna regions, northern Italy) characterized by the highest seismic hazard and finalized for the seismic stability analyses of the banks themselves. The proposed methodology includes the following steps: collection of the pre-existing information and geologic maps; deployment of in-situ investigations by collecting soil samples for geotechnical laboratory tests; definition of the geologic-geophysical and geotechnical model; individuation of the expected seismic inputs; analyses of local seismic response. In this paper, we mainly discuss the results obtained in order to illustrate how the methodology employed enables the definition of the local seismic hazard and allows performing the future stability analyses of the banks. The results are given in term of amplification factors, expected accelerograms and acceleration response spectra modified by the litho-stratigraphic characteristics of the sites.

Key words: Po River, local seismic hazard, stability analyses, amplification factors, accelerograms.

1. Introduction

The Po is the largest and most important river of Italy; its sediments and those of its tributaries have filled a large basin located between the southern Alps and the northern Apennines, giving rise to the Po Plain (Fig. 1), the largest Italian plain, where over the centuries important economic activities, extensive and densely populated urban areas, with cultural and historical heritage of great value, developed. So the main bank of the Po is a structure considered of strategic importance for the purpose of civil defense. Although, so far even strong earthquakes in sites of high seismic activity indicated generally satisfactory behaviour of the banks, precautions taken must be greater than those for ordinary constructions, because the failure and collapse of a bank could have very serious consequences, specially if the flood may involve built-up areas. For this reason, the Po River Basin Authority (AdB Po) has received funding to evaluate the stability of the banks under seismic conditions in the municipalities characterized by the highest seismic hazard along the right side between Boretto (Reggio Emilia province) and Ro (Ferrara province).

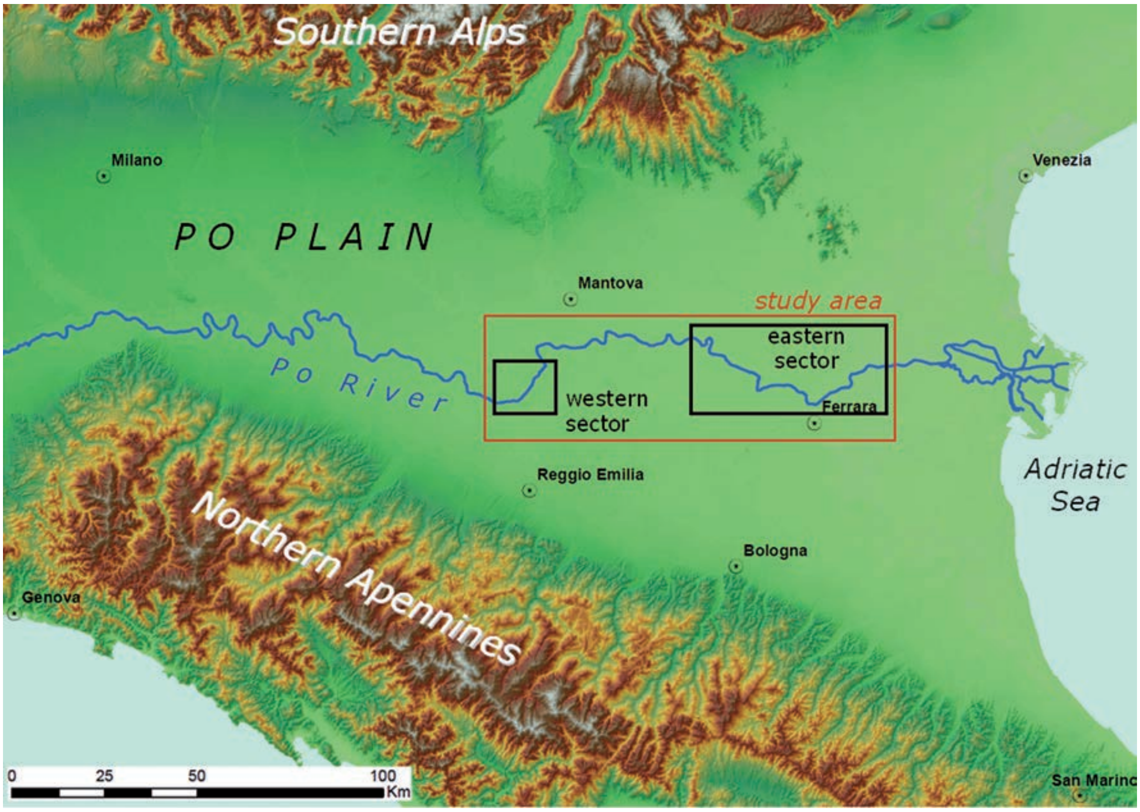

Fig. 1 - Geographic map of the location of the study area.

According to the seismic classification then in force (OPCM 3274/2003), the municipalities with the highest seismic hazard, in the tract of interest, are (Fig. 2): Boretto, Gualtieri and Guastalla (in the Reggio Emilia province), Carbonara Po, Sermide and Felonica (in the Mantova province), Bondeno, Ferrara and Ro (in the Ferrara province).

The linear development of the embankment subjected to seismic verification is about 90 km.

To carry out this study the AdB Po has formalized an agreement with the Interregional Authority for the Po River (AIPO) and the Regional Governments (Emilia-Romagna and Lombardia). The feasible project entrusts the coordination of activities to assess seismic hazard at the sites to the Geological, Seismic and Soil Survey of Emilia-Romagna Region (SGSS). The adopted procedure is derived from a previous study for the verification of stability under seismic conditions of the flood expansion areas of some tributaries of the Po in Lombardia and Emilia-Romagna

(Compagnoni *et al.*, 2010; Pergalani, 2010; Pergalani *et al.*, 2013). This study was carried out by a working group of geologists, geophysicists and engineers of Milan Polytechnic - DIS (PoliMI), Florence University - DICeA and SGSS, Siena University (DST-UniSI), under the coordination of the AdB Po.

In this project, to define the local seismic hazard, seismo-tectonic investigations, geological, geophysical, geotechnical and numerical analyses were carried out in the following phases and activities:

- definition of the geological and geophysical models (by the SGSS);
- definition of the input motions (by the INGV-BO, CNR-IDPA and Siena University);
- definition of geotechnical parameters through laboratory analysis (activities coordinated by AIPO, performed at the geotechnical laboratories of AIPO, Parma University, Milan University and Turin Polytechnic);
- analyses of the local seismic response, in term of expected amplification (PoliMI and Ferrara University).

