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Contribution of ambient vibration recordings (Free-field and buildings) for post-seismic analysis: the case of the Mw 7.3 MARTINIQUE (French lesser ANTILLES) earthquake, november 29, 2007

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1 **CONTRIBUTION OF AMBIENT VIBRATION RECORDINGS**
2 **(FREE-FIELD AND BUILDINGS) FOR POST-SEISMIC ANALYSIS:**
3 **THE CASE OF THE MW 7.3 MARTINIQUE (FRENCH LESSER**
4 **ANTILLES) EARTHQUAKE, NOVEMBER 29, 2007**

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18 **ABSTRACT**

19 Following the Mw 7.3 Martinique earthquake, November 29th, 2007, a post-seismic survey was
20 conducted by the Bureau Central Sismologique Français (BCSF) for macroseismic intensities
21 assessment. In addition to the inventories, ambient vibration recordings were performed close to the
22 particularly damaged zones in the free-field and the buildings. The objective of the paper is to show
23 the relevancy of performing ambient vibration recordings for post-earthquake surveys. The analyses of
24 the recordings aim at explaining the variability of the damages through site effects, structure
25 vulnerability or resonance phenomena and to help the characterization of the post-seismic building
26 integrity. In three sites prone to site effects, we suspect damage to be related to a concordance
27 between soil fundamental frequency and building resonance frequency. Besides, the recordings of
28 ambient vibrations at La Trinité hospital before and after the earthquake allow us to quantify the
29 damage due to earthquake in terms of stiffness loss.
30

31 **HIGHLIGHTS:**

- 32 • We performed ambient vibration recordings in both soil and structure after a damaging
33 earthquake
- 34 • We investigate the sources of damage to buildings
- 35 • We compare pre-and post earthquake recordings to evaluate damage grade
- 36 • We propose recommendations for the use of such recordings in post seismic survey.

37 **KEYWORDS:** Ambient vibrations, site effect, resonance, post-earthquake survey, damage,
38 Martinique earthquake.
39

40 INTRODUCTION

41 A large part of knowledge in the fields of earthquake engineering and engineering seismology has
42 been accumulated during post-seismic surveys all around the world. These surveys have many
43 different objectives: (1) estimate the buildings safety right after the earthquake, (2) characterize the
44 ground motion by establishing macroseismic maps, (3) provide feedback for earthquake engineering
45 by studying damage features and, eventually (4) help urban planning in defining zones with ground
46 motion amplification and induced effects (liquefaction, landslides...). However, the knowledge of the
47 structural damage causes is prior information necessary to relevantly reach these objectives. For a
48 given deformation capacity, e.g. associated to a building class, damage will only depend on the
49 building response to the ground motion. The building response depends on the incident seismic
50 motion (that can be largely affected by the site response) and its representing parameters (maximal
51 amplitude, frequency content...) with regard to the structure and its dynamic properties (e.g. Clough &
52 Penzien, 1993). Thus, two key parameters among those influencing the seismic demand can be
53 considered: 1) the resonance frequencies of the site and 2) the building resonance frequencies.

54 Seismic noise recordings in free-field and ambient vibration recordings in buildings are robust and low
55 cost methods for estimating the soil and structure low-strain resonance frequencies. Since the 1990s
56 and the widespread studies for site effects based upon the Horizontal to Vertical Noise Spectral Ratio
57 (HVNSR), several papers have shown the relevancy of HVNSR to partially explain damage locations
58 and/or grades (e.g., Anderson et al., 1986; Guéguen et al, 1998; Duval et al, 2006; Theodoulidis,
59 2008). However, other studies show that HVNSR alone cannot be directly linked to damage
60 distribution (Mucciarelli et al, 1998, 1999; Trifunac et al, 2000; Tertulliani, A. et al., 2012) and the
61 damage variability can also be related to the building capacity rather than the site characteristics
62 (Chatelain and Guillier, 2008).

63 Besides, ambient vibration recordings in buildings have gained more and more interest for last
64 decades, for earthquake engineering and civil engineering applications. The elastic fundamental
65 frequency is a key-parameter in earthquake engineering for building response assessment (e.g.
66 Michel et al., 2010a, 2010b) and structural health monitoring (e.g. Carden and Fanning, 2004, Dunand
67 et al., 2004).

68 The joint approach (i.e. free-field and building investigation) can be relevant for post-seismic
69 evaluation of the origin of the damage variability and building integrity. Gallipoli et al (2004), Gosar et
70 al. (2009) and Mucciarelli et al. (1999, 2010) showed by ambient vibrations applications that soil-
71 structure resonance could play a major role in damage location.

72 Following the 29th November 2007 Mw=7.3 Martinique earthquake, a post-seismic survey was set up
73 to collect macroseismic data by the Bureau Central Sismologique Français in charge of the definition

74 of the macroseismic intensities after earthquakes (Schlupp et al., 2008). During this survey, the
75 authors performed ambient vibration recordings in highly damaged zones.

76 The scope of this paper is to show a case study of the usefulness of the joint utilisation of ambient
77 vibration recordings in free-field and building to (1) improve the evaluation of the damages, (2)
78 understand the origins of the damage variability by understanding the low-strain response of the soil
79 and building and (3) show the relevancy of these information to complete a macroseismic study such
80 as the one led by the BCSF.

