Seismic Preservation of the Cerreto di Spoleto Historical Centre

Earthquakes cause considerable damages to historical centres, so that a suitable prevention policy is necessary to guarantee their conservation. The first step is getting a complete knowledge of the area of interest and of the existing structures. In the selected areas, a detailed analysis to understand the characteristics of the seismic input through the analysis of seismic hazard and microzoning is needed, and so is the seismic performance of buildings by monitoring the seismic response. The paper presents some results of the study carried out on the site of Cerreto di Spoleto and on a complex building of its historical centre

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Introduction

Both accelerometric records and damage data testify to the significant role of local response in the distribution of seismic effects. Indeed, given similar vulnerability conditions, differences up to 2 degrees in macroseismic intensity are observed in sites few kilometers far or even inside a single inhabited area. This spatial heterogeneity can be related to local conditions, which modify seismic motion. Quantifying and mapping this phenomenon is a fundamental tool for seismic risk mitigation.

The Cerreto di Spoleto town (Central Apennines, Italy) – composed of the historical centre, located at the top of a carbonate ridge, and the Borgo Cerreto district in the adjacent Nera River valley (Fig. 1) – was selected as a test-site for investigating the local seismic response. This test-site is characterized by some geological and geomorphological features, which predispose it to seismic wave amplification: the thick alluvial deposits filling the Nera River valley, the ridge-shape of the Cerreto di Spoleto hill, the significant variations in the jointing conditions of the outcropping limestones. The choice was also supported by the presence of a local accelerometric array, owned by ENEA, which has been in operation since the late 1980s, and by the urban fabric of the village, which hosts numerous valuable historical structures, such as the City Hall, the Theater Building and the CEDRAV building, all of which were instrumented.

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Local Seismic Response: In Site Investigation and Seismometric Measurements

Test-Site and Seismometric Measurements

The Cerreto di Spoleto area has always been characterized by a local seismicity with frequent low/moderate-magnitude earthquakes, felt with macroseismic intensity (e.g., IX MCS, both the 1328 "Appennino Reatino" and the 1703 Norcia earthquakes) [1]. In recent years, an earthquake sequence characterized by a maximum magnitude Ml=5.8 began in September 1997 and induced an increase in the rate of occurrence of low-magnitude earthquakes that persisted for more than three years. The Cerreto di Spoleto ridge is a NE–SW-trending calcareous relief, with an elevation up to 650 m a.s.l. (Figs. 1, 2). The outcropping lithotypes belong to the Umbria-Marche Apennines succession and include limestones, marls and marly-limestones from upper Jurassic up to middle Miocene. In particular, the marly limestones of the Scaglia Rossa Formation (upper Cretaceous–middle Eocene) span the entire eastern portion of the ridge, where the Cerreto di Spoleto historical centre is located (Fig. 2).

A NE-SW oriented synclinal fold represents the main structural element of this portion of the ridge, which may be ascribed to an early compressive stage during the upper Miocene–lower Pliocene. The outcropping strata show an about N315 dip southward the synclinal axis and an about N135 dip northward the synclinal axis. Strike slip and normal faults dislodged this fold in a subsequent tectonic stage, which started in the upper Pliocene [2]. More in particular, two main fault systems were identified: the first, transtensional, with an approximately NS direction; the second, extensional, with an about N330 direction.

