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DIFFERENT APPROACHES TO ESTIMATE THE LOCAL SEISMIC HAZARD: AN APPLICATION TO THE ZELANTEA ACADEMY MUSEUM IN ACIREALE (SICILY).

ABSTRACT

Mt. Etna is an active volcano, the slopes of which are densely inhabited, the southeastern one markedly, where the town of Acireale is located. The properly named volcanic hazard is mainly experienced by lava flow invasion and ash downfall. However, the hazard associated with the local and/or regional earthquake activity cannot be neglected. Then, the Zelantea Academy Museum, located in the Acireale downtown, has been chosen as "test site" for different estimates of the seismic hazard on a building of interest for the cultural heritage.

A seismic catalogue for the local earthquakes has been compiled, after the collection and revision of the still available catalogues and of coeval and recently published sources. The final catalogue includes 85 local earthquakes and the distribution of their intensity on 64 different localities identified within the Acireale municipality boundaries. A catalogue of the local seismogenic faults (able to generate earthquakes in historical times) has been compiled, too.

The coupling of both catalogues allowed us to the following conclusions: i) the most important seismogenic faults affecting the Acireale municipality do not affect the downtown, while the related local earthquakes attenuate their energy (and intensity) in short (few km) distan-

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ces; ii) the highest seismic intensity (degree VIII) at the site of Zelantea Academy Museum (in Acireale downtown) was done by the 1693 regional earthquake; iii) over the last 140 years, Acireale downtown has experienced an intensity value of VII only once, while six times the intensity was VI. In the whole, this implies a moderate seismic hazard.

The estimate of the seismic hazard at the site has been approached also by the experimental method of the recording seismic noise. Twelve measurements have been performed outside and inside the Zelantea Academy Museum. The spectral ratios HV (horizontal/vertical) show a significant amplification at about 2 Hz (probably due to a 17 m deep discontinuity of the layered shallow subsoil). The same amplification (ca. 2 Hz) has been found inside the building. At frequencies higher than 10 Hz the vertical component is larger then the horizontal one. In conclusion, the site amplification factor is moderate (about 6), while the building does not show evidence of amplification factors due to its shape.

A further approach to the estimate of the seismic hazard, based on synthetic seismograms (and spectra) produced by simulating two given earthquake scenarios was done, too. The two scenarios are respectively representative of the largest expected earthquake in the area (the 1693 event), and of a moderate (magnitude ca. 5.5) local event (as the 1818 one). Moderate to strong locally expected accelerations have been evidenced.

1. The framework of the investigation

The seismicity of Southeastern Sicily relates to the development of moderate to large earthquakes, whose magnitudes may reach values up to 7. The major examples are the shocks occurred in 1169 (highest intensity I_0=X on the MSC scale), 1542 (I_0=X) and 1693 (I_0=XI): the last one causing many thousands of deaths and shattering an area of about 15,000 km^2. More recently, the December 13, 1990 earthquake has caused severe damages, despite its moderate magnitude (M=5.5). In particular this event has made clear that seismic hazard is not only a matter of largest (but very rare) earthquakes.

Moreover, the earthquake activity characterizing the Mt. Etna volcano (Fig. 1) can either be related to the eruptive events, or have a tectonic origin, due to dislocations along regional and/or local faults. However, independently of its origin, the earthquake activity is generally extremely shallow (h<2 km) and characterized by low energy release (Mmax=5.0) for most events [1].The main faults affecting the lower eastern flank of the volcano are characterized by lengths of some kilometres and by vertical dislocations up to some hundred metres. In details, a network array of fault escarpments (locally named "Timpe") is here remarkable. These structures sharply downthrow to east the gently inclined coastal flank and produce a step-fault system that culminates with a small graben, named "San Leonardello graben". They define a highly seismogenic area, located among Acireale, Zafferana Etnea and Riposto [2].

In addition to the influence of the seismic sources, site conditions are widely recognized as an important factor in the distribution of earthquake damages in urban areas. Efficient trapping of energy in basins and/or focusing of seismic waves by irregular interfaces lead to significant spatial variations of ground motion in both amplitude and duration. Among the many approaches to the site-effect estimate, an empirical trial is to use ambient seismic noise measurements. The application of microtremors to the seismic zoning has been investigated either trough direct interpretation of Fourier amplitudes and power spectral density [3], or using computation of spectral ratios relatively to a site reference station. A further method [4] is based on computation of spectral ratios between the horizontal components of motion and the vertical component obtained at the same site.

Furthermore, the estimate of ground motion can be approached in different ways. A central problem with realistic strong ground motion assessment are the very irregular and non-uniform waveforms of acceleration seismograms even for similar earthquakes and similar environments. In terms of source models these signal features can be attributed to heterogeneities within the seismic source. Then, the resulting acceleration source time function may be simulated [5] generating a large number of simple pulses varying randomly with time.

The Zelantea Academy Museum is located in Acireale downtown, and it is hosted in a building built at the beginning of the 20th century. It is composed by different sections: a Library (more than 250,000 books, since the 14th century), an Art Gallery (pieces by Van Dick, Guercino, Domenichino, Guido Reni, among others) and the properly named museum, that includes collections of archeological finds, coins, weapons, mineral, fossils. A room capable to host conferences and concerts is available, too. Because the large variety of activities and content goods, the Zelantea Academy Museum has been chosen as "test site" for the estimation of the seismic hazard by using some different approaches.

2. The catalogues of local earthquakes and of seismogenic faults

The analysis both of available seismic catalogues [6, 7, 8, 9, 10, among the others] and of papers referring to single earthquakes was performed for the period 1865-2001. The values of the maximum intensity (Io) were compared among the differing sources. Moreover, the reported effects on structures, objects and people have been re-interpreted in terms of the MCS intensity scale; sometimes the original Io-value was discounted. The resulting catalogue includes 85 local earthquakes. In order to avoid the effects of the interpolation only the intensity values effectively obtained by the reports have been attributed at each of the 64 different localities identified inside the Acireale municipality area.

The visual analysis for the completeness of catalogue allowed to define the threshold as Io>VI, for the whole considered period. The resulting catalogue is composed by 48 earthquakes. For each of them, the date of occurrence, the maximum intensity, the responsible seismogenic fault, and the related references are reported. For some earthquake, in spite of the high intensity values (VII to VIII) no ground fractures were quoted. Figure 2 shows the distribution of the observed intensity values, referring the May 8, 1914 destructive local earthquake. In the epicentral area the intensity was IX, while damages included the total collapse of many buildings and several people killed and injured. In spite of the short distance (6-7 km) the downtown of Acireale has experienced an intensity value of V, that means no damages. This is just an example of the high attenuation of the seismic intensity with the increasing distance from the epicentral area. The main result of this behaviour of the shallow crust is that over the last 140 years Acireale downtown experienced an intensity I=VII only once, while only six times the value I=VI was there observed. The highest seismic intensity (VIII) in

Acireale downtown was felt during the 1693 regional earthquake.