The results of this study, just concluded, will be the basis for the definition of seismic stability analyses of the main bank of the Po River, which will be performed by the Bologna University - DICAM and the Florence University - DICeA.

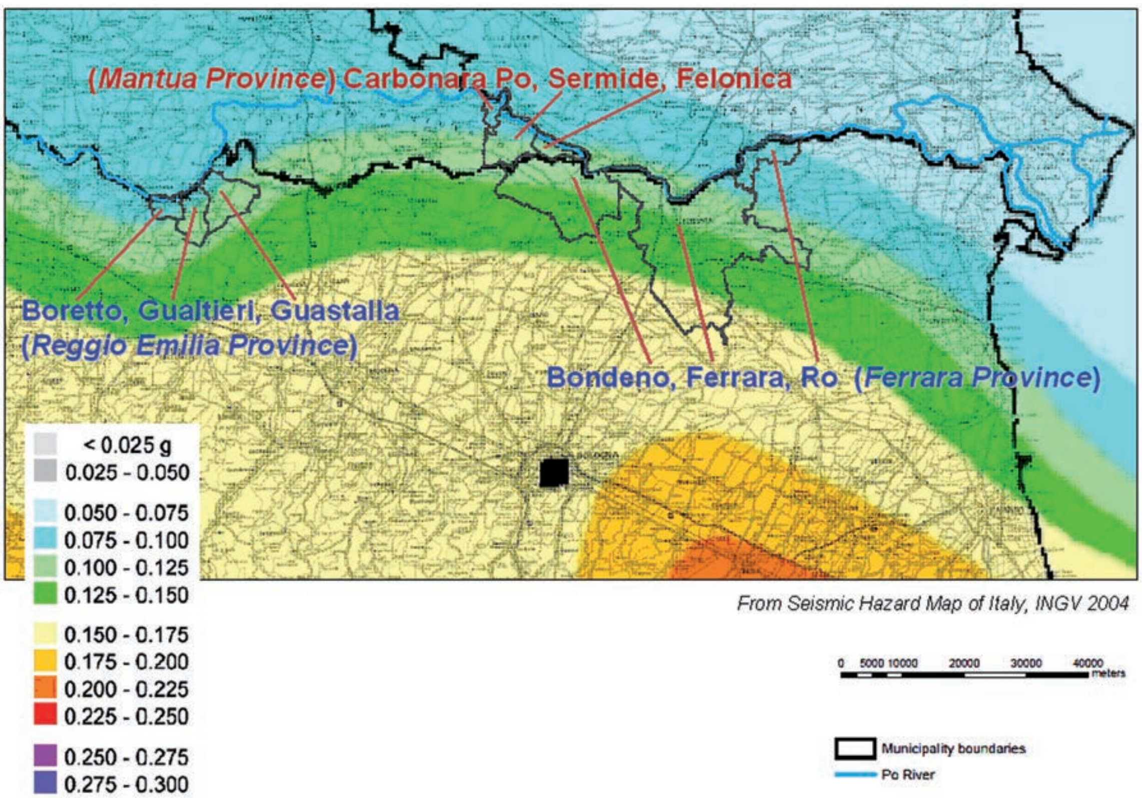

Fig. 2 - Seismic hazard map in term of expected maximum acceleration (a_{max}) considering a return period of 475 years (from Gruppo di Lavoro, 2004) of the study area with location of the interested municipalities.

2. Definition of the geological and geophysical model

2.1. Methods

To optimize resources and time and for a better planning of new investigations, the first step was the collection and critical analysis of available data.

Hundreds of stratigraphic logs have been collected and organized into a georeferred database (GIS). The sources of these data are especially water wells and cone penetration tests (CPTs); logs from continuous core drillings have been found in the Emilia-Romagna municipalities only.

In the area, deep bore-holes and seismic profiles for oil and gas research are also available.

Therefore, it was possible to hypothesize a geological model both for the bear and the deep subsurface.

Based on the collected data, new in situ tests have been planned to define in detail the internal characteristics of the bank and the stratigraphy of substratum. Hundreds of new tests (several tens of continuous core drillings at various depth, more than 300 CPTU and 30 SCPT up to 30 - 35 m depth, 3 seismic profiles with MASW and ReMi tests, tens of electrical resistivity surveys) were carried out according to a regular mesh consisting of regularly spaced transects.

In the continuous core drillings tens of samples for laboratory analyses have been collected, Down-Hole (DH) tests (more than 30 up to 30 m depth from the top of the bank and 10 up to 50 m from the base of the bank) have been performed and 40 piezometers, to monitor the groundwater, have been installed. Also groups of deepest bore-holes have been drilled, to carry out 3 Cross-Hole (CH) up to a depth of almost 150 m and 2 CH up to a depth of about 75 m.

To define the fundamental frequencies of the deposits and of the bank hundreds of ambient vibrations records have been carried out (by DST-UniSI) by using the HVSR approach (Nakamura, 1989). This monitoring has been carried out at 321 sites regularly spaced all along the study area. At each site, single-station measures on the top and at the base of the bank where carried out by following experimental standards defined in the frame of the SESAME project (SESAME European project, 2005) by also following Picozzi *et al.* (2005) and Albarello *et al.* (2011). This kind of survey allows to identify presence of resonance phenomena potentially responsible for local amplification of local ground motion and to constrain depth of main seismic impedance contrasts responsible for such phenomenon. Along the profile, array ambient vibration measurements were also carried on at two sites along the Po River (at the basis of the banks). These data were processed by using the ESAC procedure (see Okada, 2003) to retrieve apparent Rayleigh waves dispersion curve (Tokimatsu, 1997). In order to estimate the *Vs* velocity profile at depth, the approach described in Albarello *et al.* (2011) was considered. This approach is based on the joint inversion of apparent dispersion curves and HVSR measurements constrained by data provided for shallower layers by bore-hole measurements. At 4 further sites, HVSR results were inverted by considering locally available DH data as a constrain for the *Vs* values up to 30 - 50 m of depth. As a whole, 6 *Vs* profiles reaching more than 150 m of depth were determined.

To synthesize all data and to describe the lithostratigraphic features, more than 100 geologic cross-sections, carried out along significant transects based on geological characteristics, vulnerability conditions and urban exposure, have been drawn.

2.2. Stratigraphy

The lithostratigraphy of the bank and its substratum can be synthesized as described below (Fig. 3). The embankment, whose height varies from 5 m in the west at about 10 m in the east, is characterized by alternations of thin layers of dense materials ranging from sand and clayey silt, sometimes with scattered bricks. Due to a strong analogy between artificial materials and natural sediments, in the absence of certain artificial elements (bricks), sometimes it is very difficult to identify the base of the levee.

