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CRITERIA FOR A SEISMIC MICROZONING OF A LARGE AREA IN CENTRAL ITALY

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SUMMARY

The earthquake of 26 September 1997 in central Italy is one of the largest seismic events of the last 20 years in Italy. Two main events caused significant damage in a large area of Umbria and Marche Regions and site amplification phenomena were recorded even at large distances from the epicenter. After the emergency period, a detailed study of the surface effects was necessary for the post earthquake reconstruction, but in the way it should be carried out rapidly enough to allow urban planners to give instructions and codes to public administrators. Team of surveyors were trained to collect field information such as geologic and geomorphologic features and, where possible, pre-existing geotechnic or geophysic information. Such an amount of information was collected and analyzed with the aid of dynamic codes to calculate possible local site effects. A one-dimensional code, analyzing single soil columns, SHAKE [14], as well as two-dimensional codes working with finite or boundary elements, QUAD4 [9] and BESOIL [13], were used and the results are presented as response spectra or amplification coefficients.

INTRODUCTION

After the Umbria-Marche (Central Italy) Ms 5.9 Earthquake of 26 September 1997 the Italian Government decided that the amplification due to local effects had to be taken into account in repair and reconstruction.

A working group, formed by researchers of the Servizio Sismico Nazionale (SSN) and the Istituto di Ricerca sul Rischio Sismico-Consiglio Nazionale delle Ricerche (IRRS-CNR), has been charged to define a procedure able to give the needed information on about 1000 villages in six months. The working group was also charged of the guide of the activity.

Under this constraints the working group decided the following procedure [11]:

1. selection of 60 sample villages: the criterion was selecting them among those showing the highest degree of damage and representative of the main geologic and geomorphologic features of the area struck by earthquake, in view of the extrapolation of the results to the entire area;
2. collection of the basic geologic, geomorphologic and geotechnic data;
3. field surveys, which implied a geologic and geomorphologic survey at a detailed scale (1:5,000);
4. definition of the seismic input for the numerical analysis;
5. computation of site amplifications through one-dimensional and two-dimensional soil modeling, by finite and boundary elements methods;
6. definition of a set of standard local effect situations and of a table giving the values of the amplification factor for each situation.

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THE UMBRIA- MARCHE SEISMIC SEQUENCE

The seismic sequence started in the Umbria-Marche Apennine on September 4th 1997 with a ML 4.4 earthquake located near the village of Colfiorito, close to the boundary between Marche and Umbria Regions. Several aftershocks with magnitude lower than 4 followed in the subsequent weeks. On September 26th at 00.33 GMT, an earthquake Ms 5.5 occurred with epicenter located between the villages of Cesi and Colfiorito. It was followed straight after by a stronger earthquake at 9.40 GMT (Ms 5.9; Mw 6.0), which represents the largest earthquake of the entire seismic sequence and caused damages as large as IX in the MCS macroseismic intensity scale. The epicenter was located north of the previous one, between the villages of Colfiorito and Annifo. Few minutes later a third shock occurred (ML 4.7) located more northward. Strong ground motion accelerographs of the National Electric Company, recorded peak ground accelerations as high as 0.5 g at the village of Nocera Umbra in both the main earthquakes. In the following weeks the seismic activity was very high with more than 2,000 shocks since September 26th to October 11th with about 20 earthquakes exceeding magnitude 4 until to October 14th.

It is interesting to point out the migration of the seismic activity during the entire sequence. Until to October 12th, the seismic activity, which was initially concentrated in the northern part of the area, migrated in the southern part, between the villages of Sellano and Preci, where on October 14th, at 15.23 GMT an earthquake of Ms 5.5 occurred. Finally, on March and April 1998, two earthquakes larger than 5 in magnitude, occurred more than 20 Km northward of the first sequence. This jumping-like activity seems to highlight the activation of several interconnected faults rather than a single segment of a main seismogenic structure.

The epicentral distribution of the first two sequences shows a NW-SE trend for a total length of about 30 Km. Fault plane solutions, computed by CMT method, indicate a dip-slip mechanism along a primary plane NW-SE, with a T axis oriented NE-SW. The depth of the foci shows a concentration between 4 and 8 Km, increasing westward.