Concerning seismogenic faults, we studied the lower Southeastern flank of Mt. Etna; in detail the area located among Acireale, Fleri, Zafferana Etnea, S. Alfio and Riposto (see Fig. 3). This area is characterized by faults having a well remarkable development on the ground surface. This allowed us to perform some accurate field survey. Moreover, this area is densely inhabited since long time, and a large bibliographic information on local seismic phenomena, covering at least the last two centuries, is available. The identification and the mapping of the tectonic structures have been performed through repeated field surveys, the analysis of stereo-pairs (scale 1:33.000 by I.G.M.), and the collection of both unpublished reports and recent bibliography. Fourteen main alignments have been recognized (see Table 1).

The direction of the alignments, their length, the morphologic evidence, the displacement and the downthrow side have been reported in table 1. The main direction of the alignments is about N20W in the eastern part of the area, and ca. N40W (structures nrs. 4, 5, 7, 8) in the southwestern part. The fault length varies between 0.4 km (Praiola fault) and 8-9 km (S. Leonardello fault and Macchia-Stazzo fault). The morphologic evidences consist in both fault escarpments and flexures due to the superposition of lava flows on the fault escarpments. The observed vertical dislocations range from 5 up to 200 metres (southernmost segment of structure nr. 5), with generally eastward down-throw side. Only the faults nr.11 and nr.13 show western down-throw side. Few evidences of horizontal dislocations have been detected. The correlation between ground cracks and active faults might not be always significant; however, the use of ground cracks to identify seismotectonic faults in the investigated area is largely justified by the shallowness of the considered earthquakes [11]. Only 11 structures, among the 14 ones reported in table 1, have been recognized as responsible for earthquakes with Io>VI, during the last 150 years. Some of them are also characterized by creep phenomena (see table 1). The faults nr.11 and nr.14 are affected only by aseismic creep, whereas the S. Giovanni fault (nr.12) is the solely no active one.

N°	Fault name	Direction	Lenght (km)	Morphologic evidence	Down-throw side	Activity in the last 130 years
1	Moscarello	N 20W	5.5	Escarpment	east	earthquakes
2	S. Leonardello	N 20W	8.0	Escarpment	east	earthquakes and creep
3	S. Venerina	N 30W	3.0	Flexure	east	earthquakes
4	Zafferana Etnea	N 45 W	3.0	Flexure	east	earthquakes
5	S. Maria Ammalati-Linera	N 40W	5.0	Flexure	east	earthquakes and creep
6	Pozzillo-T. Fago	N 30W	1.0	Escarpment	east	earthquakes
7	Fiandaca	N 45W	3.0	Flexure	east	earthquakes
8	Fleri	N 45W	3.0	Flexure	east	earthquakes
9	S. G. Bosco	N 13W	2.0	Flexure	east	earthquakes and creep
10	Guardia	N 25W	1.2	Flexure	east	earthquakes and creep
11	Macchia-Stazzo	N 20W	9.0	Escarpment	west	creep
12	S. Giovanni	N 7W	1.5	Escarpment	west	no activity
13	Pozzillo-C.se Carpinati	N 7E	1.5	Escarpment	west	earthquakes and creep
14	Praiola	N 10W	0.4	Escarpment	east	creep

Table 1 - Features of the main faults located on the southeastern flank of Mount Etna. Numbers refer to figure 3.

The most important result of our investigation is that seismogenic structures affecting the territory of the Acireale municipality do not affect its downtown. This fact, associated with the high energy attenuation behaviour above described, let us to consider almost negligible the seismic hazard induced by local faults on the downtown of Acireale.

3. The geology of Acireale

The geology of the city of Acireale is the result of the combined effects related to (i) the volcanic and tectonic processes, (ii) the Late Quaternary sea-level changes and (iii) to human activity. The backbone of the urban area is represented by a sedimentary slope. This substratum is consisting mainly of marls and claystones with a thickness of up to 800 m. Such a heterogeneous sedimentary substratum is dissected by lava flows, which form the most representative rocks cropping out in the city. The lava flows consist mainly of basalts. For the sake of convenience we may divide our model in two levels, one related to the subsurface geology and another one to the deeper units. The subsurface geology varies from site to site, whereas the parameters of deeper units are supposed to be almost constant across the downtown. The shallow geological stratigraphy at the site of Zelantea Academy Museum is reported in Figure 4.

The parameters of the deeper units, formed by lavas. claystones, marls and limestone are reported in Table 2. After all, the total thickness of the layer stack overlying the crystalline basement reaches about 6000 m.

Layer	*Thickness*	*C*	*Density*	*Q*
Lava	100 m	1500 m/s	2200 kg/m^3	50
Claystone	500 m	1500 m/s	2100 kg/m^3	50
Marls	300 m	1700 m/s	2200 kg/m^3	100
Limestone	5000 m	2600 m/s	2500 kg/m^3	150
Basement	∞	3500 m/s	2800 kg/m^3	300

Table 2: Geotechnical parameters for the area of Acireale, estimated in conservative way from Casadio and Elmi [12] and unpublished reports.

4. Experimental measurements of microtremor

Seismic tremor, commonly called seismic "noise", exists everywhere on the Earth surface. It is also called *microtremor* because it involves very small oscillations (10^{-15} [m/s^2]^2 in acceleration), much smaller than those induced by earthquakes of any size in the near field. It mainly consists of surface waves, which are the elastic waves produced by the constructive interference of the P and S waves in the layers near the surface. Seismic noise is mostly produced by wind and sea waves. Also industries and vehicle traffic locally generate tremor, although essentially at high frequencies (some Hz), which are quickly attenuated. In areas without local noise sources, in absence of wind and on flat rocky basements, the seismic noise spectrum decreases at high frequencies and has two peaks at 0.14 and 0.07 Hz, probably due to large ocean waves, which are only slightly attenuated even at thousands of kilometres from the ocean due to the wave-guide like properties of surface waves. Local effects due to anthropic and natural sources can add to this general trend. However, much more interesting is the fact that the background seismic noise acts as an excitation function for the local resonances of both subsoil and buildings. In fact, the background seismic noise will excite proper frequencies of a subsoil, making them clearly visible in the tremor spectrum measured above it. In exactly the same way, if a building has resonance frequencies, seismic background noise will excite the resonance frequencies on the tremor spectrum measured inside the building.