Close to the Borgo Cerreto district, the Nera River alluvial valley is characterized by a width varying from 210 to 350 m along a distance of about 1 km. The valley is primarily filled with coarse to sandy–silty alluvial deposits, while its edges are characterized by slope debris that laterally pass to the alluvial deposits. The geological substratum of the valley is composed of limestone and marly limestone, ascribable to the Umbria-Marche succession; these deposits are intensely folded and faulted. In particular, close to Borgo Cerreto the Nera River valley hosts a main thrust associated with E-verging folds and north–south trending thrust faults linked by southwest–northeast trending right strike-slip faults [3]. The geological setting of the bedrock of the Nera River valley close to Borgo Cerreto district is characterized by northwest dipping strata up to 50° in the western edge of the valley and up to 30° in the eastern edge. In the southern portion of the valley, the bedrock is set as an asymmetric anticline with axis north–south oriented, which may be ascribed to an early compressive stage during upper Miocene–lower Pliocene. In the considered area, the geographical orientation of the Nera River valley is controlled by a north–south oriented main fault, which is also responsible for a lowering of the Meso-Cenozoic Umbria-Marche pelagic succession outcropping all along the western side of the alluvial valley. This fault is part of a strike-slip and normal-fault system that dislodged the preexisting folds in an upper Pliocene tectonic stage [2]. On the basis of some collected borehole data, the alluvial deposits that fill the valley result very heterogeneous, since they consist of silty–sandy clays and sands with interlayered coarse-gained levels and travertine deposits (mainly composed of concretionary silty sands). The maximum thickness of the alluvial deposits is 55 m. The shape of the Nera River valley, in correspondence of the Borgo Cerreto district, is characterized by a constant depth and a variable width from north to south, inducing a significant variation in its depth/half width (H/D) shape ratio [4]. Moreover, the remarkable heterogeneity of the alluvial deposits induces high lateral contrasts of impedance and can strongly modify the local seismic response.

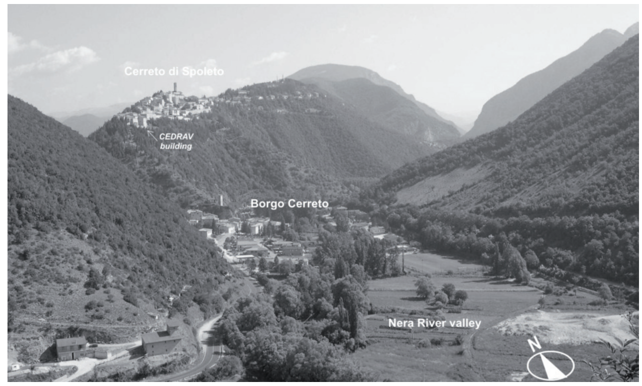

FIGURE 1 Panoramic view of the Nera River valley, close to the Cerreto di Spoleto ridge
Source: ENEA and Sapienza University of Rome