81 **DESCRIPTION OF THE CASE STUDY**

82 The 29th November 2007 Martinique earthquake occurred at rather great depth (152 km) with a
83 moment magnitude of 7.3 (Guéguen, 2012) located in the northwest at 30 km of the island. The
84 French Accelerometric network (RAP <http://www-rap.obs.ujf-grenoble.fr>, Pequegnat et al., 2008)
85 recorded ground motions due to the main shock in 34 stations in Martinique (Fig. 1). The horizontal
86 Peak Ground Accelerations (PGA) is ranging from 0.3 to 4 m.s⁻² through the island. The local
87 variability is large, e.g. in Fort-de-France from 0.4 to 2 m.s⁻² over several hundreds meters, indicating
88 the importance of local soil conditions. Macroseismic intensities using EMS98 (Grünthal et al., 1998)
89 on the island were estimated between V and VI-VII (Fig. 1). We performed ambient vibration
90 recordings in free-field and in buildings in three sites (Fig. 1), selected for the high level of structural
91 damages compared to the macroseismic intensities estimated in the town.

92

93 Figure 1

94

95 Site 1. In Le Francois, damage due to the earthquake did not exceed grade 2 (EMS98) except for two
96 school buildings, which suffered damage up to grade 3. The building A of Anne Marc school (Fig. 2) is
97 a two-storey building with reinforced concrete (RC) frames built in 1973 without earthquake-resistant
98 design on ancient mangrove, sedimentary deposit prone to site effects (Guéguen et al., 2011). It
99 exhibits a low lateral stiffness in the longitudinal direction and a soft story at the ground floor. After the
100 earthquake, we observed cracks at the bottom of several columns of the ground floor as well as
101 numbers of cracks in partition walls and falls of mortar (damage grade 3 EMS98).

102

103 Site 2. In La Trinité, the AFPA buildings (E and H) were strongly damaged. Both structures, built in the
104 1970s without earthquake-resistant design, were studied but this paper focuses on building E. It is a
105 two-storey building with RC frames and a soft ground floor (Fig. 2). This building is divided by thin
106 filled joints into 4 L-shaped blocks, sensitive to torsion due to the eccentricity of the rigidities.
107 Moreover, infill brick walls are not symmetrically distributed. It suffered slight structural damage (small
108 cracks in columns at the ground floor) and moderate non-structural damage (large cracks in partition

109 walls). According to soil studies during the construction, these buildings are founded on sedimentary
110 deposits.

111

112 Site 3. The hospital of La Trinité is a RC infilled frames structure built in 1974. Excluding low-rise
113 aisles, three high-rise blocks (called A, B and C) are respectively 9, 8 and 7 stories above the ground
114 level and separated by 5 cm joints filled by Styrofoam (Fig. 2). After the earthquake, small cracks
115 appeared in the structural system, larger cracks and plaster falls in the infill walls and false ceiling
116 pieces fell down, associated to moderate damage (grade 2).

117

118

Figure 2

119 **EXPERIMENTS, PROCESSING AND RESULTS**

120 Ambient vibration recordings in free field and in structures were at least 15 min. long with
121 seismometers (Lennartz 3D 5s and LITE) and a 24-bits Cityshark digitizer (Chatelain et al., 2000) at a
122 sampling frequency of 150 Hz to 200 Hz. The N component of sensors, were oriented in one of the
123 main direction of the studied building. The free-field recordings were analyzed using Horizontal to
124 Vertical Noise Spectral Ratio (HVNSR) method where the Fourier Transforms of at least 30 s windows
125 selected with an anti-triggering STA/LTA (Short Term Averaging, Long Term Averaging) algorithm are
126 averaged and smoothed following Konno and Ohmachi (1998) procedure ($b=40$). The HVNSR is given
127 by the ratio of the quadratic mean of the horizontal spectra by the vertical one and interpreted
128 following the SESAME project recommendations (Bard, 2004). If the SESAME criteria are fulfilled, the
129 frequency of the peak is likely to be related to the fundamental frequency of the site.

130 Depending on the importance of the building, on the complexity of the structure and on the severity of
131 the damages, one must adapt the experimental procedure. Ambient vibrations in buildings were
132 recorded with one or two sensors simultaneously. Several processing techniques were used
133 depending on the number and position of the recording points. For single station recordings at the
134 building top, the Power Spectral Density (PSD) spectra have been estimated (square of the Fourier
135 Transform amplitude) using the same procedure as for the ground without smoothing. Interpretation of
136 these spectra in terms of building dynamic properties may be ambiguous and were done with caution.
137 For simultaneous recordings at different points, the Frequency Domain Decomposition (FDD, Brincker,
138 2001) is used as in Michel et al. (2010a). Peaks in the first singular values can be interpreted as
139 resonance frequencies and singular vectors as modal shapes. The knowledge of modal shapes is
140 crucial for the interpretation of structural modes, but their quality depends on the number and position
141 of recording points.

