SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

AMBIENT VIBRATIONS IN SEISMIC STUDYING THE UNESCO CULTURAL HERITAGE SITE OF SAN GIMIGNANO (ITALY)

Enrico LUNEDEI[1], Giacomo PERUZZI[2] and Dario ALBARELLO[3]

San Gimignano is a village in Tuscany (Central Italy), whose historical hamlet is included in the UNESCO World Heritage List (http://whc.unesco.org/en/list/550). Several well-preserved medieval towers of considerable historical importance are in it and represent a very important tourist attraction. Historical earthquakes are documented in the area and this makes these monuments potentially exposed to seismic damages. In order to improve the knowledge about the seismic risk of this cultural heritage, the Tuscany Region promoted the RISEM project (*RIschio Sismico negli Edifici Monumentali* - seismic risk in monumental buildings; http://www.risem.unifi.it/), involving the universities of Florence and Siena. The project included three work packages. The first one was devoted to evaluate seismic hazard, including site response, in the San Gimignano hamlet. The second was devoted to the structural characterization of each tower by the use of historical documents and direct measurements. The third part was devoted to the estimate of possible damages expected at each tower as a consequence of possible future earthquakes.

In this frame, ambient-vibration monitoring was used in the first and second work packages. In particular, measurements in streets, squares and fields were used to constrain the geological/seismic model to be used for site response assessment, while measurements inside the buildings contributed to evaluate dynamical response of the towers.

As concerns the first aspect, a single-station measurement campaign was carried out by using a three component portable seismograph (Tromino®, http://www.tromino.eu/). Ambient-vibration measurements were processed to obtain HVSR (Horizontal-to-Vertical Spectral Ratio) curves (SESAME project, 2005; Picozzi *et al.*, 2005; Albarello & Castellaro, 2011), which allow detecting seismic resonance phenomena. Peak frequency f_0 of each HVSR curve, which estimate the resonance frequency attributed to the main impedance contrast in the subsoil, is shown in Figure 1 by a chromatic code. The tendency of this frequency value indicates the presence of a resonant interface gently deepening from the south-west (where the seismic bedrock outcrops) to the north-east. In order to constrain the S-wave velocity profile in the area above this resonant interface, the survey was completed by laying out five seismic arrays, whose acquisitions were processed by the ESAC technique (Okada, 2003) to obtain the Rayleigh dispersion curves. One of them, located where the substratum outcrops, points out the S-wave velocity of the bedrock, while the others were inverted, by means a genetic-algorithm procedure, jointly to relative near HVSR curves, obtaining the local S-wave velocity profile. They, together a profile relative to a pre-existent down-hole test located near the hamlet, were approximated by a single power law pattern in the form $V_S(z) = V_0 \cdot z^x$, where V_S is the S-wave velocity at the (adimensional) depth z. A fitting procedure gave the values V_0 = 227 m/s and x =

---

[1] PhD, Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, Siena (Italy), lunedei@unisi.it

[2] Dr, Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, Siena (Italy), peruzzi31@student.unisi.it

[3] Prof., Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, Siena (Italy), dario.albarello@unisi.it

0.25. In this way (see, *e.g.*, Albarello *et al.*, 2011), the depth H of the resonant interface in correspondence of each single-station measurement point, was estimated by the formula:

$$H \cong \left[\frac{V_0(1-x)}{4f_0}\right]^{\frac{1}{1-x}} = \left[\frac{227(1-0.25)}{4f_0}\right]^{\frac{1}{1-0.25}} \cong 149 \cdot f_0^{-\frac{4}{3}}$$

with f_0 in hertz and H in metres. This allowed the definition of the overall pattern of the resonant surface representative of the seismic bedrock buried morphology.