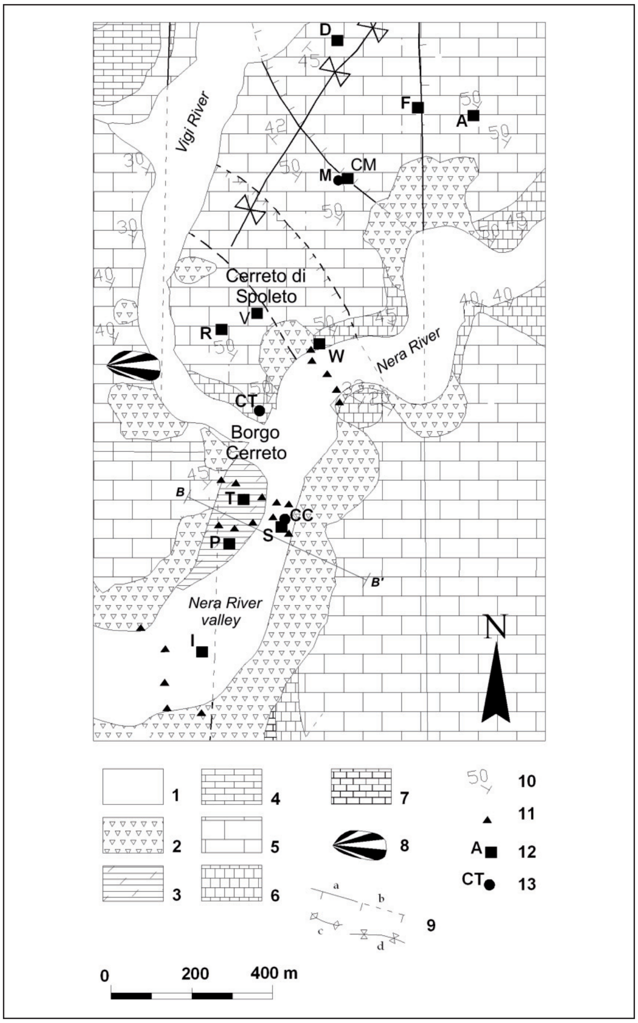

FIGURE 2 Geological map of the Cerreto di Spoleto area: 1) alluvial deposits; 2) slope debris; 3) travertine deposits; 4) Scaglia Variegata Formation (middle-upper Eocene); 5) Scaglia Rossa Formation (upper Cretaceous – middle Eocene); 6) Scaglia Bianca Formation (lower Cretaceous – middle Cretaceous); 7) Marne a Fucoidi Formation (lower Cretaceous); 8) alluvial fan; 9) certain fault (a), uncertain fault (b), anticlinal axis (c), synclinal axis (d); 10) attitude of beds; 11) noise measurements; 12) velocimetric temporary ENEA stations; 13) accelometric permanent ENEA stations
Source: ENEA and Sapienza University of Rome

In autumn 2001, a temporary velocimetric array was installed both on the ridge and in the alluvial plain. The stations (Fig. 2) were instrumented with data acquisition units (K2 KINEMETRICS), triaxially arranged short-period seismometers (SS1 KINEMETRICS) and GPS for absolute timing. A reference station (R), representative of the local outcropping bedrock, was installed at the bottom of the ridge, far from tectonic elements. The array operated for about two weeks in STA/LTA acquisition mode. Owing to the high seismic activity of the area, probably still related to the 1997 seismic sequence, about 40 small-magnitude earthquakes were recorded on the whole. Moreover, three ambient noise surveys were carried out in the Nera River alluvial valley (Fig. 2); recordings were obtained in each site by three triaxially arranged short-period seismometers, connected to a K2 data acquisition unit, and by a TROMINO recording device.

Results for the Ridge

The recorded ambient noise was sampled with a 40 s moving time window and FFT transformed to the frequency domain in order to get, for each station, the average spectra of the 3 components (NS, UP, WE) and the average Horizontal to Vertical Spectral Ratio (HVSR). The only significant effect was observed at station M, where the average HVSR points out a clear amplification band on the NS component, in the 6-8 Hz frequency range.
The recorded seismic events were analyzed in both time and frequency domains. The individual wave forms were examined in order to identify possible recurrent characteristics in the different stations. Also in this case the only significant effect was observed at station M (Fig. 3a), where most of the records show a clear wave train after the arrival of S waves, corresponding to an about 6 Hz frequency. The shape of the time-histories is typical of trapped waves [5, 6] and the delay between the disperse phase and the direct P-wave points out a deep trapping channel [7]. Subsequently, all the earthquake records were FFT transformed to the frequency domain and smoothed by a running average Hanning window. From the resulting spectral amplitudes, average spectral ratios referred to the reference station were computed for each station. Additionally, the azimuthal distribution of energy [8] on the horizontal plane was analyzed using a 10°step, both on complete and filtered signals. In