Ground seismic noise can be used to identify: 1) the resonance frequencies of sub-soils in a passive and fast way, 2) the resonance frequencies of buildings.

Since the first empirical studies of Kanai and Tanaka [3], the most popular method is the HVSR (Horizontal Vertical Spectral Ratio) technique, which consists of studying the ratio between the spectra of the horizontal components of motion and the vertical ones, was widely divulgated by Nakamura [4]. It is recognized that HVSR is able of providing a reliable estimate of the main resonance frequencies of subsoil.

The theoretical bases of HVSR are relatively simple in a 1-D layered configuration. Let us consider a system (see Fig. 5) where layers 1 and 2 differ for their density value ($\rho 1$ and $\rho 2$) and seismic wave propagation velocities (V1 and V2). A wave travelling across layer 1 is (partially) reflected at the transition with layer 2, and the reflected wave will interfere with incident waves and will give a maximum amplitude (fundamental resonance frequency), when the wavelength of the incident wave (λ) is 4 times (or odd multiples) the thickness *h* of the first layer. In other words the fundamental resonance frequency (*fr*) of layer 1 for the P waves is: $f_r=V_{P1}/(4h)$, while the fundamental resonance frequency for the S waves is: $f_r=V_{S1}/(4h)$.

Theoretically, this effect is addable so that the HVSR should show (as relative maxima) the resonance frequency of layers. This, together with an estimate of seismic velocities which is generally available at least as a first approximation, allows one to predict the thickness *h* of the first (or more that one) layer. This information is mostly contained in the vertical component of motion, but the idea of using the ratio of horizontal to vertical spectra rather than the vertical spectrum alone derives from the fact that the ratio provides for an important normalization of the signal for *a)* frequency content, *b)* instrumental response and *c)* overall signal amplitude if the recordings are taken at times of higher or lower noise levels. This normalization, which makes signal interpretation simpler, is at the basis of HVSR popularity.

Considering buildings, the modes of vibration that are of interest for the seismic vulnerability are the horizontal ones. The frequency of resonance (natural frequency) of a given building is mainly due to its height. The natural frequency is approximately given by the relationship 10 Hz / (number of floors). The measurement of the noise at the different floors, represents the experimental way to the estimate of the natural frequency of a building [13]. If the value of natural frequency of the building is close to the one of the ground amplification, a double resonance effect is to be expected in case of seismic ground shaking. The presence of double resonance effects represents the worst condition in terms of amplification of the motion (then of the safety) both for the building and its contents

Class	Number of floors	resonance frequency. [Hz]
A	1-2	10-5
B	3-5	5-2
C	>5	<2

Table 3. Classification of the buildings based on the number of floors and the estimated frequency of resonance (see text for details).

4.1 The data collection

Microtremor measurements were carried out at the ground surface and inside the building that hosts the Zelantea Academy Museum (Fig.6). The building is just composed by a ground floor and a first floor; then its natural frequency should be ranging from 5 to 10 Hz.

Seismic signals have been recorded with a digital tromometer (Tromino ™). which is an instrument specifically designed to accomplish this task. Tromino relies on a patent pending design which optimizes the measurement of seismic tremor in the range 0.1 - 200 Hz. It is a highly portable (see Fig. 7) all-in-one device (dimensions: 10x7x14 cm, weight 1 kg) equipped with three orthogonal velocimeters, powered by two 1.5 V AA batteries, which includes an internal GPS antenna and does not have any external cable. The ground motion is amplified, converted into digital form, organized, transferred to a Compact Flash card and then to the PC, where the storage, analysis and review of the data are performed through a proprietary software.

Figure 8 shows the map of the building and the location of the microtremor measurements. The values of significance have been obtained taking a HVSR value equal to 2 as threshold. In Figure 9 the values of amplification function of the soil are reported. The site shows significant amplifications (from 4 to 6) in the frequency band 1-3 Hz (top of the figure). This is probably due to the extremely layered structure of the shallow sub-soil at the site (see Fig. 4). Moreover, the comparison of the two horizontal components (north-south and east-west) evidences almost the same amplitude over the whole examined frequency range, excluding some slightly higher values of the E-W horizontal component in the frequency band 1-3 Hz.

Concerning measurements performed inside the building, the horizontal to vertical spectral ratios show the fundamental (F.M.) and the highest (H.M.) modes of vibration of the building are around 3 and 4 Hz, respectively (Fig. 10). However, these frequency peak amplitude are less than 2, while their values are not close to the one of the ground amplification (around 2 Hz). This allows us to exclude significant double resonance effects.

5. Simulations for earthquake scenarios

The computation of ground motion can be attacked by considering different scenarios.

The most prominent earthquake which had shaken the urban area of Acireale (X degree for the observed Intensity) occurred on January 11, 1693 in the Gulf of Catania. Its magnitude was estimated by various authors to M≅7, which corresponds to a seismic moment of about $2*10^{19}$

Nm. The epicentral distance from Acireale was about 25 km. Assuming a seismic stress drop of 200 bars for this event, which corresponds to the lower value estimated for the 1990 earthquake, a source area of about 200 km^2 is obtained.

The latter scenario corresponds to a local earthquake having magnitude M≅5.5, slightly smaller than the shock that occurred on February 20, 1818. The observed intensity in Acireale was VIII. The source parameters for the simulation are the same as estimated for the 1990 earthquake. The epicenter is supposed to be situated about 5 km southward the downtown. The focal depth of both earthquakes has been fixed to 15 km.

The acceleration source time function was simulated according to the procedure proposed by Boore [5], modified by Langer [14]. Its essence is the generation of a band-limited random sequence of random pulses. Global source parameters are accounted for by applying a band-pass filter to the Gaussian white noise, i.e. $C\,M_0\,S(f,f_0)\,P(f, fmax)$ where C is a constant for geometrical spreading and radiation pattern, M_0 the seismic moment of the event, f_0 the corner frequency, $S(f,f_0)=f^2/(1+(f/f_0)^2)$, $P(f,fmax)=(1+(f/fmax)^{2q})^{-1/2}$, q the parameter of the steepness of the high frequency decay (here q=4). The corner frequency f_0 can be related to the size of the source (its radius r_0) after Brune [15] by: $f_0=0.372\ c/r_0$, where c is the shear-wave velocity. Finally the seismic stress drop is given by: $sd=7M_0/(16r_0^3)$.