The substratum of the embankment is frequently made by a horizon of variable thickness of alternations of sandy silt and fine and very fine sand of natural levee environment, with presence of layers, of various thickness (ranging from centimetres to decimetres), of sand and clay loam. In some cases, the substratum consists of clayey and silty deposits of floodplain environment; in this case, levels of peat and organic material are frequent. The passage between natural levee and floodplain facies is often interfingered.

In the river side fines sediments, from clay to silty sand, and sandy facies are predominant.

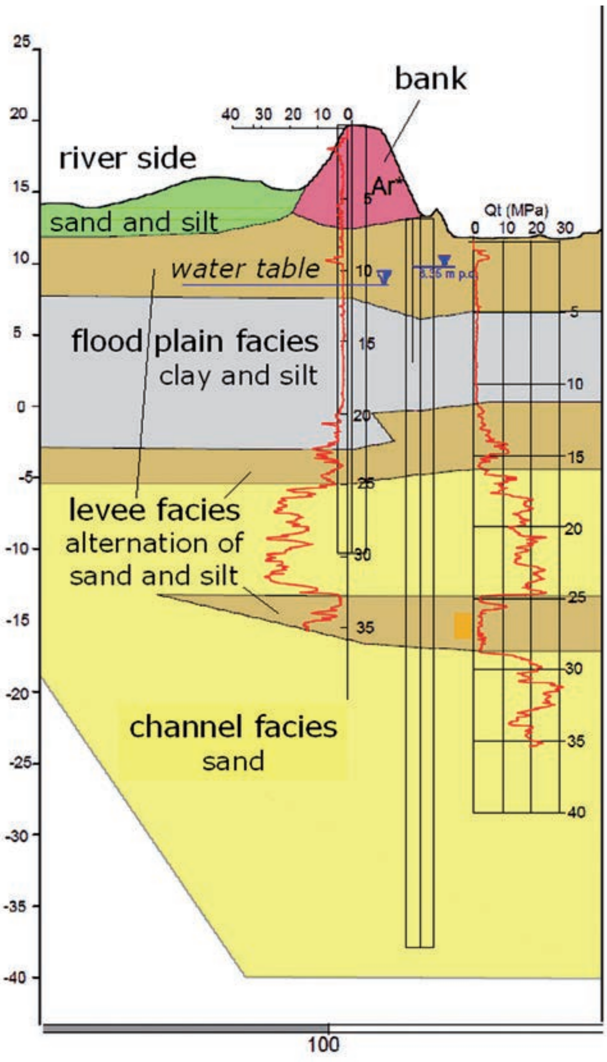

Fig. 3 - Synthetic litostratigraphy of the bank substratum; in the figure the values of the CPTU are reported.

The sequence continues downwards with prevailing sands attributed to a river channel environment. These sands vary from medium-fine to coarse and very coarse, with local presence, in the western sector, of pebble. The thickness of this sandy horizon is generally of 20-30 m, sometimes higher. This horizon is an important aquifer generally confined; sometimes, close to the bank and in the river side, this sandy horizon is in contact with the phreatic aquifer.

Tests on samples of organic material collected during drilling have been provided ages ranging from about 1490 years BP in the floodplain deposits 15 m deep and age of 26100 BP for a sandy horizon 30 m deep.

The substratum of the alluvial succession, made by Lower Quaternary marine sands, is very deep, more than 500 m, in the western sector (Reggio Emilia province, Fig. 4) and rise toward east where is at depth of about 110 - 120 m in the Bondeno - Ferrara west area (Fig. 5) (RER - ENI, 1998). In this area, Miocene marls have been drilled from depth of 130 m. This rising of the substratum is due to the presence of a buried thrusts and folds ridge named Ferrara Folds (Pieri and Groppi, 1981).

Others important stratigraphic unconformities are also present within the alluvial succession, corresponding to boundary between alluvial cycles (RER - ENI, 1998; Lombardia - ENI, 2002; Ferrara province - RER, 2007).

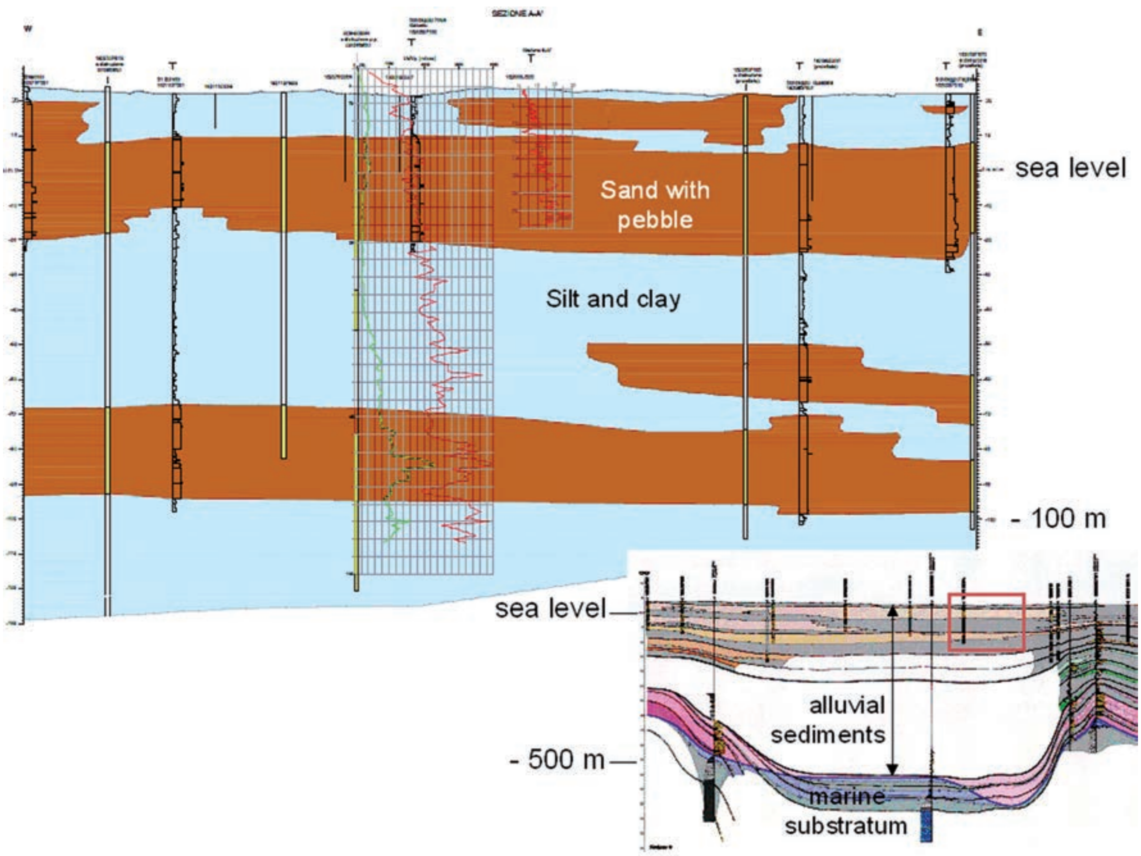

Fig. 4 - Geological model of the western sector; in the figure the values of the bore-hole, CH and CPT are reported.