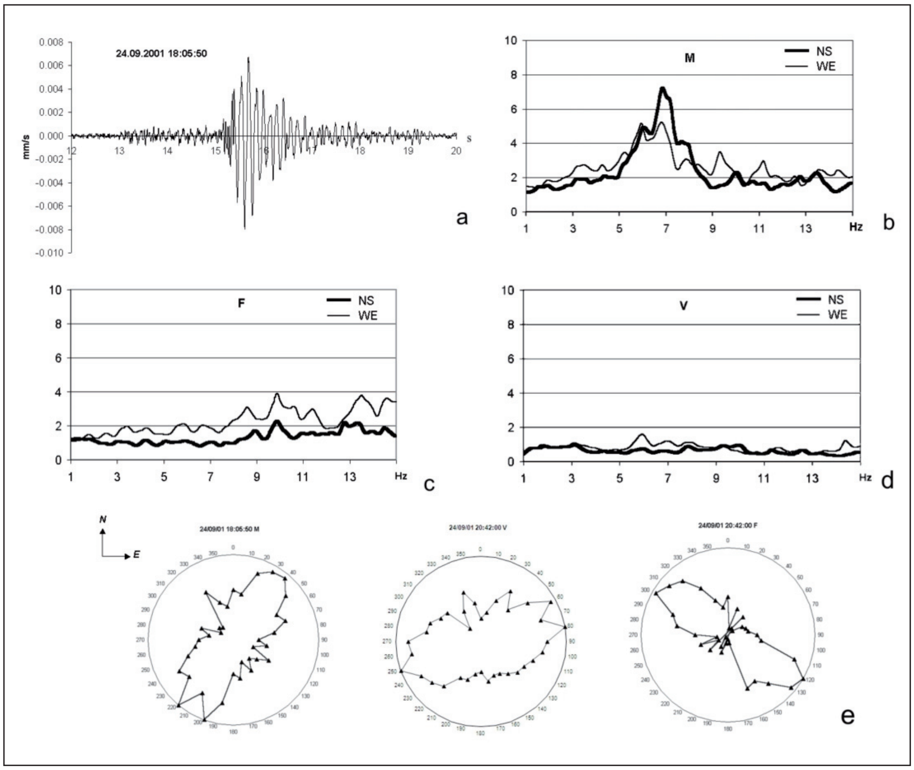

FIGURE 3 a) Example of velocimetric record obtained at station M; b) Average SSR recorded by the velocimetric array at station M; c) Average SSR recorded by the velocimetric array at station F; d) Average SSR recorded by the velocimetric array at station V; e) Examples of azimuthal distribution of energy obtained at stations M, V and F (see Fig. 2 for location) on total signals
Source: ENEA and Sapienza University of Rome

line with the results obtained from ambient noise data and time history analysis, the spectral ratios at station M exhibit a clear peak in the 6-7 Hz frequency range, significantly higher on the NS component (Fig. 3b). The azimuthal distribution of energy at station M, computed on the signals filtered in the 6-7 Hz range, points out a N20°-40°E direction for 8 out of 14 events (Fig. 3e, left). The amplification at station M can be associated with a wave train arriving after the direct S wave, with an apparent dispersive character. In general, both these features are indicative of fault-trapped waves. However, differently from the findings obtained in other studies on trapped waves [7, 9], the main direction of ground motion amplitude at station M is not parallel to the fault strike, which is about NW-SE oriented in proximity of the station.

Stations A and F show an energy distribution (Fig. 3e, right) roughly perpendicular to the direction of the ridge (NE-SW); in line with the reports by Chavez-Garcia et al. [10], and considering that these two stations are located near the top of the relief, the above findings can be ascribed to a topographic effect. The same effect is not observed at station V (Fig. 3e, middle), which is indeed located far from the top, along the western slope of the hill. Stations F, M, V are located in fault zones (Fig. 2), though neither amplification nor evidence of trapped waves are observed at stations F (Fig. 3c) and V (Fig. 3d). Since the stations are on the same outcropping geological formation and this formation is characterized by significant jointing, the assessment of rock mass condition was considered as a further feature to be taken into account. Hence, geomechanical surveys were carried out. The map of rock mass classes (Fig. 4) thus obtained shows that the contact between intensely jointed rock masses astride fault zones and moderately jointed rock masses does not appear all along the tectonic elements. In particular, station M is located on one of these contacts, whereas at stations F and V the fault zones are surrounded by a low-velocity,