Strong ground motion is seriously affected by wave propagation effects caused by changes due to absorption, reflection and refraction at the boundaries of the geological structures. In particular the subsurface geological structure is of principal importance in this context. Since there is no simple way to account for wave propagation effects we have calculated the transfer function of the propagation medium using Haskell [16] matrices for a 1D-model. In order to represent the seismic loading at the studied we have chosen the peak ground acceleration as inferred from the synthetic spectra.

The synthetic spectra for the two above earthquake scenarios have been computed at the Zelantea Academy Museum site; they are shown in Figure 11. The highest values of the acceleration are observed in the frequency band 9-11 Hz for both spectra. Comparing our results the hypothetical scenario with the local earthquake of smaller magnitude appears to be slightly more critical than the other one. This is somewhat surprising since the earthquake of January 11, 1693 is the largest one occurred in the region, and one commonly refers to it for hazard evaluation. However, the relatively vicinity of the source may produce this effect. In any case, the 1818 local earthquake represents a rare event, like the 1693 one. Then, the seismic loading of the site, as estimated by simulations, may be qualitatively defined moderate.

6. Conclusions

The main goal of the present investigation was the estimate of the seismic hazard at a site of interest for the cultural heritage, by using different approaches. The results obtained at the "test site" of the Zelantea Academy Museum (located in Acireale downtown; southeastern side of Mt. Etna volcano) are intriguing.

From one side, the most important seismogenic structures affecting the lower southern flank of Mt. Etna do not affect the Acireale downtown. This fact, associated with the evidence that the local earthquakes highly attenuate their energy in short (few km) distances allowed that during the last 140 years, the seismic intensity by local earthquakes in Acireale downtown reached the value of VII only once. This induced us to choose two possible earthquake scenarios, the largest regional earthquake (1693, magnitude 7), and an hypothetical earthquake located few kilometres southward from the downtown, having some features of the large 1818 earthquake. The simulated spectra have evidenced a slightly larger value for the acceleration due to the smaller (but closer) earthquake. The complex structure of the shallow subsoil at the site is responsible of the moderately high peak ground acceleration values obtained by applying the two earthquakes scenario parameters

Finally, microtremor measurements at the site of the Zelantea Academy Museum have evidenced a moderate site amplification factor (about 6). Conversely, no evidence of amplification factors due to the building shape was found.

In conclusion, the seismic hazard for the Zelantea Academy Museum can be qualitatively defined from low to moderate.

Moreover, the results obtained by the present investigation confirm, as previously observed in the urban areas of Ragusa-Ibla [17] and Catania [18, 19], that the combined use of: i) seismic history of the area, ii) detailed geo-structural survey, iii) experimental measurements of seismic noise, and iv) strong ground motion simulations, is a very powerful tool for the estimate of the ground shaking of a given site. This allows us to suggest the use of a "standard procedure" in order to characterize the seismic hazard of a given building located at a given site. In the whole, we suggest the different kinds of information, as follows:

1) the seismic history of the area (town and/or locality). Basically a catalogue including the observed effects produced by the past earthquakes (both local and regional) that have shaken the investigated site;
2) the identification and characterization of the local seismogenic faults;
3) detailed geological surveys, based also on the collection of available geotechnical data from drillings and/or geophysical investigation;
4) seismic noise measurements, in order to define both the local site amplification due to the layered structure of the subsoil and the fundamental modes of vibration of the building;
5) the definition of one (or more) earthquake scenario, on the base of which the expected ground shaking spectrum may be computed (simulation based on the detailed knowledge of the subsoil at the site).

In this way, each investigated building would be characterized in terms of seismic loading at the site, as well as of the presence (if any) of amplification effects. This can be helpful for the organizations devoted to the maintenance and restoring of buildings of interest for the cultural heritage.

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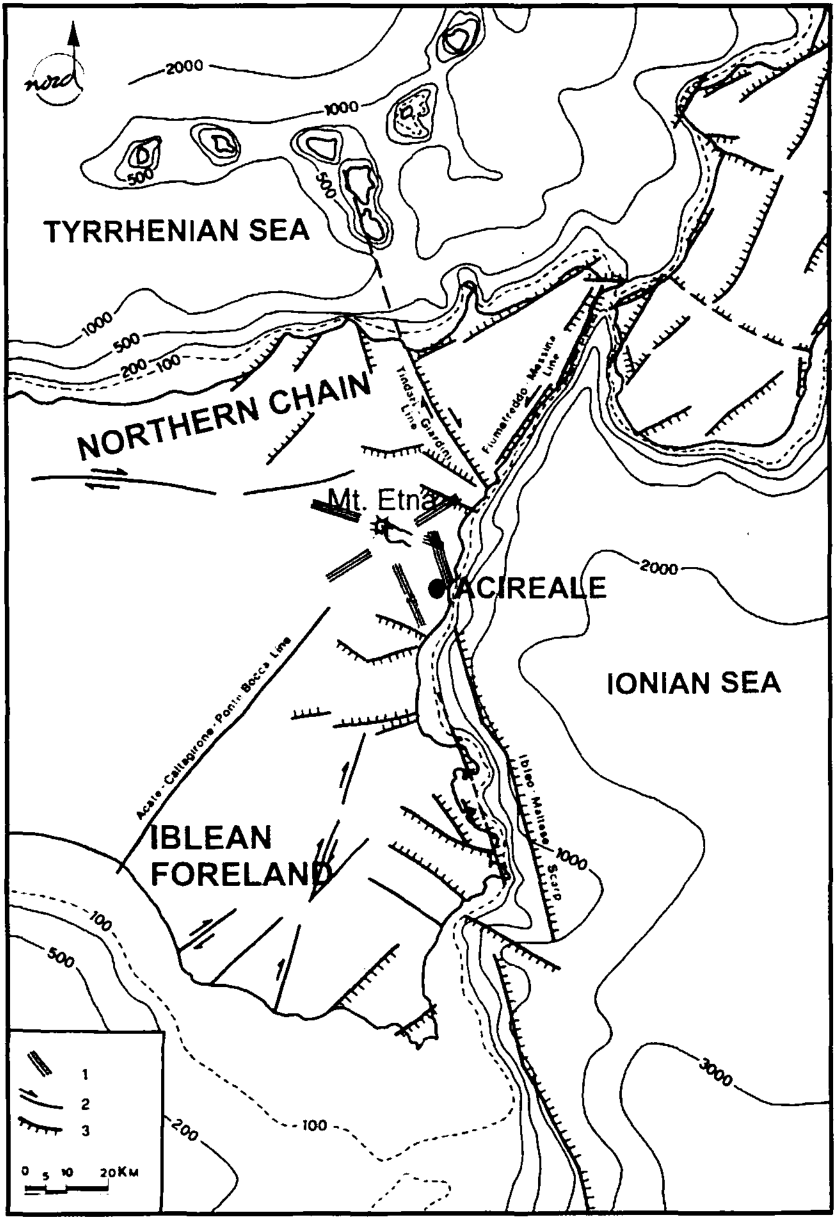


Figure 1 - Sketch map of Eastern Sicily with the main structural units, and the location of Mt.Etna volcano and Acireale.