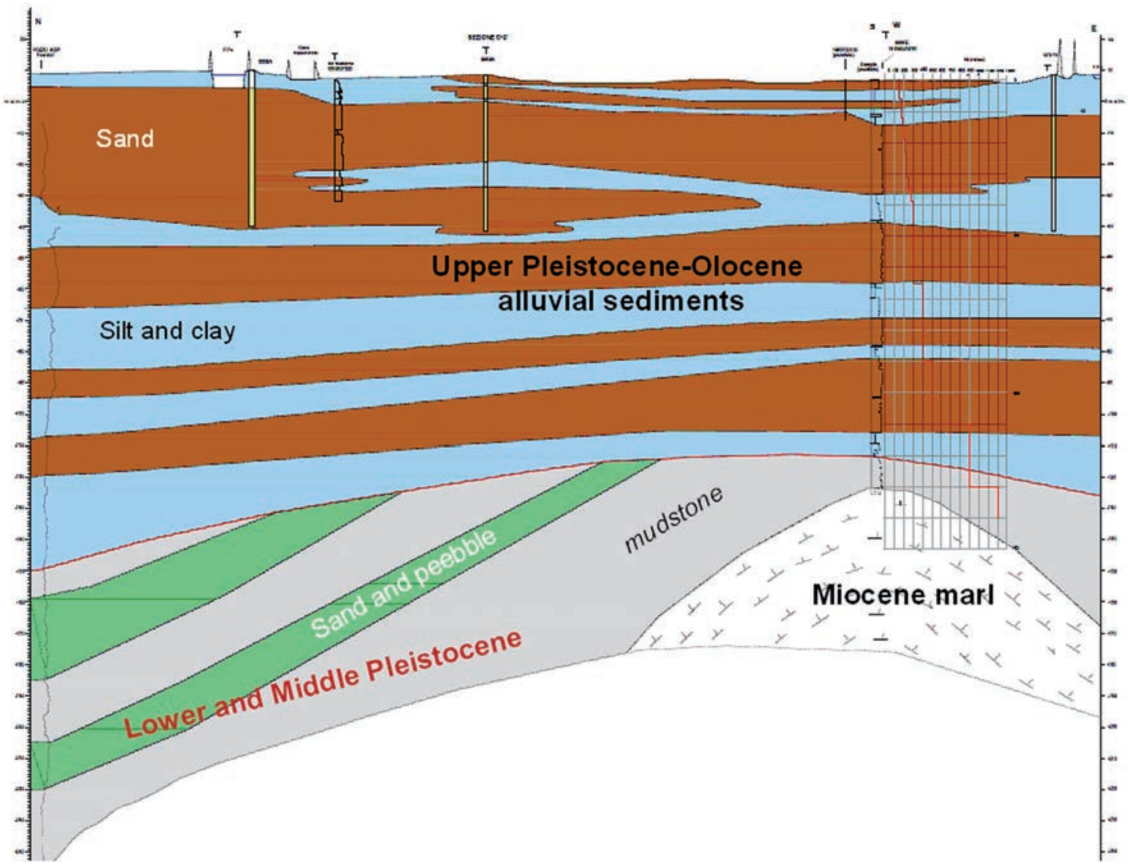

Fig. 5 - Geological model of the Ferrara area; in the figure the values of the bore-hole, CH and CPT are reported.

2.3. V_S and seismic bedrock

For the analysis of local seismic response we also tried to define profiles of V_S and to identify the seismic bedrock.

SCPT and DH tests indicate low values of V_S, about 200 - 250 m/s, sometimes even < 200 m/s, in the upper fine deposits. V_S values increase in the sands below where reach, and sometimes exceed, 350 - 400 m/s.

The deep CH tests indicate that V_S remain relatively low up to depth of about 80 m in the Boretto-Gualtieri area (western sector) and up to depth of about 120 m in the Bondeno - Ferrara area (eastern sector); from these depths V_S increases rapidly and exceeds 800 m/s.

Processing of single-station ambient-vibration measurements indicates presence of resonance peaks at relatively low frequencies, in the whole area: in the range 0.65 - 0.7 Hz in the westernmost sector (Reggio Emilia area) and in the range 0.8 - 1.0 Hz in remaining areas. Peaks at frequencies much higher, between 5 and 11 Hz have been also observed locally.

In the Mantova province and in the east Ferrara area, also peaks at very low frequencies, between 0.2 and 0.5 Hz, have been observed. These peaks at very low frequencies are less pronounced than the previous ones but are persistent and tend to shift to higher frequencies approaching Bondeno and disappear in the Ferrara area.

These peaks are indicative of seismic impedance contrasts at various depths. Given the values of V_S and the lithostratigraphic succession of these areas, the frequency peaks around 0.65 to 0.7 Hz in the Reggio Emilia area and those around 0.8 to 1.0 Hz in the Ferrara province are compatible with impedance contrasts at depths indicatively between 100 and 150 m while the peaks at lower frequencies (0.2 - 0.5 Hz) may be due to the impedance contrasts at depths of hundreds of metres.

The results of ambient vibration tests are consistent with those of the other geophysical tests and the stratigraphy. In fact, the comparison with the available stratigraphic data (RER - ENI, 1998; Lombardia - ENI, 2002; Ferrara province - RER, 2007) indicates that the observed impedance contrasts can correspond to the known main stratigraphic unconformities.

In the Reggio Emilia area the seismic bedrock has been identified with the lithologic boundary between fine sediments and a sandy body tens of metres thick at a depth of 80 m, corresponding to the top unconformity of the last Middle Pleistocene alluvial cycle (Fig. 4).