These directions are in good agreement with the structural framework of the area, represented by a conjugate system of normal faults oriented along the axis of the Apennine. The repeated earthquakes gave cumulative effects: the final estimated maximum intensity was as high as IX-X in the MCS scale. This peculiar seismic sequence caused the collapse of several buildings and the severe damage to many of them, also because the high vulnerability of old masonry buildings. Despite the amount of damage fortunately only 11 people died, 126 injured, but the homeless were more than 25,000. The estimated monetary losses were more than 2 billion of dollars.

The seismic sequence occurred in a zone that is one of the most active in Italy [1,12]. Seismicity rates are as high as 0.5 events per year above magnitude 4, while maximum expected magnitudes are as high as 6.5. Analyses carried out taking into account elapsed time since the last destructive earthquakes of the area (renewal processes [12]) highlight that the study area was likely to produce peak ground accelerations as high as 0.2 g since january 1997 in the following 30 years.

GEOLOGIC OVERVIEW AND SAMPLE AREAS SELECTION

The investigated area is located in Central Apennines, across the Umbria-Marche regional boundary. The Umbria-Marche sedimentary sequence, composed of limestones, marly limestones, marls and flysch sequences represent the stratigraphy of the study area.

The central Apennines are made up of several tectonic units put straight since the Oligocene as a result of convergence and collision between the continental margins of the Corsica-Sardinia block and the Adriatic block [2]. The main compressive phase started in the Tortonian and the lack of Pliocene-Pleistocene marine deposits proves that after the Miocene the area was definitively uplifted. The compressive structures were dissected by normal faults during the Quaternary, and, according to the most recent studies [3,10], these are related to the crustal thinning processes occurring in the Tyrrhenian Tuscan area. The Quaternary normal faults led to the formation of intramountain basins, of which the Colfiorito plain is a clear example, and the seismicity of the area is mainly related to the activity of these faults.

The geomorphologic setting is characterized by a general conformity between structural-lithologic elements and morphologies. High relief zones are found in correspondence with the calcareous ridges and hilly and smooth areas correspond to the flysch deposits, in the zone of Nocera Umbra and Camerino. Even the drainage network is influenced by the structural pattern and the main drainage lines are located along the trace of the main faults and fractures. Climatic factors, especially the last glacial and interglacial period, influenced the landscape evolution and the deposition type. Stratified periglacial slope waste deposits, mainly formed by Scaglia Rossa and Maiolica cobbles, occur extensively on calcareous slopes [4,5,6]. The alluvial terraces also refer to the glacial periods; they are placed at different levels over the valley bottom and are often interbedded with slope deposits; three main levels are found in the area but the number can vary according to local conditions.

Lacustrine deposits are found in correspondence of intramountain basins; they can reach thickness of 100 m and are formed by more or less regular alternances of conglomerates, clays and sands; they are dated lower-middle Pleistocene. Finally travertine deposits are widespread all over the area; they are mainly formed by spring water whose chemical content is connected to the activity of deep faults and fractures; the age of these deposits is referred to middle Pleistocene up to nowadays.

According to the geomorphologic framework of the area, three main geomorphologic features were taken into account for the site selection:

hill tops (mainly on limestones and marly limestones) ;

valley-like morphologies (formed by alluvial deposits, lacustrine deposits or slope waste deposits and travertine) ;

slopes (slope deposits, travertine or colluvial deposits).

Geologic and geotechnic data

The collection of geologic, geomorphologic and geotechnic data is fundamental for the site geology reconstruction. The survey aimed to identify the relationships between lithologic units, to map the main structural features and to estimate the thickness of surface deposits and their degree of cementation, in order to assign the proper geotechnic value. Therefore soil columns and data coming from geophysic or geotechnic site tests and geotechnic laboratory tests were always reported on forms, where available. Two-dimensional cross sections were drawn to better understand the stratigraphic and tectonic features of each site. The geomorphologic map was only aimed to represent the forms and the processes acting on the examined landscapes.

Lithotechnic map has been derived from the geologic map by grouping geologic units considered homogeneous from the phisical and mechanical point of view; the available data, coming from laboratory and geophisic tests, allowed to assign to each lithotechnic unit the geotechnic parameters needed for the dynamic analyses: the shear wave velocity; the Poisson coefficient; the soil unit weight; the initial shear modulus; the initial damping coefficient (Table 1).

Relationships between shear modulus decay and damping coefficient variation as a function of the shear strain were also assessed.