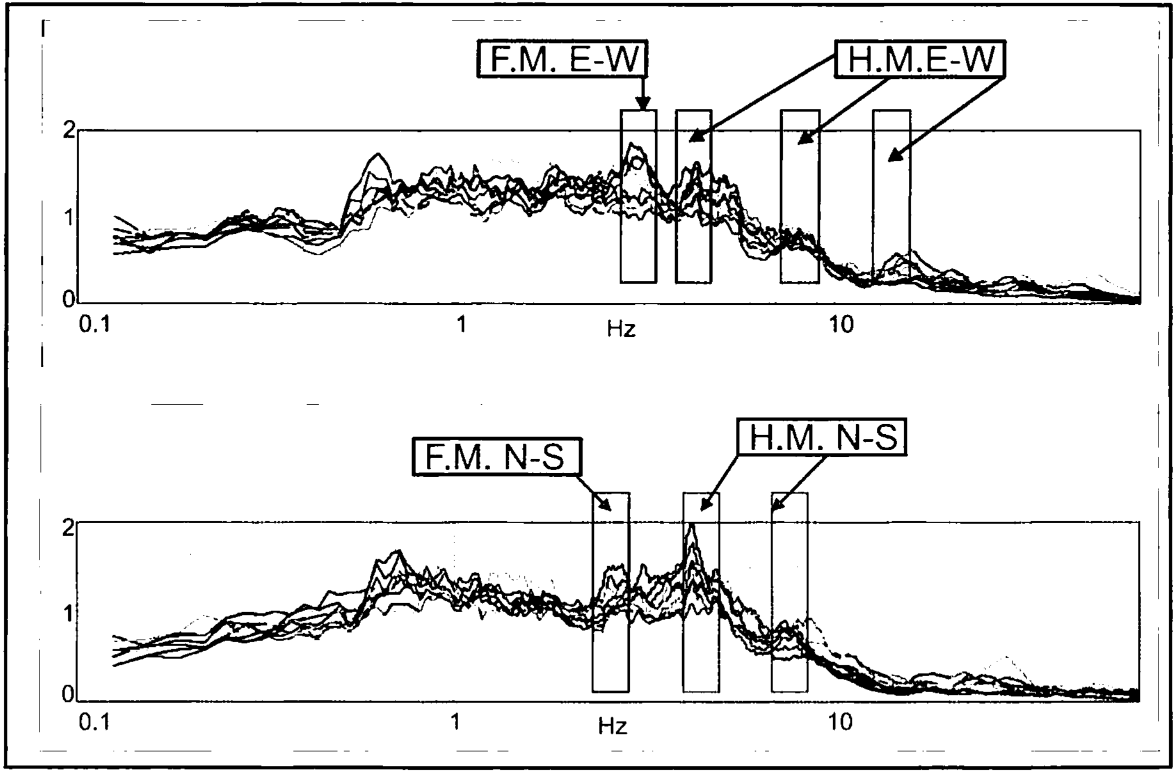


Figure 10 – Horizontal to vertical spectral ratios showing the fundamental (F.M.) and the highest (H.M.) modes of vibration of the building. All measurements performed inside the building are shown.

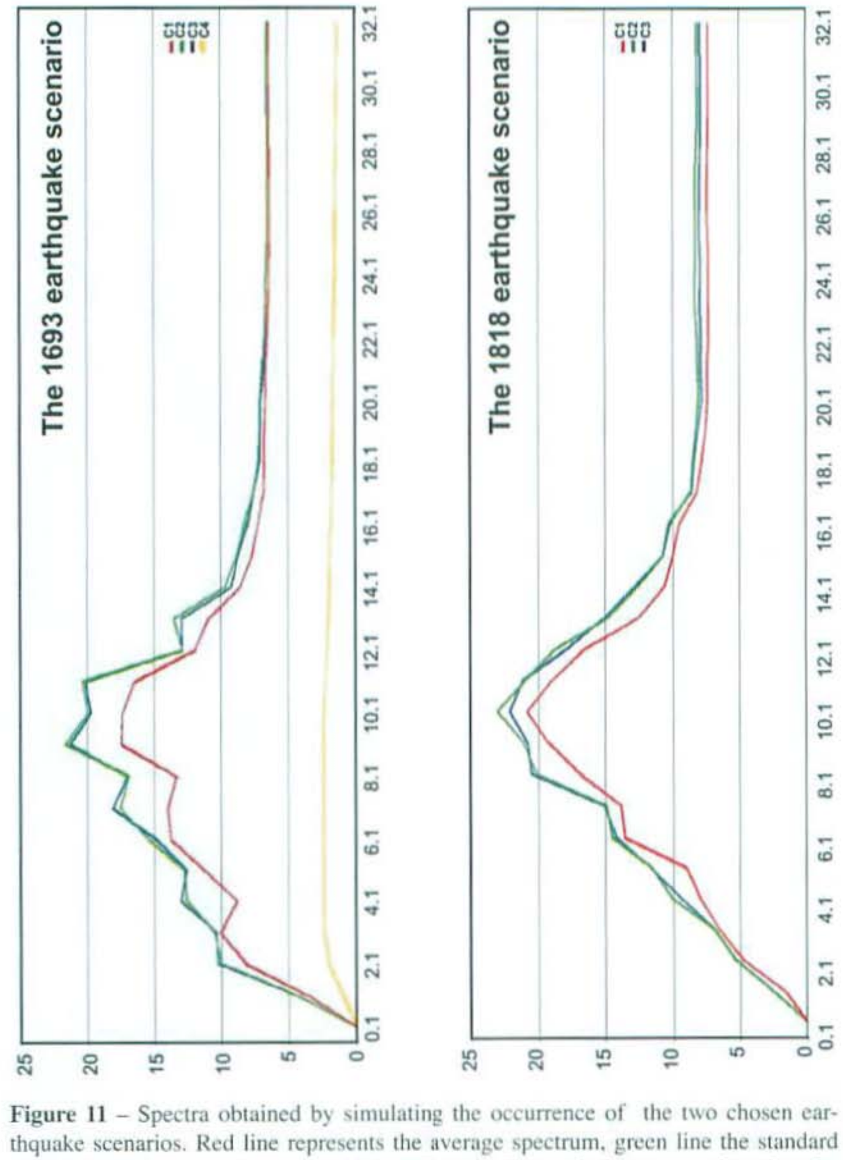


Figure 11 – Spectra obtained by simulating the occurrence of the two chosen earthquake scenarios. Red line represents the average spectrum, green line the standard deviation, the blue one the peak hold; in yellow the Eurocode 8 spectrum, based on the soil class B is shown.