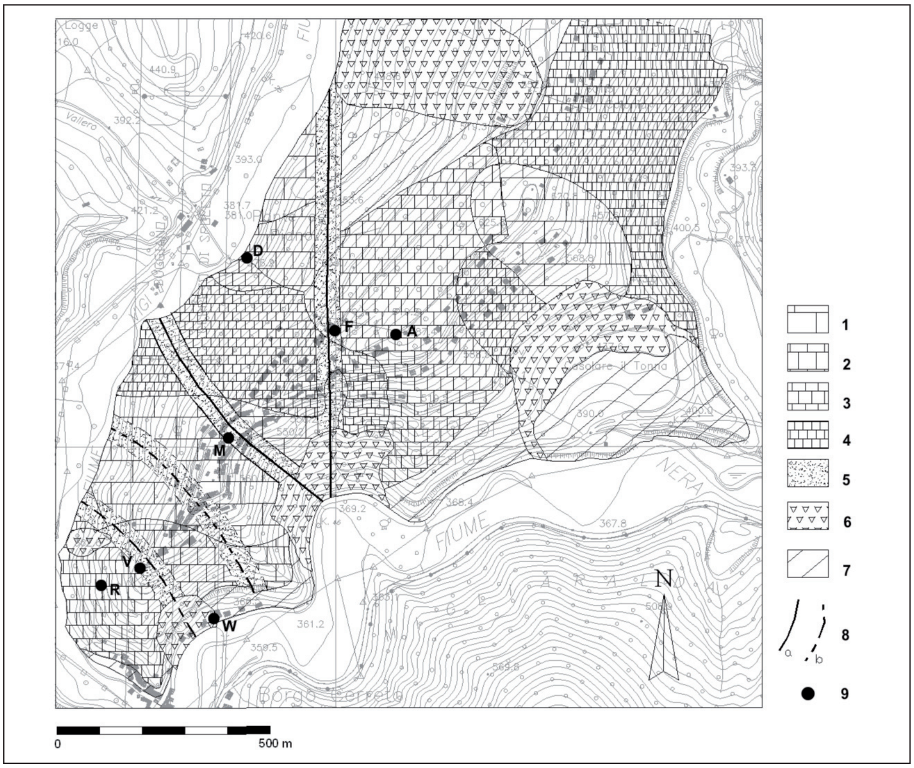

FIGURE 4 Map of rock mass classes: 1) moderately jointed rock mass (Class A); 2) highly jointed rock mass (Class B); 3) intensely jointed rock mass (Class C); 4) very intensely jointed rock mass (Class D); 5) rock mass from intensely jointed to mylonitic, lying astride each fault (Class E); 6) slope and landslide debris; 7) not classified rock mass; 8) certain (a) and uncertain (b) fault; 9) velocimetric station

Source: ENEA and Sapienza University of Rome

intensely jointed, rock mass. The high velocity contrast between the fault zone and the surrounding rock mass at station M could be assumed as responsible for the observed trapped mode and the related amplification effect, while at stations F and V the low impedance contrast at shallow depth (< 1 km) does not allow the trapped mode eventually originated at greater depth to be observed and, above all, does not induce ground motion amplification. It is worth noting that the velocimetric array was deployed in order to highlight possible topographic amplification effects along the ridge; the findings however, at least with the low energy level of the recorded ground motion, do not point out any topographic amplification. As a matter of fact, the only station of the ridge, where amplification was observed (M), does not show the energy polarization orthogonal to the ridge axis, which could be expected [10] in relation to a topographic effect and is observed in the other stations (A, F) located at the top of the ridge [11].

Results for the Alluvial Valley

Bard & Bouchon [4] showed, via numerical modelling, how both geometries and physical parameters of soft soil and bedrock control the 2D seismic amplification effects within a valley-like system. Their results proved that the higher is the shape ratio H/D (with H=maximum depth of the alluvial deposits and D=half-width of the valley), the greater are the constructive interferences between S and P waves, which are scattered by the soft soil/bedrock interface [12], and the near surface waves, which are originated by reflections and scattering phenomena at the edges of the valley. This interaction is responsible for 2D amplification phenomena, characterized by a clear resonance frequency recordable all over the alluvial fill (generally well recognizable by the HVSR obtained from noise measurements as well as by the receiver functions obtained from the weak motion records), whose value depends on SH and SV waves. When the shape ratio H/D decreases for a given impedance contrast, the constructive interference still exists, leading to wave propagation being dominated by both 1D and laterally propagating surface wave effects (i.e., 1D+lateral wave amplification). This last condition was observed in the Nera River valley close to Borgo Cerreto; the recorded seismic response is indeed characterized by a more complex spectral evidence, where both 1D resonance peak and higher frequency peaks, due to the interaction of lateral waves, can be distinguished by the spectral ratios to the reference station – SSRs (Fig. 5). The performed 2D numerical modelling [13] demonstrated that the wave amplification is close to the fundamental frequency and is increased by the contribution of the surface waves propagating throughout the entire sediment fill. It proved, moreover, that the effects due to lateral waves are much more intense close to the valley edges and assume a symmetrical distribution within the valley, if homogeneous conditions of the alluvial deposits are modelled; on the other hand, this effect loses its symmetrical distribution if a heterogeneous alluvial fill is considered (Fig. 6).