Table 1: Geotechnic parameters for the lithotechnic units (Vs shear waves velocity; ν Poisson coefficient ; γ soil unit weight ; Go shear modulus at low strain; ξ initial damping coefficient)

Surface deposits (increasing values of Vs)	**Vs (m/s)**	**ν**	**γ (kN/m3)**	**Go (MPa)**	**ξ**
Colluvial deposits	300	0.35	17.7	162	0.03
Debris	400	0.35	19.6	320	0.01
Clayey fluvial-lacustrine deposits and silty-clayey	400	0.4	19.6	320	0.04
Sandy-gravel fluvial-lacustrine deposits and sandy	400-700	0.35	19.6	320-980	0.01
Travertine (type 1-2)	550-1000	0.3	19.6	605-2000	0.02
Bedrock formations (in stratigraphic order)	**Vs (m/s)**	**ν**	**γ (kN/m3)**	**Go (MPa)**	**ξ**
Flysch deposits	1000	0.3	20.6	2100	0.005
Schlier	1000	0.3	21.6	2200	0.005
Bisciaro	1200	0.25	22.6	3312	0.005
Scaglia Cinerea (average values)	1000	0.3	21.6	2200	0.005
Scaglia Variegata	1200	0.25	22.6	3312	0.005
Scaglia Rossa	1500	0.25	23.5	5400	0.005
Marne a Fucoidi	1200	0.25	22.6	3312	0.005
Maiolica	1500	0.25	23.5	5400	0.005
Calcare Massiccio	2000	0.25	24.5	10000	0.005

SEISMIC INPUT

The seismic input for site amplification analyses has been derived from the seismic hazard studies carried out for the entire country [12]. For the definition of the seismic input a probabilistic approach has been adopted, as the area affected by the earthquakes sequence is located in a region with several dissected seismic structures, still not very well known and identified as defined seismic sources. Therefore, being impossible to separate the seismic hazard contribution coming from all possible sources to each village, the cumulative contribution, on a probabilistic basis was derived from all relevant neighboring seismogenetic areas, which better represents an envelope of the expected seismic actions.

The probabilistic approach also fits with the aim of the project that is the evaluation of a set of parameters to be entered in codes for building restoration and future building construction.

Seismic input has been defined as the uniform probability spectra with a return period of 475 years7.

The elastic pseudo-acceleration response spectra at 10% probability of being exceeded in 50 years for the 60 most damaged municipalities are calculated: they refer to rock or stiff soil conditions in free field. The maximum values of the spectral ordinates are in the range 0.45-0.75 g at a period of 0.2 s. In the analyses only the spectra labeled Gualdo Tadino, Spello and Preci have been used, applying the Gualdo Tadino spectrum for all municipalities with maximum spectral ordinates lower than 0.55 g, the Spello spectrum for all municipalities with maximum spectral ordinates between 0.55 and 0.65 g and the Preci spectrum for the municipalities with maximum spectral ordinates higher than 0.65 g. The reference spectra (Figure 1) correspond approximately to three reference earthquakes of magnitude 6 scaled in distance (about 5, 10 and 15 Km); in Figure 1 is also shown, for comparison, the elastic spectrum derived from the design spectrum for the area of the Italian code: the design spectrum has been scaled of a factor 9, accounting for the safety factor and the behavior factor.

Since most of the site amplification analyses required accelerations as reference input, non-stationary time-histories matching both the reference spectra and the peak ground accelerations have been generated and they are shown in Figure 2. Maximum peak ground accelerations have been scaled to the expected peak ground acceleration values of the three reference villages, previously calculated by hazard studies

ANALYSIS

The amplification effects were evaluated in two main steps. First hazardous situations were identified for each of the 60 villages and classified according to Table 2. As second step, a numerical analysis was performed on point sites or two-dimensional sections, crossing the inhabited areas.

The computer codes available for the analysis evaluate the entity of local site amplifications with different methods; the most suitable code was selected for every site condition.