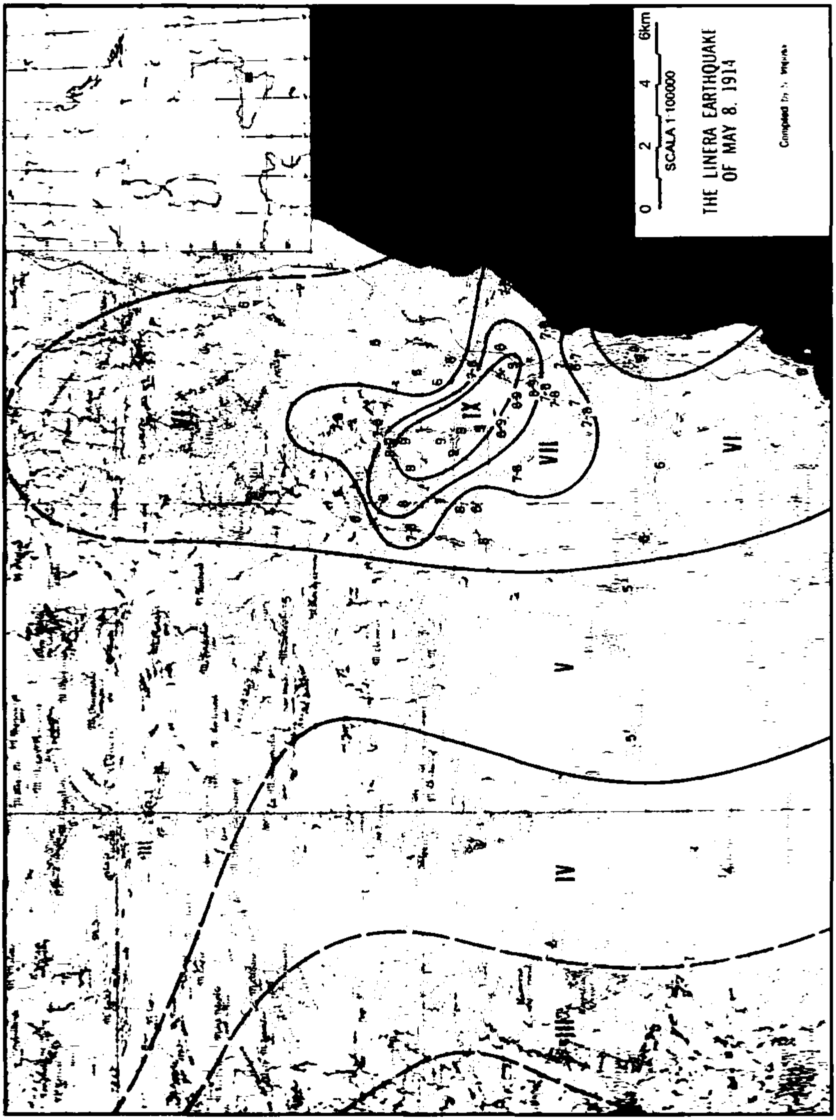


Figure 2 – Distribution of the intensity values relating the May 8, 1914 local destructive earthquake. Note the sharp decrease of the intensity while increasing the distance from the epicentral area.

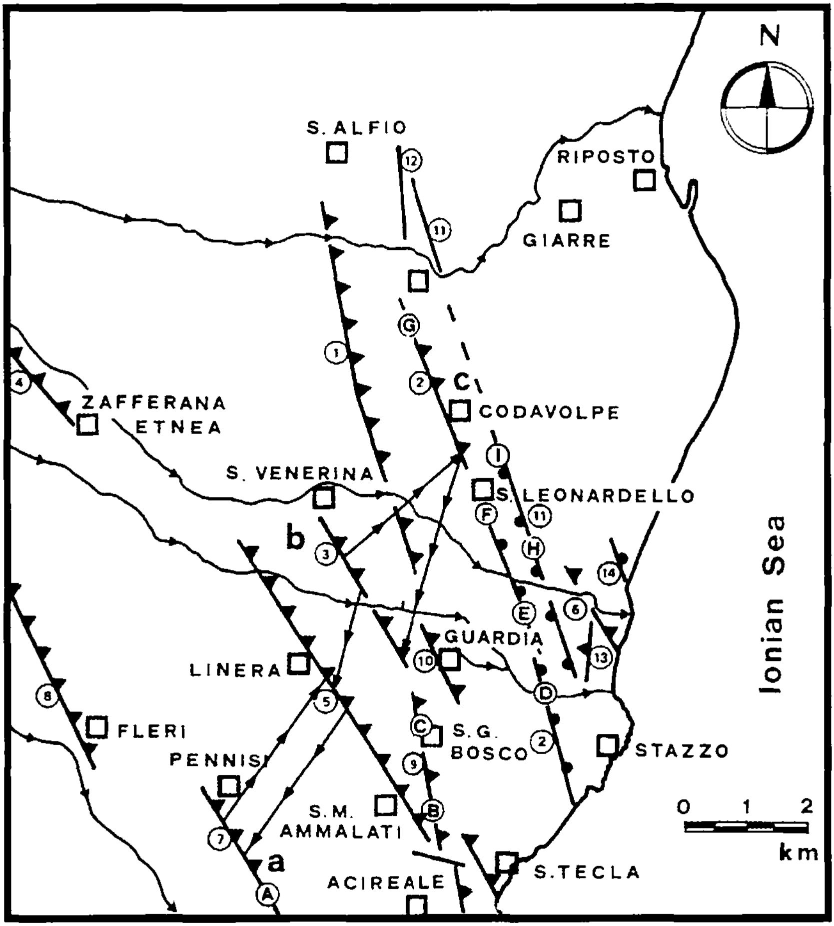


Figure 3 - Structural map of the eastern flank of Mt. Etna, with of the main seismogenic faults (see text for details).