In the Bondeno and Ferrara area, where the buried Ferrara ridge reaches the maximum altitude, the seismic bedrock has been identified with the base of the alluvial sediments at the depth of 120 m (Fig. 5). In this area the H/V peaks also show the maximum amplitude.

In the Mantova province and to the east of Ferrara, areas located on the northern slope of the buried Ferrara ridge, the seismic bedrock is at greater depths and has been identified with the base of the last Middle Pleistocene alluvial cycle at a depth of 160 m.

3. Definition of the input motions

The definition of expected input motion was performed by considering seismic hazard estimates at four sites considered as representative to the different parts of the area under study: Guastalla, Sermide, Ferrara and Bondeno. The definition of the input motion has been performed in two steps. First of all reference spectra have been determined at each site from a probabilistic analysis, then 6 measured accelerograms (spectrum-compatible) have been selected and considered as possible input motions.

Two different probabilistic approaches for seismic hazard estimates were considered on purpose. The first one is the standard Cornell-McGuire approach in the implementation adopted for the compilation of the national seismic hazard map of Italy (Stucchi *et al.*, 2011). In particular, results provided by Stucchi *et al.* (2011) and available in the WEB (http://esse1.mi.ingv.it/) for reference soil configuration [soil A by following the Norme Tecniche per le Costruzioni (NTC, 2008)] have been considered to determine *PSA* values corresponding to an exceedance probability of 5% in 50 years for a 5% value of damping.

Since most of significant earthquakes occurred in the area in historical time (see, e.g., CPTI Working group, 2004) and no instrumental registration is available, a second probabilistic approach was also considered which was developed to evaluate seismic hazard from macroseismic information (Albarello and Mucciarelli, 2002). In particular, the implementation provided by D'Amico and Albarello (2008) and the dataset provided by Stucchi *et al.* (2007) were considered to determine the reference macroseismic intensity (i.e, the intensity characterized by and exceedance probability of 5% in 50 years) at the sites of concern. Then, the deaggregation procedure provided by Albarello (2012) was applied to identify the magnitudedistance pairs most representative for the local hazard. These pairs were considered to retrieve an expected reference response spectrum at the sites of concern by using empirical attenuation relationships provided by Ambraseys *et al*. (2005). To provide conservative estimates, expected value at each ordinate was increased by +1 standard deviation.

In this way, at each site two reference response spectra were determined and used to retrieve spectrum-compatible observed accelerograms to be used as input motions for local seismic response evaluations.

To this purpose, for each possible *j-th* accelerogram in the European Accelerometric Database (Ambraseys *et al*., 2004), a misfit value δ_j has been considered in the form:

$$\delta_j = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Sa_j(T_i) - Sa_t(T_i)}{Sa_t(T_i)}\right)^2} \tag{1}$$

where N is the number of spectral ordinates considered for each accelerogram in the range 0.1 - 2.0 s:

$$Sa_j(T_i) = \frac{PSA_j(T_i)}{PGA_j} \tag{2}$$

is the ordinate of the response spectrum of the *j-th* accelerogram for the *i-th* period T_i [$PSA_j(T_i)$] normalized to the respective PGA value and:

$$Sa_t(T_i) = \frac{PSA_t(T_i)}{PGA_t} \tag{3}$$

is the ordinate of the reference response spectrum at the site of interest as deduced form the hazard map for the *i-th* period T [$PSA_t(T_i)$] normalized to the respective PGA value.

In this way, by considering accelerograms characterized by the least d_j values, two sets of 6 accelerograms were obtained at each site in correspondence of the two hazard analyses performed. To provide most conservative evaluations, the set characterized by larger ground motions was determined at each site and used as input motion for following analyses. In this way, input motion for Ferrara and Bondeno was provided by macroseismc hazard estimates while the

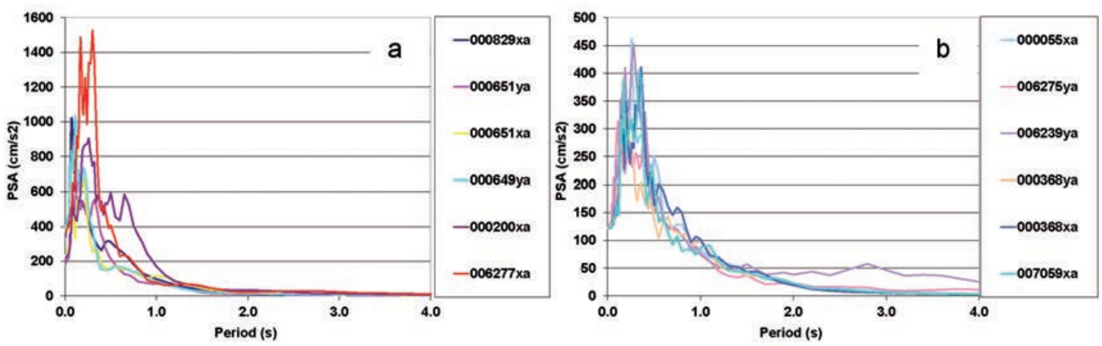

Fig. 6 - Acceleration response spectra for the macro-area of Ferrara (a), macroseismic hazard, and for the macro-area of Guastalla (b), standard hazard.

standard hazard estimates were used to determine the input motion for the remaining sites.

As an example in Fig. 6 the acceleration response spectra for the macro-area of Ferrara (a - macroseismic hazard) and for the macro-area of Guastalla (b - standard hazard) are reported.

4. Analyses of the local seismic response

The analyses of the local seismic response have been performed through the following steps.

The first step has been the analyses of the geologic, geophysical and geotechnical data for each macro-area, finalized to the individuation of the simplify stratigraphic sequences, located at the base of the banks, considering all the geologic cross-sections. In particular, the geologic analyses have pointed out that the sequences have been characterized by the material of the embankment (Ar) and 3 geologic units: A - sands, B - silts and sands and C - clays. So, for each geologic cross-sections, the relative stratigraphic sequence has been identified and the geologic cross-sections characterized by similar stratigraphic sequences have been grouped.

The second step has been the comparison between the results of the different geophysical investigations (DH, CH, MASW, REMI, SCPTU) to obtain the values of the shear waves velocities (V_S) for each geologic unit representative of the stratigraphic sequences and the individuation of the typical seismo-stratigraphic sequences. In Fig. 7, as an example, the geophysical investigation for the macro-area Guastalla are reported and in Fig. 8 the seismo-stratigraphic sequences (P1 - P14) for the same macro-area are plotted, showing for each sequence the correspondent numbers of the grouped geologic cross-sections, the number of the DH or SCPTU, the different geologic units, their thickness and the values of the V_S.