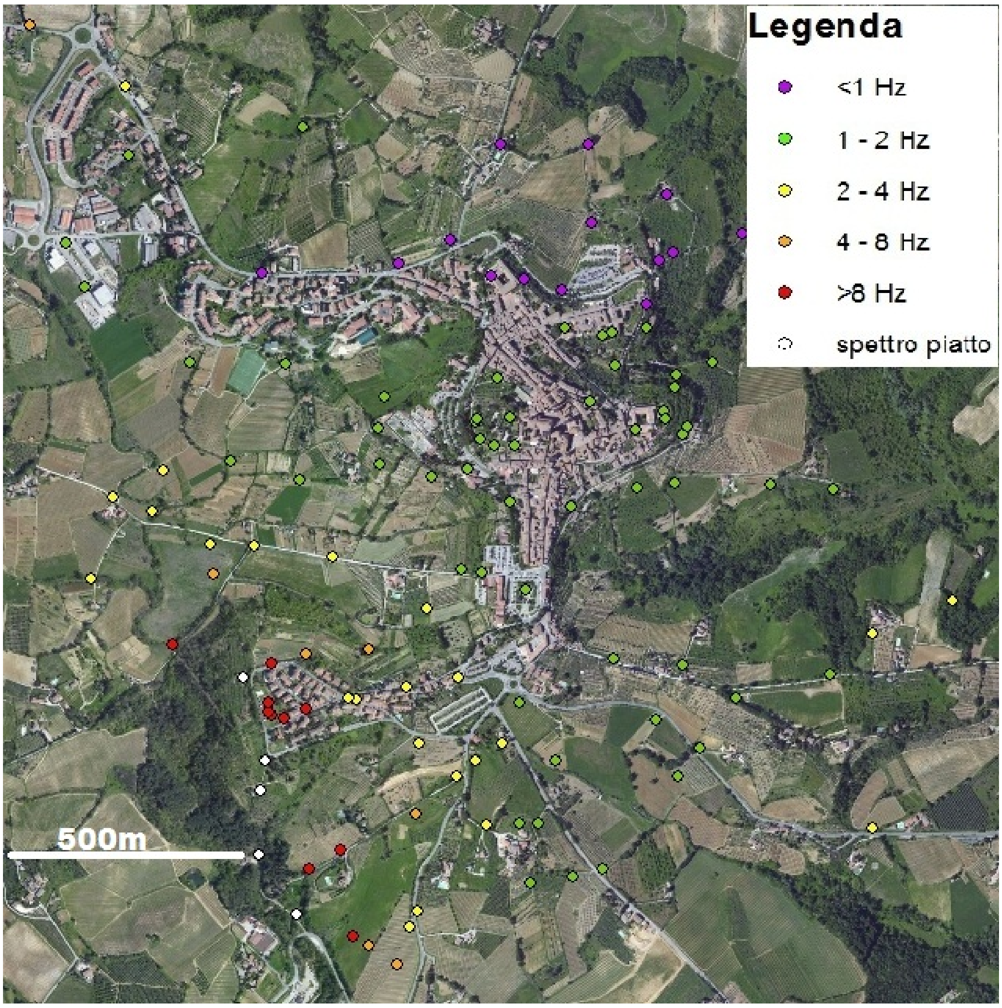

Figure 1. Localizations of the single-station ambient vibration measurements; colours point out the peak frequency values f_0 (“spettro piatto” = no peak); the San Gimignano hamlet is in the centre of the map

As concerns the second work package, single-station ambient-vibration measurements were performed in the towers to identify the relative fundamental (elastic) resonance frequency. This parameter is of main interest in realizing structural models of the towers. As a whole, twelve towers were monitored. For each of them, measurements were carried out in each accessible level as well as in the free-field at one or two sites just outside from each tower. Standard Spectral Ratios (SSR) were obtained, for each level, as the ratio between the average spectral amplitudes of ambient vibrations obtained inside and outside the buildings along the three spatial directions (two horizontal, parallel to the building faces, and the vertical). Peaks in the SSR curves are considered as representative of natural frequencies of the structure. In all the cases, a clear peak is detected in the SSR curves for each spatial direction, whose an example is shown Figure 2. In some cases, secondary peaks also appear, probably representative of higher modes or of interactions with other buildings located nearby. As several SSR curves were obtained for almost each tower, relative to its different levels, the range of the peak frequencies were considered as a lower bound for the relevant experimental uncertainty. Finally, the linear relationship $T_0 = C_T \cdot h$ was assumed between the fundamental period along the horizontal directions ($T_0=1/f_0$) and the relative tower height h (Figure 3). The coefficient was estimated as C_T = 0.0144 ± 0.0004 s/m, a value in line with those obtained in different sites of the world for various building's kinds (masonry, concrete, etc.). As the measurements were asynchronous, no information was obtained about modal shapes.