Seismic Monitoring of a Complex Building in the Historical Centre

Buildings of historical centres are usually masonry construction, often characterized by materials with very low strength, very poor mortar, ineffective connections between orthogonal walls and between the walls and the floors. The analytical study and the numerical modelling of these structures are very hard. Therefore, especially if the attention is focused on the seismic behaviour, the experimental dynamic analysis becomes of great importance and is often the only way to investigate their actual behaviour. The dynamic response of a structure can be analysed in presence of both free and forced vibrations. It is worth reminding that the use of forced vibrations is not always possible for old structures. In fact, the construction could be damaged, especially if it is in bad conditions or already damaged [14, 15, 16, 17].
As previously reported, three buildings located in the Cerreto di Spoleto historical centre were object of an experimental dynamic study. A complete analysis, as described above, was carried out on the building of

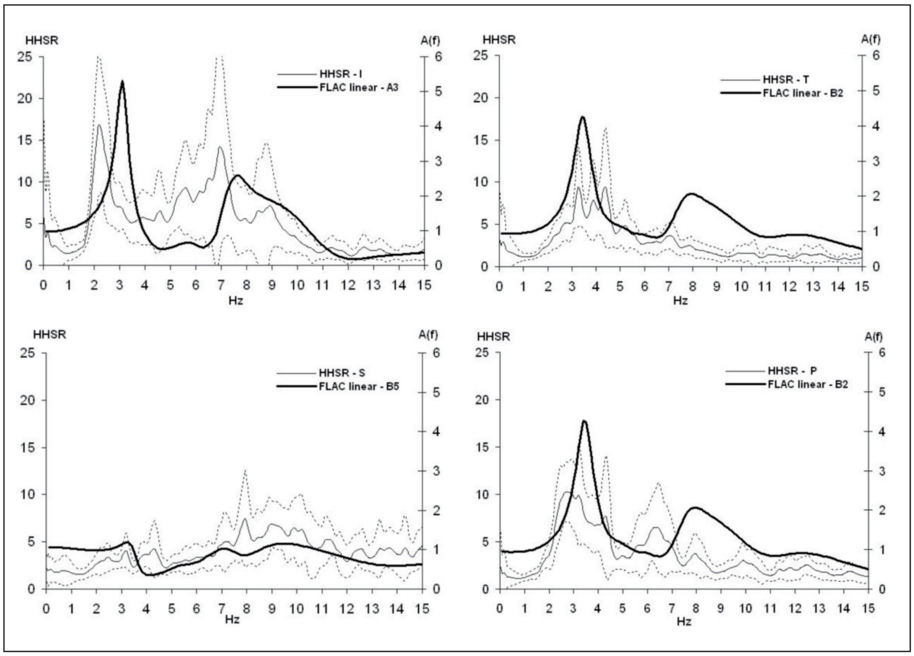

FIGURE 5 Comparison between SSRs ± standard deviation (dashed lines) from weak motions and 2D numerically modelled A(f), for the velocimetric stations I, T, S and P (see Fig.2 for location)
Source: ENEA and Sapienza University of Rome

the Centre for Anthropological Documentation and Research in Valnerina (CEDRAV).

The CEDRAV Building

The CEDRAV building, built as a monastery in the 14th century, presents a very irregular geometry both in plan and elevation (Fig. 7). The foundations are not at the same level and the first level is partially embedded into the ground and is mostly founded directly on the rock. Also the second level is partially founded on the rock, and for the N-W portion of the building the foundation is not known in detail. The main structure also includes S. James' Church. Three additional structures are connected to the main building: a small squared shape structure at the E side; a rectangular building at the N corner; another rectangular building at the W side, connected to the CEDRAV by means of a masonry arch. All these connections have a strong influence on the dynamic behaviour of the CEDRAV building. In particular, torsional modes with very low damping and possible coupling with principal modes of the buildings will be generated.