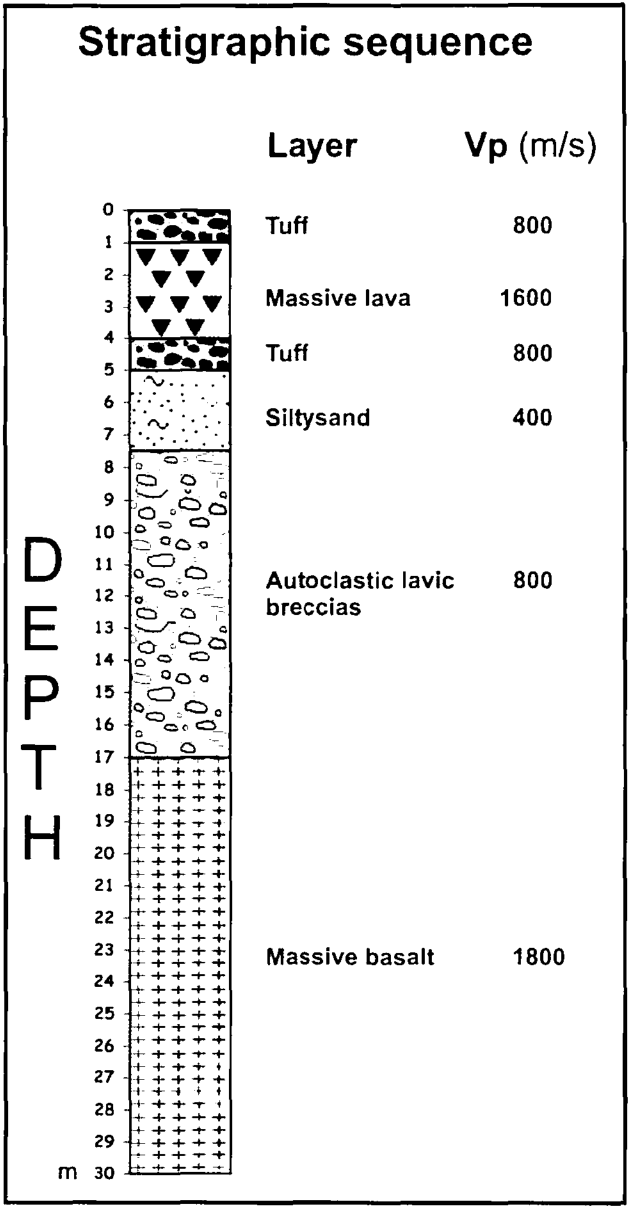
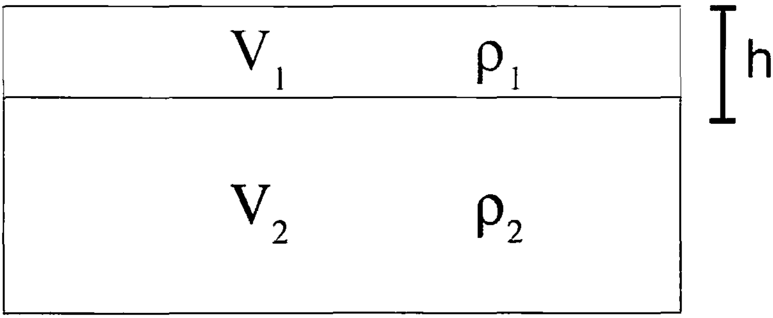


Figure 4 – Stratigraphic section of the subsoil at the Zelantea Academy Museum site (data from drilling).


V_1
ρ_1
h
V_2
ρ_2

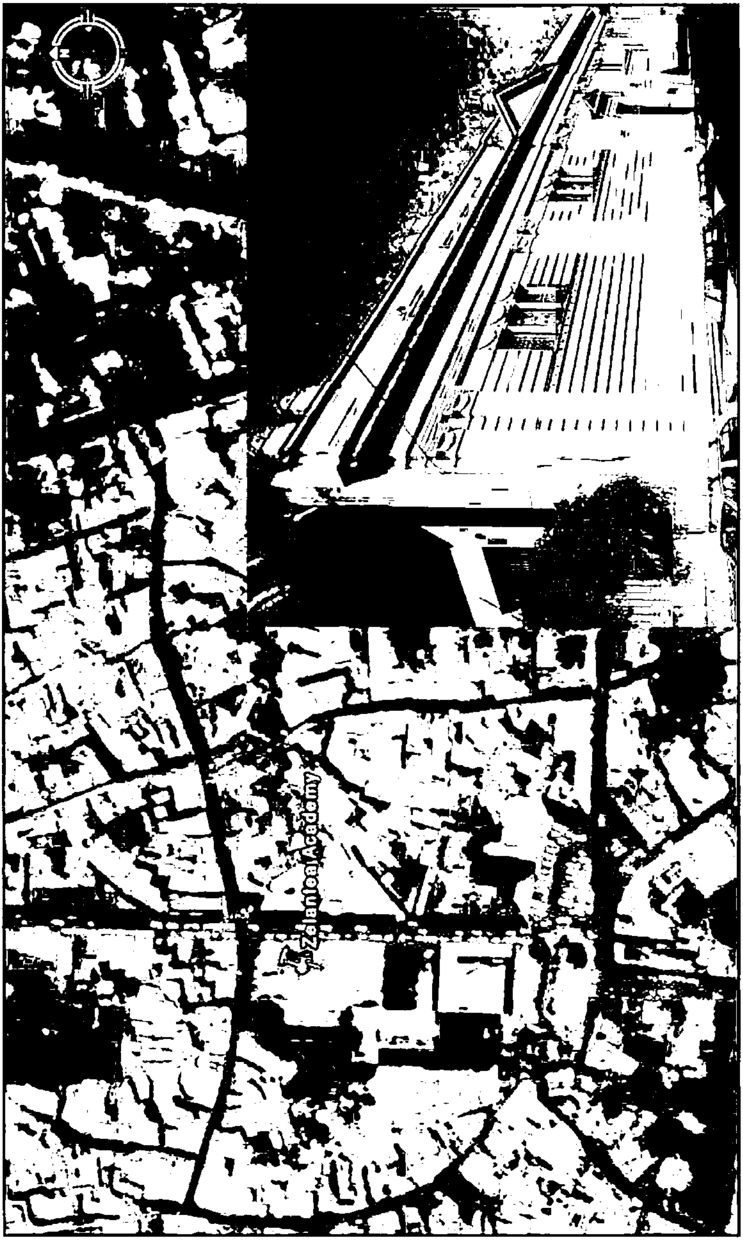


Figure 6 –Picture of the building hosting the Zelantea Academy Museum, and its location in an aerial photo of Acireale downtown