In conclusion, comparing Figures 1 and 3 clearly shows that the main proper frequency of many studied towers falls close to the resonance frequency of the hamlet and this fact reveals a possible enhancement of the seismic risk for the Medieval towers of San Gimignano.

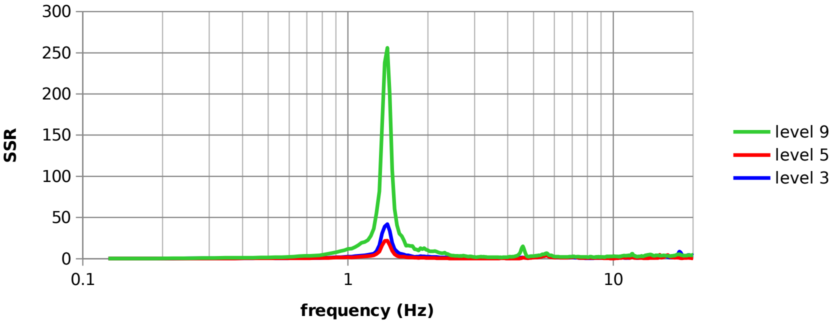

Figure 2. Example of SSR curves relative to different levels of a tower

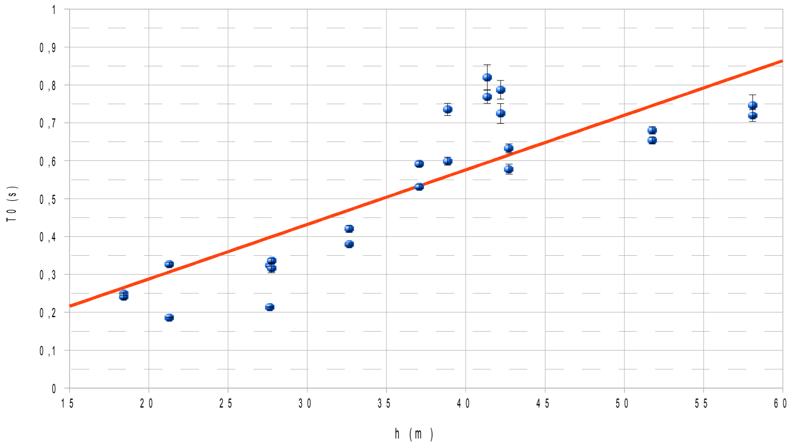

Figure 3. Trend of the towers' fundamental periods ($T_0=1/f_0$) versus the total towers' heights; red line is the relationship $T_0 = C_T \cdot h$

REFERENCES

Albarello D, Cesi C, Eulilli V, Guerrini F, Lunedei E, Paolucci E. Pileggi D and Puzzilli LM (2011): "The contribution of the ambient vibration prospecting in seismic microzoning: an example from the area damaged by the 26th April 2009 l'Aquila (Italy) earthquake", *Boll. Geofis. Teor. Appl., 52(3), 513–538*, doi:10.4430/bgta0013

Albarello D and Castellaro S (2011): "Tecniche sismiche passive". *Ingegneria Sismica*, Anno XXVII, 2 (Suppl.), 32–63 (in Italian)

Okada H (2003): *The microtremor survey method.* Geophysical Monograph Series, SEG, 129 pp.

Picozzi M, Parolai S and Albarello D (2005): "Statistical analysis of Horizontal to Vertical Spectral Ratios (HVSR)", *Bull. Seism. Soc. Am.*, 95(5), 1779–1786, doi:10.1785/0120040152

Picozzi M and Albarello D (2007): "Combining genetic and linearized algorithms for a two-step joint inversion of Rayleigh wave dispersion and H/V spectral ratio curves", *Geophys. J. Int.*, 169, 189–200

Site Effects Assessment using Ambient Excitations (SESAME) European project, 2005. Deliverable D23.12, Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measurements, processing and interpretation