One-dimensional analyses have been performed on soil columns using the SHAKE program [14]. The program has been designed to analyze sites approximable as horizontal infinite layers with shear waves propagating in the vertical direction. Each layer is homogeneous and isotropic with known thickness, mass, shear modulus

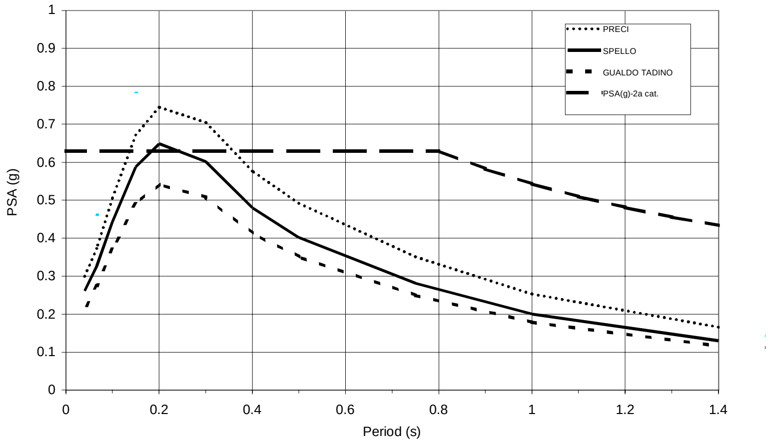

Figure 1: Selected reference spectra.

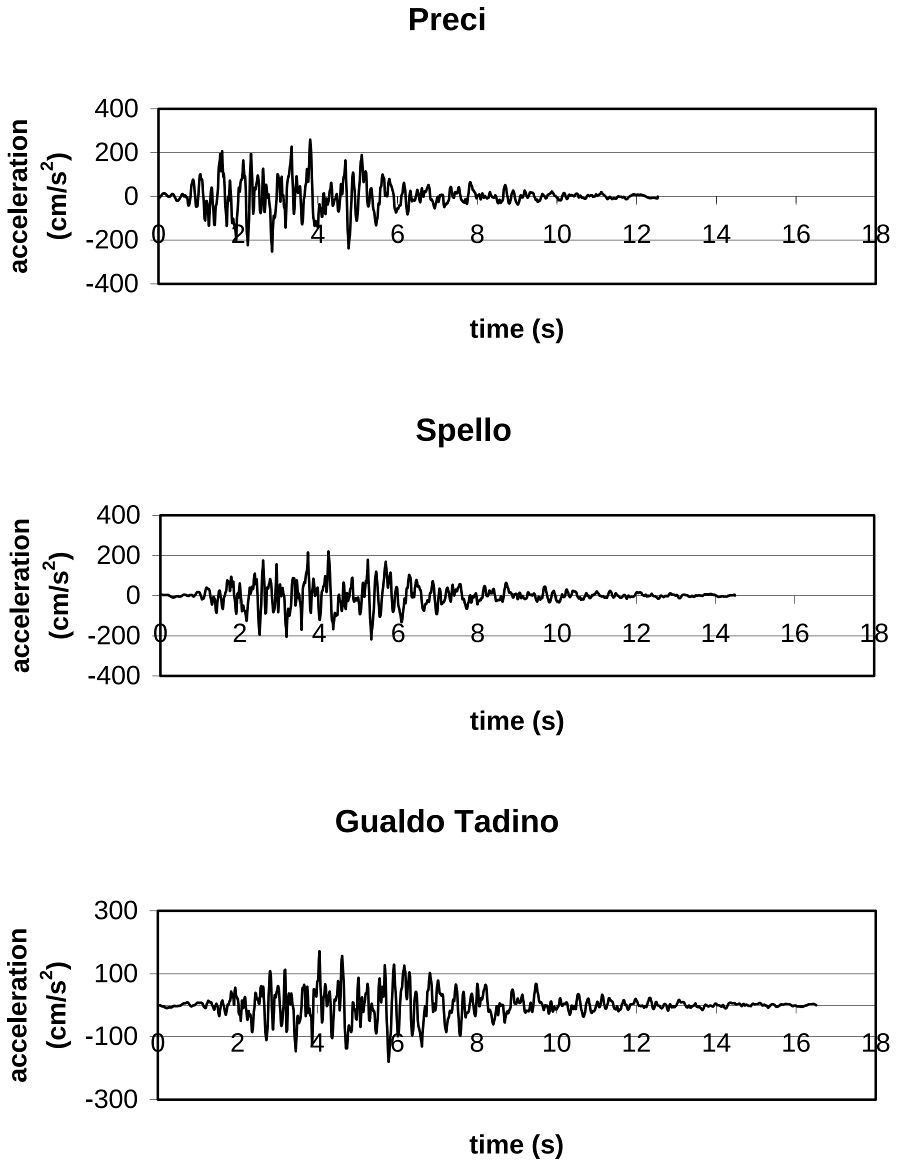

Figure 2: Non-stationary artificial time-histories accelerations generated

and damping factor, the program also incorporates non-linear soil behavior. Only few cases were analyzed: wide valleys of soft sediments, which could be well approximated by a soil column in each point.