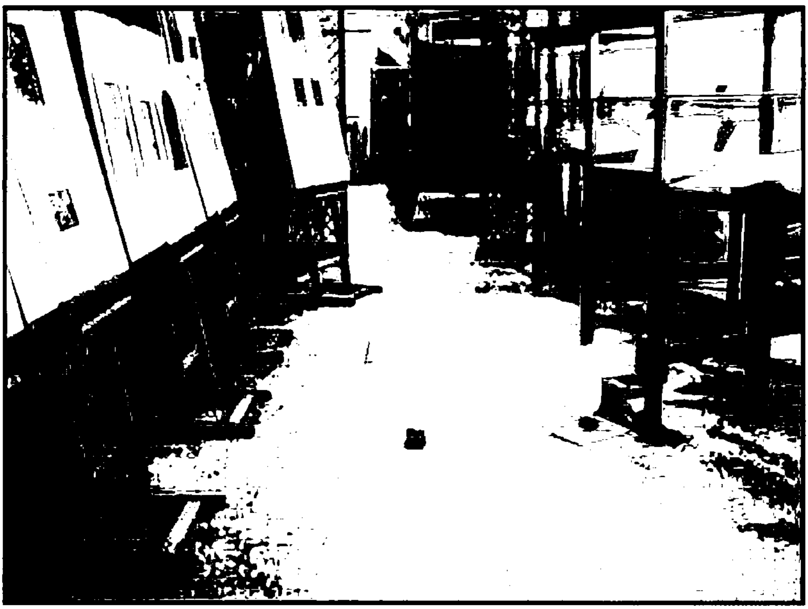


Figure 7 – Two pictures showing the seismic microtremor data aquisition instrument outside and inside the Zelantea Academy Museum.

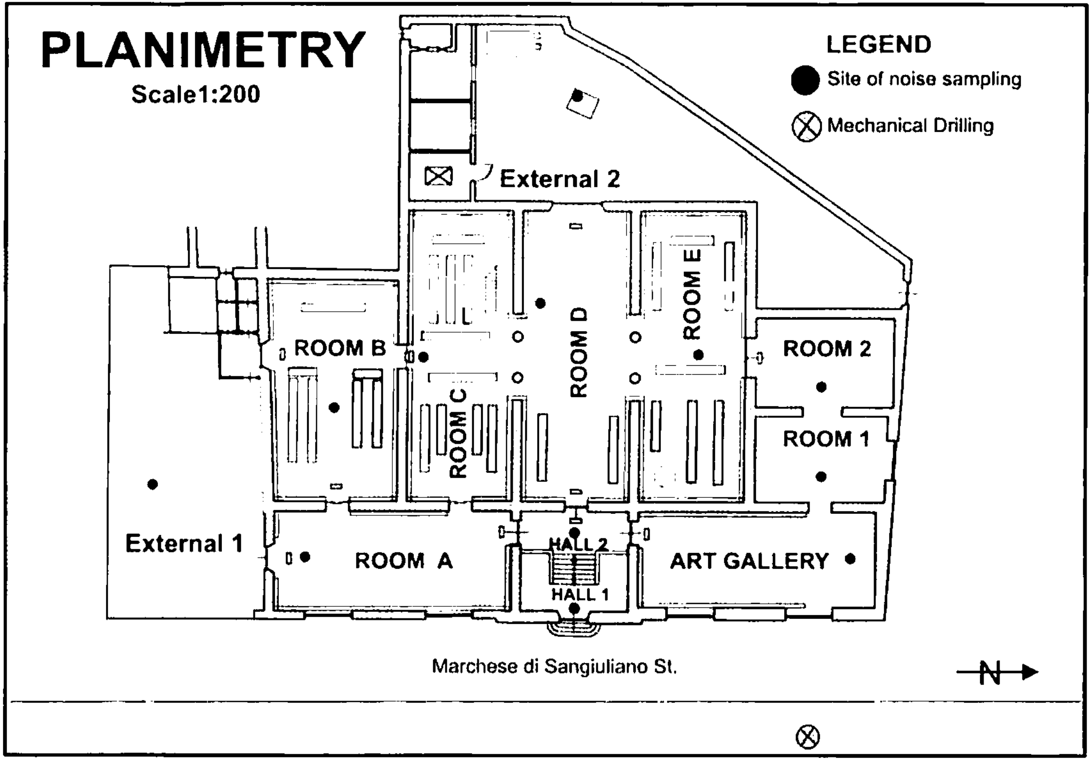


Figure 8 – Plan of the building hosting the Zelantea Academy Museum. The dots indicate the sites of micro-tremor measurements.

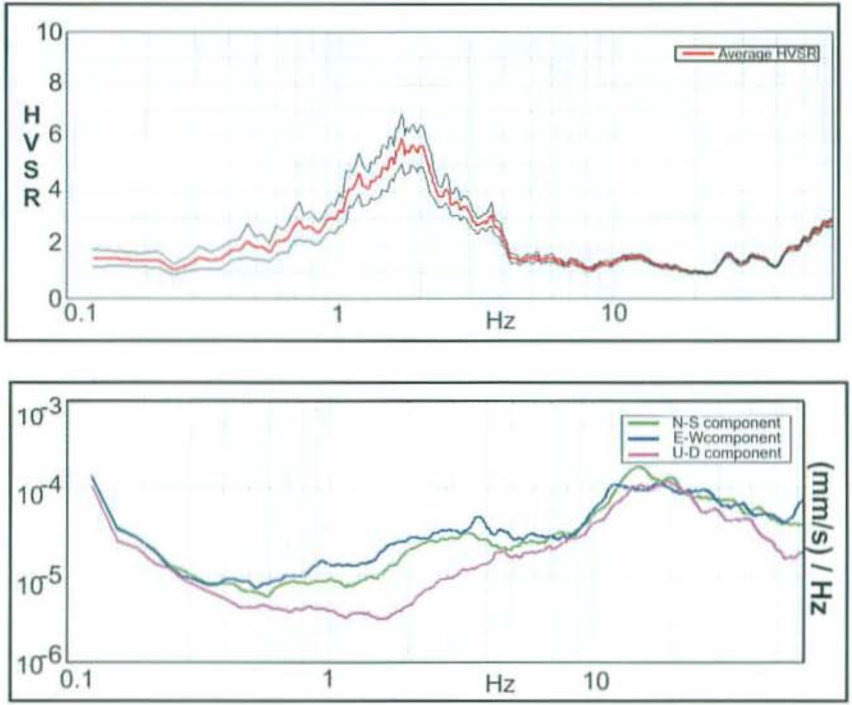


Figure 9 – (bottom) Horizontal (north-south and east-west) and vertical (up-down) spectra of the microtremor recorded at one of the two external recording site; (top) average ratio (red line) between horizontal and vertical component spectra (grey lines mark the standard deviation);