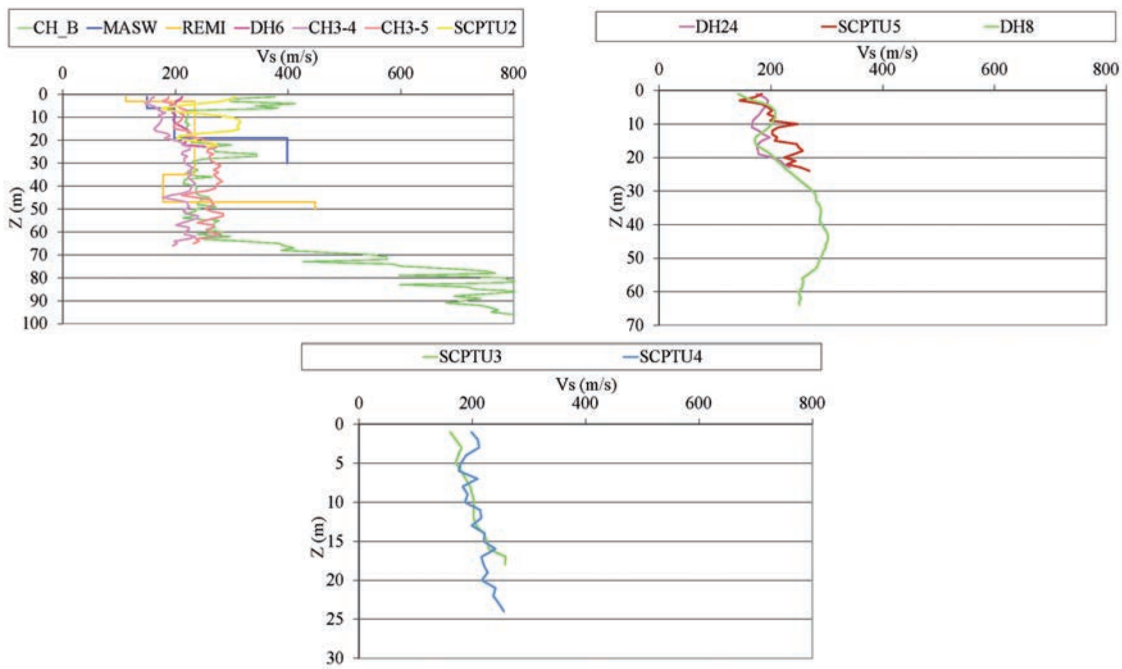

Fig. 7 - Geophysical investigations for the macro-area Guastalla.

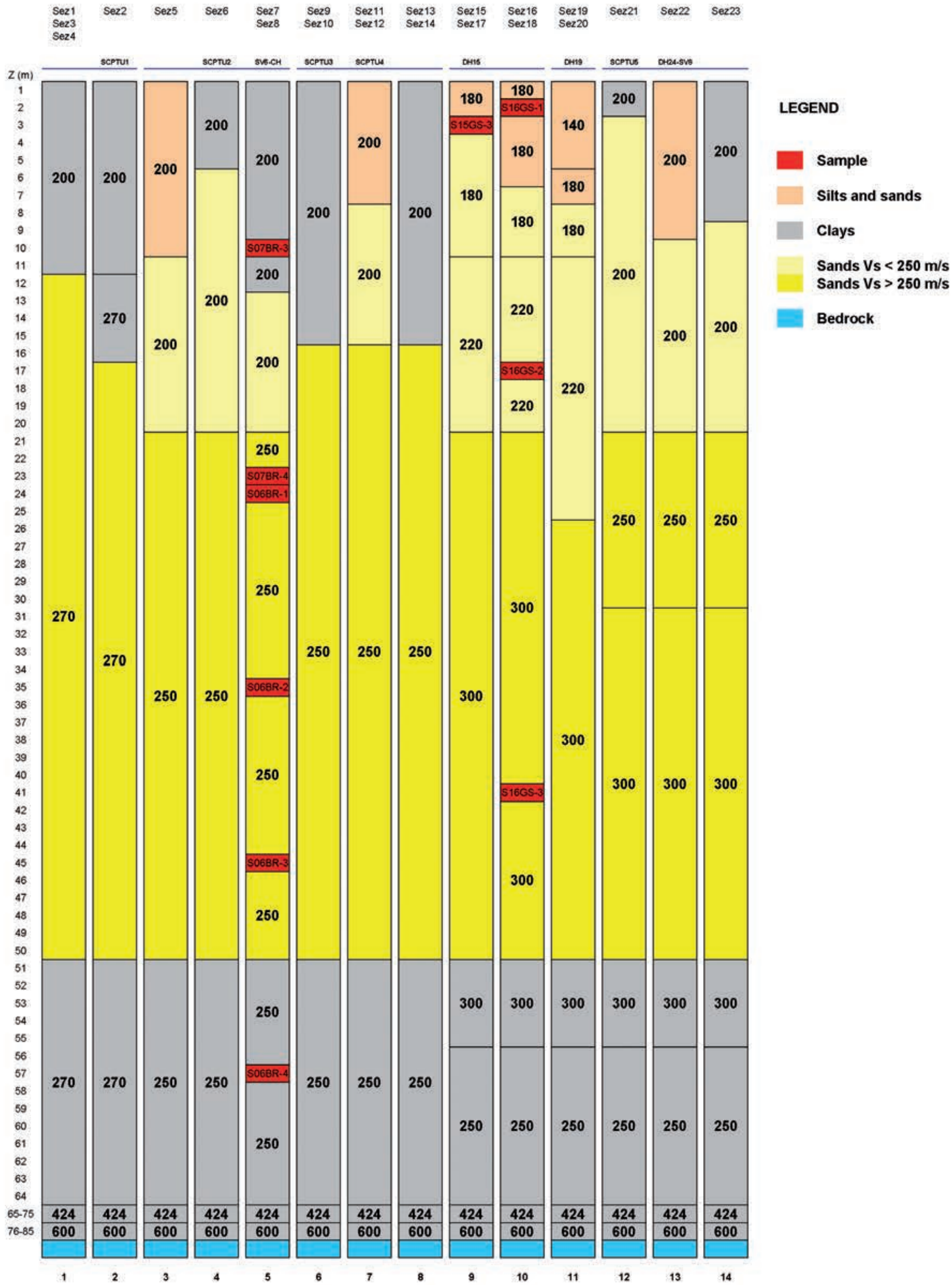

Fig. 8 - Seismo-stratigraphic sequences for the macro-area Guastalla: the thickness of each layer is given on the left (m), and the shear wave velocity values are given on each layer of the column (m/s).