Experimental Analysis and Numerical Model

The structure was damaged by the Umbro-Marchigiano earthquakes of September 26th and October 14th, 1997. Most of the cracks were opened by the event of October 14th, because the epicentre was closest to the site and the structure had already been damaged by the previous shocks. Following these two earthquakes, the structure was first instrumented using temporary arrays in order to characterize its dynamic properties. Then a permanent accelerometer network was installed, using 36 channels. The permanent deployment recorded several seismic events in about one year [18].
Spectral analysis allowed to point out the following considerations: the building behaves like a very complex and rigid system; translational and torsional frequencies are close to one another; mode coupling occurs; damping percentage is low. Coupling of the frequencies and low damping caused beating effect even under low level shaking. The results obtained from the permanent array were very similar to those from velocimetric network. As a matter of fact, seismic

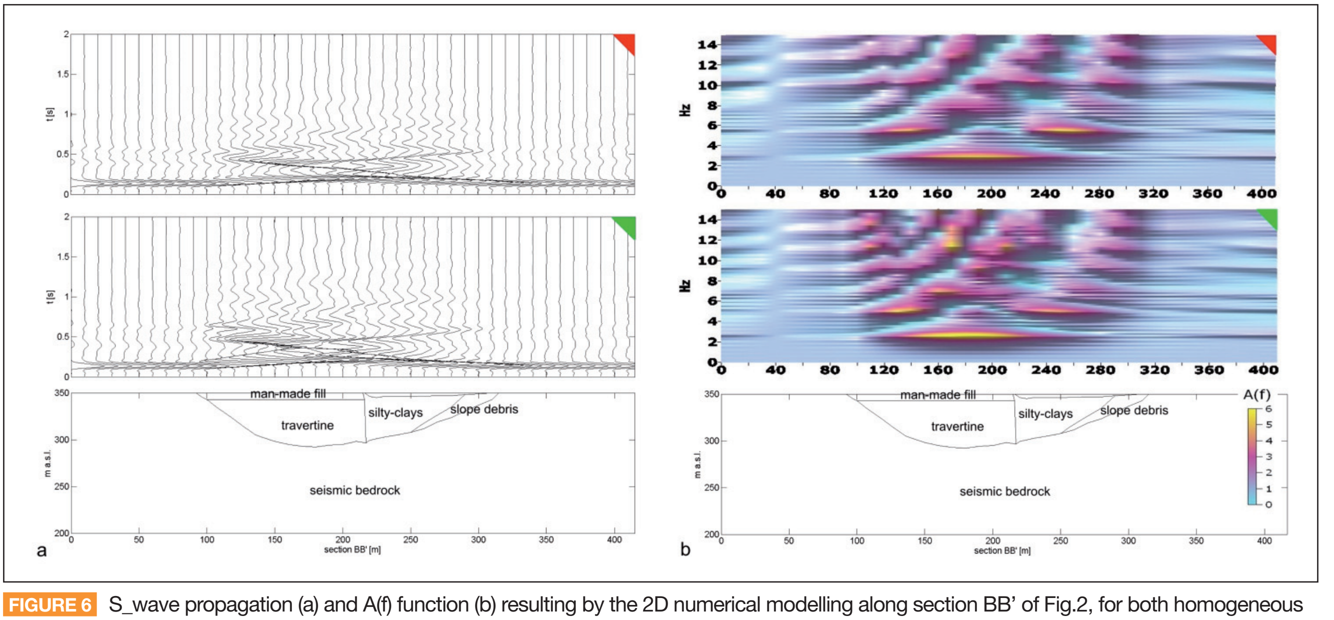

FIGURE 6 S_wave propagation (a) and A(f) function (b) resulting by the 2D numerical modelling along section BB' of Fig.2, for both homogeneous (red right corner) and heterogeneous (green right corner) conditions
Source: ENEA and Sapienza University of Rome