Some of the two-dimensional cross-sections have been analyzed using the finite element program QUAD4 [9] designed to evaluate the non-linear response of soils.

The advantages of the use of the QUAD4 program [9] are the possibility of representing any two-dimensional section and the capability of analyzing the non-linear response of the soil. Therefore it was mainly used to analyze soft sediments in valley-like morphologies. Some disadvantages are the simultaneous application of the acceleration at each boundary nodal point, which does not take into account phase differences and the excess of damping given by the integration techniques, which are of approximate stable type.

Two-dimensional analyses using boundary element method has been performed through the BESOIL program [13], which allows taking into account geometrical configurations such as basins, ridges and cliffs. Any angle of incidence of the waves coming from the bedrock can be considered and both vertical and horizontal shear waves are analyzed. The disavantage is to perform only elastic analyses, so that, some assumptions on the soils' degradation are needed when non linear soil response has to be taken into account.

In particular the boundary element method has been employed when analyzing ridges and slope toe morphologies.

Table 2: Classifying table for qualitative local effect situations

Code	Type
1	Active landslide
2	***Dormant landslide***
3	Potentially unstable area
4	Soft soil (low density fills, saturated soils with abundant fine fraction)
5	Cliff with height ≥ 10m
6	Ridge area
7	Valley filled by alluvial deposits
8	Slope toe, slope debris and alluvial fan
9	Stratigraphic-tectonic contact between two lithologic units with different geotechnic characteristics

Response parameters

The soil response has been synthetically expressed in terms of elastic spectra, calculated either for soil columns, in the one-dimensional analyses, or for each nodal point on the ground surface, in the two-dimensional analyses.

The spectral intensity SI [8] has been selected to represent the seismic amplification as it relates better to structural damage than other ground motion parameters. Spectral intensity has been computed in the period range 0.1-0.5 s, which is the range of fundamental periods of most of the structures in the area:

$$\mathrm{SI(PSV)} = \int_{0.1}^{0.5} \mathrm{PSV}(\mathrm{T}, \xi)\mathrm{dT} \qquad (1)$$

where PSV are the pseudo-velocity spectral ordinates, T is the period and ξ is the damping, set to 5% of the critical damping.

The spectral intensities were computed for the following seismic motions:

SI (input), spectral intensity of each reference spectrum;

SI (output), spectral intensity of each computed amplification spectrum;

SI (code), spectral intensity of the Italian code spectrum for the second seismic category zones.

Then, three coefficients were defined on the basis of the following ratios:

$$\mathrm{Fa} = \frac{\mathrm{SI(output)}}{\mathrm{SI(input)}} \qquad (2)$$

is the amplification coefficient pertaining to local site conditions;

$$\mathrm{Fb} = \frac{\mathrm{SI(input)}}{\mathrm{SI(code)}} \qquad (3)$$

is the amplification coefficient which states the relation between seismic hazard for reference site conditions (rock or stiff soil) and the seismic protection level imposed by the Italian seismic code, for the second category zone, in absence of site amplifications;

$$\mathrm{A} = \frac{\mathrm{SI(output)}}{\mathrm{SI(code)}} = \mathrm{Fa} \cdot \mathrm{Fb} \qquad (4)$$

is the amplification coefficient, accounting for both site effects and seismic hazard variability.

To derive SI (code) a set of assumptions is needed, as the Italian seismic code only gives the design spectrum. In particular two factors should be considered: the ratio between the allowable stresses and the yield stresses, α, and the behavior factor, q. For the former an average value 2 can be assumed according to the Italian code, while for the latter the value may vary in the range 3-6 for usual buildings.

If the value 2 is assumed for the first factor and the value 4.5 for the behavior factor, the resulting Fb values are: for Preci = 1; for Spello = 0.85; for Gualdo Tadino = 0.70.
For any other value than 4.5, other Fb*'s can be calculated, keeping the constant, as:

$$\mathrm{Fb^*(q)=Fb\ (4.5/q)} \qquad (5)$$

where q is the assumed behavior factor. Therefore the coefficient Fb*(q) is only a scaling parameter depending on the level of structural ductility which is adopted.