The third step has been the choice of the static and dynamic parameters for each geologic unit, particularly the unit weight, the initial damping ratio (D_0) and the decay curves of the shear modulus (G) and damping ratio (D) with the shear strain (g), finalized to the numerical analyses.

The values of the unit weight were obtained by the geotechnical tests performed on the samples: as an example for the macro-area Guastalla, to the geologic unit B (silts and sands) and C (clays) the values between 17.0 - 18.0 kN/m^3 have been applied, for depth less than 20 m; to the geologic unit A (sands) the value of 18.0 kN/m^3, for the sands with V_S < 250 m/s, and the value of 19.0 kN/m^3, for the sands with V_S > 250 m/s, have been applied; to the geologic unit C the values of 20.0 kN/m^3 for depth between 50 - 75 m and 21.0 kN/m^3 for depth between 75 - 85 m have been used; finally the values of 22.0 kN/m^3 have been associated to depth more than 85 m.

D_0 and the decay curves of G and D with g have been collected using the dynamic laboratory tests as resonant column performed on samples, in Fig. 9 the decay cures have been plotted (macro-area Guastalla).

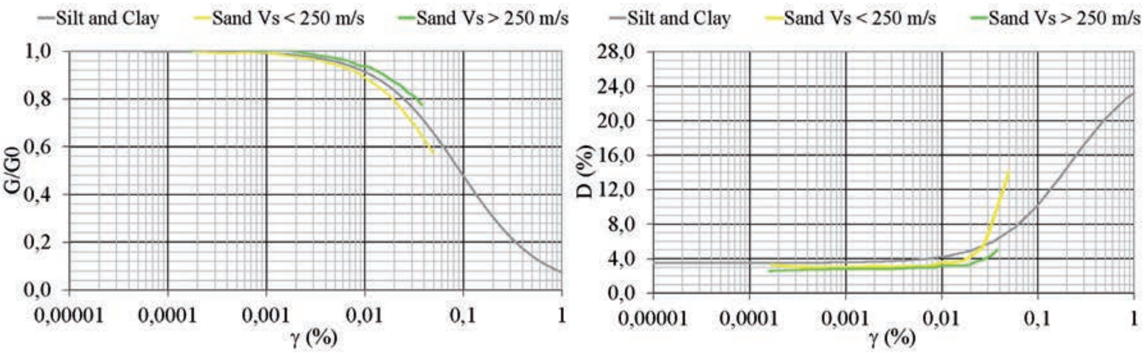

Fig. 9 - Decay curves for the different geologic units: behaviour of the G/G_0 and D curves with the shear strain.

The numerical analyses, for each typical seismo-stratigraphic sequence, have been performed using a one-dimensional (1D) numerical code. In the code the soil profile is idealized as a system of homogeneous, visco-elastic sub-layers of infinite horizontal extent. The response of this system is calculated considering vertically propagating shear waves. The bedrock is considered deformable, to avoid the energy of reflection waves into the model, in fact a rigid layer reflects all the reflected waves from the surface, whereas in the case of the deformable layer, the waves are spread into the bedrock. The code adopts the equivalent linear analysis using an iterative procedure to obtain, in each iteration, the characteristics of the soil compatible with the effective strain in each layer. Therefore, the process is iterative and the code works in the frequency domain, using the Fourier analysis.

In each seismo-stratigraphic sequence the 6 accelerograms, assigned for each macro-area, have been applied and the results have been given in term of average amplification factors (*Fa* and *FH*)and average acceleration response spectra at 5% of the critical damping; particularly the amplification factors have been defined as the ratio between the spectral intensities (*si*) of the output and input motions, calculated from the pseudo-velocity (*PSV*) and pseudo-acceleration (*PSA*) response spectra, in the period ranges 0.1 - 0.5 s and 0.5 - 1.5 s (Pergalani *et al.*, 1999):

$$Fa_{0.1\text{-}0.5} = \frac{si_{0.1\text{-}0.5}\,(PSV\text{output})}{si_{0.1\text{-}0.5}\,(PSV\text{input})} \qquad Fa_{0.5\text{-}1.5} = \frac{si_{0.5\text{-}1.5}\,(PSV\text{output})}{si_{0.5\text{-}1.5}\,(PSV\text{input})}$$

$$FH_{0.1\text{-}0.5} = \frac{si_{0.1\text{-}0.5}\,(PSA\text{output})}{si_{0.1\text{-}0.5}\,(PSA\text{input})} \qquad FH_{0.5\text{-}1.5} = \frac{si_{0.5\text{-}1.5}\,(PSA\text{output})}{si_{0.5\text{-}1.5}\,(PSA\text{input})} \qquad (4)$$

In Table 1, for the macro-area Guastalla, the values of the *Fa* and *FH* are reported, and in Fig. 10 the average acceleration response spectra for each stratigraphic sequence are plotted.

Table 1 -Value of the amplification factors (*Fa* and *FH*) for the analyzed 14 seismo-stratigraphic sequences.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
$Fa_{0.1\text{-}0.5}$	1.8	1.8	1.5	1.5	1.5	1.7	1.6	1.7	1.8	1.7	1.8	1.5	1.4	1.4
$Fa_{0.5\text{-}1.5}$	2.1	2.1	2.1	2.1	2.1	2.0	2.0	2.0	2.2	2.1	2.3	2.2	2.2	2.2
$FH_{0.1\text{-}0.5}$	1.7	1.7	1.4	1.4	1.4	1.6	1.5	1.6	1.7	1.6	1.7	1.5	1.3	1.3
$FH_{0.5\text{-}1.5}$	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.9	2.1	2.1	2.2	2.1	2.1	2.1