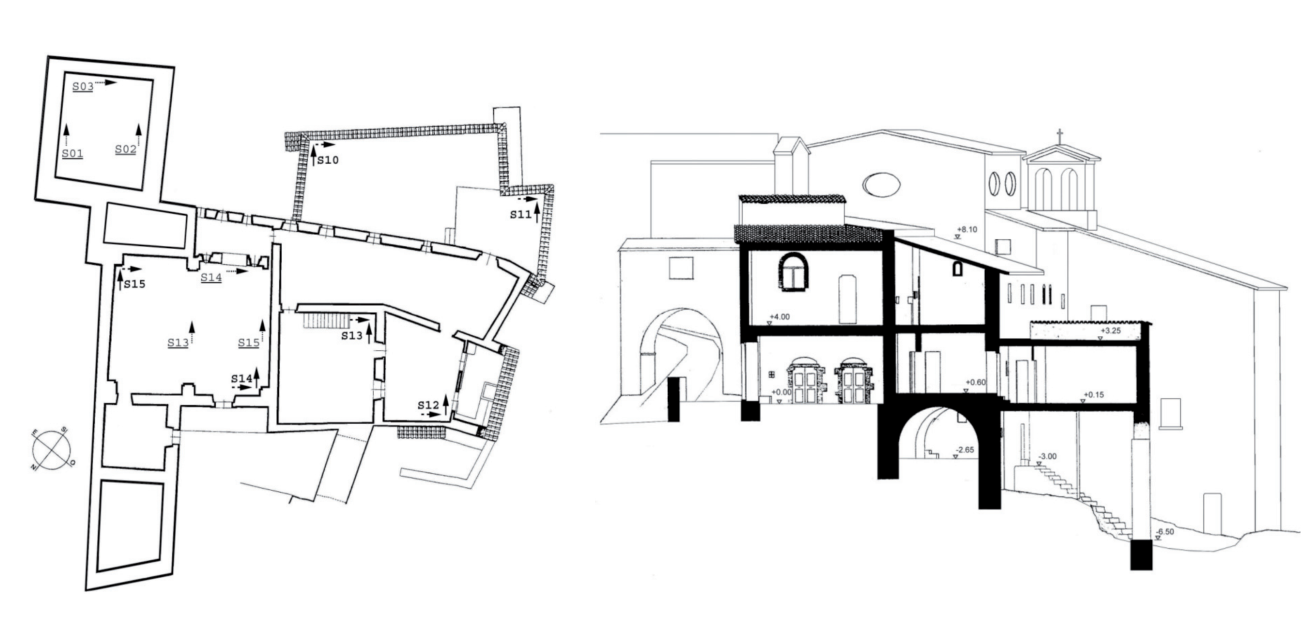

FIGURE 7 Plan and vertical section
Source: ENEA

events of almost the same intensity levels were recorded with the temporary array.

The experimental results were compared with those obtained from the finite element analysis. Due to the low energy level of the recorded events, a linear model was used, which included also the adjacent structures in order to reproduce the complex behaviour raised from the onsite measurements [19]. Walls, floors and vaults were modelled using 4-node shell elements, having both membrane and bending behaviour. The final model contained about 5100 elements and 4900 nodes, and then 27000 degrees of freedom. The structure was supposed to be constituted by a unique homogeneous and isotropic material. The Young's modulus was chosen, so that the first numerical frequency matches the first experimental frequency. In this way, we obtained a quite good correspondence between most of the numerical and experimental frequencies.

As reported in Table 1, very close frequencies were found, due to the structural complexity. The experimental data showed this behaviour too. In fact, many substructures behaved also as separated structures, but being linked they mutually influence each other.

Conclusions

The Cerreto di Spoleto ridge case-study pointed out that rock sites can show seismic amplification effects other than the topographic one. In particular, the seismic response in a rock mass ridge can be affected by rock mass jointing: adjacent rock masses with significantly different jointing and specific geometries can be regarded as responsible for trapped wave

Mode	1	2	3	4	5	6	7	8	9	10
Freq. (Hz)	6.35	7.01	7.17	7.61	7.98	8.55	9.26	9.27	9.69	9.71

TABLE 1 Numerical frequencies
Source: ENEA and Sapienza University of Rome

amplification. On the other hand, the results obtained in correspondence to the Nera River alluvial valley close to Borgo Cerreto highlighted the main role of the combined effect due to the heterogeneity of the alluvia and to the shape of the valley bedrock in causing amplification effects. The experimental analysis of the building pointed out that its structural behaviour is typical of historical constructions in which several changes, repairs and additions have been made over the centuries and allowed to analyze some aspect of the structural behaviour, such as the presence of resonance frequencies in small intervals, and the dynamic coupling between two frequencies very close to one another.

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