According to the Italian seismic code (Decree of 16 January 1996 of the Ministry of Public Works), for static analysis, seismic actions are represented by a set of horizontal forces proportional to the weight, through a seismic coefficient K:

$$K = C \cdot R \cdot \varepsilon \cdot \beta \cdot \gamma \cdot I \tag{6}$$

where C is a coefficient of seismic intensity, which depends on the seismic category zone (0.07 for second category zones), that is the seismic protection level assumed by the law in absence of site amplifications; R is a response coefficient which assumes the value of 1 in the period range 0-0.8 s; ε is the “foundation coefficient”, which assumes the value of 1 for rock or stiff soil and 1.3 for loose alluvial deposits shallower than 20 meters; β, γ,I are coefficients depending on the structure typology, geometry and class of importance.

It was proposed to modify the seismic coefficient as follows:

$$K^{*} = C \cdot Fb^{*}(q) \cdot R \cdot Fa \cdot \beta \cdot \gamma \cdot I \tag{7}$$

introducing the coefficient Fb*(q) to take into account the seismic hazard given on a probabilistic basis, for reference site conditions, and substituting the foundation coefficient ε with the amplification coefficient Fa, to account for geotechnic and topographic effects.

RESULTS

After analyzing the 60 sample villages, a generalization of the stratigraphic and morphologic situations was produced, to characterize the geologic framework of the area struck by the seismic sequence. This generalization is synthesized in Table 3, where the zones of possible amplifications are grouped by morphology types (valley, ridges or slopes), lithologic units and thickness and a value of Fa is assigned to each group.

Table 3: Table of the amplification coefficients for the geologic and geomorphologic situations

Local effect situations	**Lithologic units**	**Thickness**	**Fa**
Cliff with height ≥ 10 m	Debris	< 10m	1.2
		10-20m	1.4
		20-30m	1.6
	Travertine	< 10m	1.1
		10-20m	1.3
		20-30m	1.4
Valley filled by alluvial deposits	Clayey fluvial-lacustrine deposits and silty-clayey alluvial deposits; colluvium	< 10m	1.2
		10-20m	1.5
		20-30m	1.7
	Sandy-gravel fluvial-lacustrine deposits and sandy-gravel alluvial deposits	< 10m	1.1
		10-20m	1.2
		20-30m	1.4
Slope toe, slope debris and alluvial fan		< 10m	1.2
		10-20m	1.5
		20-30m	1.7
Ridge area	Ratio height/width		Fa
	< 0.1		1.0
	0.1-0.2		1.2
	0.2-0.3		1.4
Unstable area and potentially unstable area	Investigations to evaluate the instability and to define the feasibility of interventions of stabilization		
Soft soil (low density fills, saturated soils with abundant fine fraction)	Investigations to evaluate the feasibility of interventions of consolidation		
Stratigraphic-tectonic contact between two lithologic units with different geotechnic characteristics	Investigations to evaluate the differential sinking under seismic conditions and the consequent interventions on foundations		

As Table 3 points out largest amplifications are produced by slope toe, slope debris and alluvial fan morphostratigraphic feature, generally characterized by loose deposits and by lithologic sequences with high seismic impedance contrast between bedrock and overlying soils, such as fluvial-lacustrine clays, silts and colluvium.

Superposition has been assumed between stratigraphic and morphologic effects, such as a ridge in uncemented formations: in this case the resulting amplification coefficient is the product of the coefficients of the two effects.

Hazardous situations such as landslides and potentially unstable areas, very soft soils and high seismic impedance contacts, were not evaluated as they require site specific studies. In those situations general prescription were given for further investigations and countermeasures to be adopted.

CONCLUSIONS

The procedure described in the paper provide to be a suitable tools for site effects assessment in post-event situation when time and budget constraint are present; in fact about 1000 sites have been surveyed and an estimate of possible amplification established in less than 6 months. The average cost was also relatively small: about 1,500 US $ for each site. This procedure seems to be suitable also when studying relatively large areas for land use planning purposes: fast and chip methods, even if a certain degree of approximation is inevitable, seem to be preferable in such conditions.

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