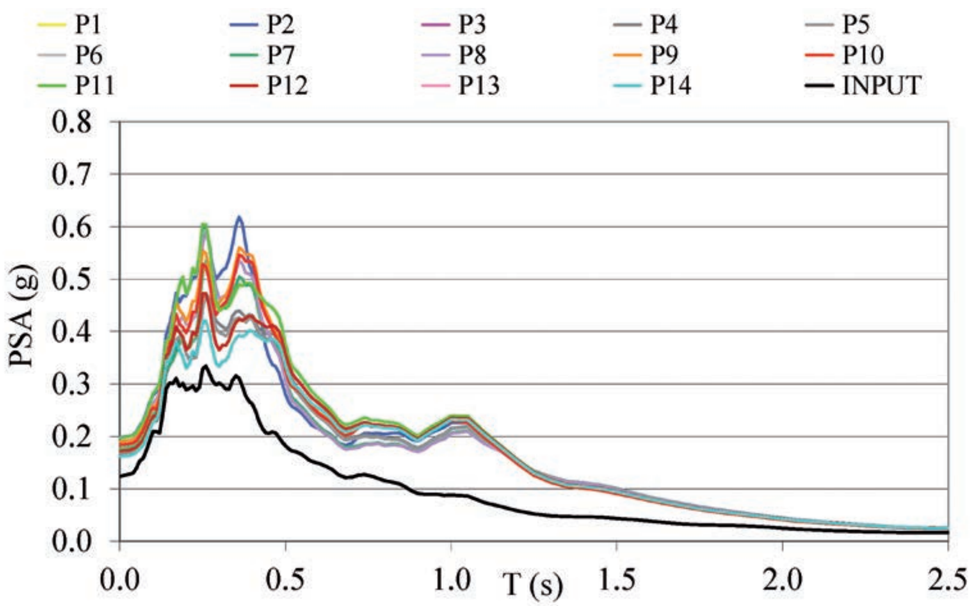

Fig. 10 - Curves of the average acceleration response spectra for the analyzed 14 seismo-stratigraphic sequences.

Starting from these values and analyzing the obtained average acceleration response spectra for each stratigraphic sequence, the different sequences are grouped considering the similar behaviour. In Fig. 11 the grouped average acceleration response spectra were plotted: as shown, the 14 sequences have been grouped in 3 groups.

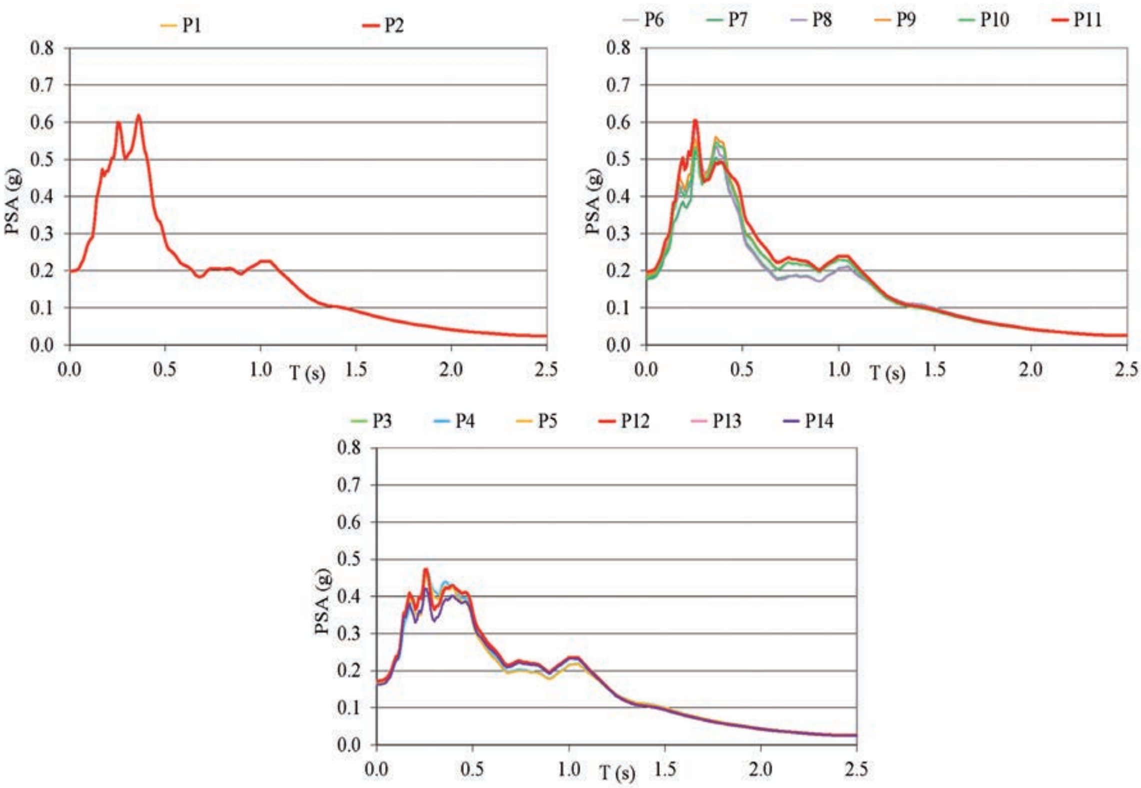

Fig. 11 - Curves of the average acceleration response spectra, grouped in 3 groups.

For each group, an acceleration response spectrum has been chosen as representative and the results, in term of 6 amplified accelerograms, their representative parameters and values of *Fa* and *FH*, have been associated to the correspondent geologic cross-sections. These data will be used as input motions for the stability analyses of the banks.

5. Conclusions

The aim of the paper was pointing out a methodology for the evaluation of the local seismic analyses, finalized to the stability analyses of the bank areas of the Po River (Lombardia and Emilia-Romagna regions, northern Italy) in the lack of a specific national code.

The proposed methodology included the following steps: collection of the pre-existing information and geologic maps; deployment of in-situ investigations by including the collection of soil samples for geotechnical laboratory tests; definition of the geologic-geophysical and geotechnical model; individuation of the expected seismic inputs; analyses of local seismic response.

Particularly, in this paper, we discussed the evaluation of the seismic hazard, considering two approaches: macroseismic hazard and probabilistic hazard. The two approaches provided different results: the most conservative evaluations (i.e., the set characterized by larger ground motions) was finally considered as input motion for the numerical analyses.

The results are given in term of amplification factors, expected accelerograms and acceleration response spectra modified by the litho-stratigraphic characteristics of the sites. These outcomes will be used for the evaluation of the stability analyses, under dynamic condition, of the bank areas of the Po River. The results show the presence of amplification, particularly considering the high period range (0.5 - 1.5 s) due to the characteristic of the litho-stratigraphic sequences.

The high reliability of the results obtained by the project was the result of the large amount of data and processing procedures actually considered and points out the necessity to have, in this kind of analyses, a multidisciplinary approach.

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