142 For both ground and structure, the resonance frequencies obtained from ambient vibration recordings
143 are valid for low strains. During strong motion, nonlinear response of the soil (e.g. Régnier et al.,

144 2012), the building (e.g. Michel and Guéguen, 2010) and the soil–structure interaction can temporarily
145 make the observed natural frequencies shifting to lower frequencies. Nonetheless, Puglia et al. (2011)
146 showed that the frequencies variations due to nonlinear soil behavior were not relevant (during the
147 l’Aquila earthquake for which acceleration up to 0.7 g were recorded) from building design standpoint.
148 In this article, we study the link between damage and the similarity in the natural linear frequencies of
149 the soil and the structure.

150

151 In the Anne Marc School (site 1), both soil and structure recordings were performed to evaluate and
152 compare the soil and structure responses. The analysis of the recordings (Fig. 3) shows that the peak
153 frequency of the HVNSR in free field (1.75 Hz) and the first peaks of the PSD in the structure in both
154 directions (1.6 and 1.8 Hz in the longitudinal and transverse directions, respectively) are very close. It
155 indicates that the structure is sensitive at low strain to the 1D resonance frequency of the soil and,
156 thus, that a resonance between soil and structure eventually occurred during the Martinique
157 earthquake, inducing higher damage.

158

159 Figure 3

160

161 In the AFPA building (site 2), the same procedure was followed but with more recording points. Free-
162 field recordings were performed at different ground levels (S1, 3 m from the building at the same level,
163 S2, 15 m from the building downhill, Fig. 2). Frequency peaks are clearly observed at 2.4 and 2.8 Hz
164 in the HVNSR for S1 and S2, respectively (Fig. 4), the difference of the frequencies being certainly
165 due to the variation of the deposit thickness.

166 In three of the 4 L-shaped blocks of the building (named L1, L2 and L3), we recorded ambient
167 vibrations simultaneously at the ground floor, the first and the second stories. The chosen sensor
168 placement, however, did not allow to fully understand the dynamic behaviour of the building. The
169 fundamental modes appear between 2.7 and 4.3 Hz and include bending and torsion. These modes
170 are quite close to the fundamental frequency of the ground found previously (2.4 to 2.8 Hz). However,
171 the other AFPA building (building H), not detailed here, has higher resonance frequencies (3.5 to 4.5
172 Hz) and was therefore less prone to resonate with the ground but was more damaged than building E
173 (damage grade 3) also with typical damage due to torsion. In this case, the design of the structure
174 (lack of symmetry in the load bearing system) was therefore probably the main cause of damage
175 during the earthquake.

176

177

178 Figure 4

179

180 Finally, in the hospital building (site 3), full-scale ambient vibration recordings have been performed
181 several months before the event. After the Martinique earthquake, we recorded ambient vibrations in
182 the building to analyse the evolution of its dynamic behaviour related to damage.

183 As illustrated in Fig.5, the soil at his site is prone to site effect with a clear peak at 2.4 Hz. The Fourier
184 transform of the recordings at the top of the block A shows that the building resonance frequencies are
185 close to the HVNSR peak around 2.5 Hz.

186

187 Figure 5

188

189 Data recorded in 93 points of the structure before the earthquake has been reprocessed using FDD
190 technique (Brincker et al., 2001) (Fig. 6). In this dataset, two close clear peaks carried by the 2 first
191 singular values indicate the presence of 2 modes around 2.5 Hz. The first mode at 2.45 ± 0.03 Hz is the
192 first longitudinal bending mode of the whole building (Fig. 6). The second mode at 2.56 ± 0.03 Hz is the
193 first transverse bending mode of the structure. The modal shape indicates that these modes are partly
194 coupled to torsion but with differences for each block. The amplitudes of the higher modes are lower
195 and are not detailed here.

196

197 Figure 6

198

199 The PSD of the ambient vibration recordings in the structure at the same position before and after the
200 earthquake have been calculated (Fig. 7). Assuming only a moderate frequency decrease, the
201 knowledge of the pre-earthquake structural behaviour allows interpreting the peaks of the post-
202 earthquake recordings. The first longitudinal mode has shifted from 2.45 ± 0.03 Hz to 2.00 ± 0.05 Hz, i.e.
203 $18 \pm 4\%$ frequency drop. Moreover, the first transverse mode has shifted from 2.56 ± 0.03 Hz to
204 2.15 ± 0.05 Hz, i.e. $16 \pm 4\%$ frequency drop. Dunand et al. (2004) already used this technique at a larger
205 scale after the Mw=6.8 Boumerdes, Algeria earthquake (May 21, 2003) and suggests a value of 40%
206 frequency drop as a limit for the building to be impossible to retrofit (difference between orange and
207 red classification). The observed damage is therefore noticeable but not critical as denoted by the
208 assigned damage grade 2 EMS. However, such comparisons are still lacking in the literature to
209 propose a relationship between frequency drop and damage grade.

210 Ambient vibration recordings in free field were as well performed before and after the earthquake. The
211 soil fundamental frequency at 2.4 Hz is found to be the same. The resonance of the building before
212 the earthquake (2.45 Hz for the first mode) is very close from the soil fundamental frequency.
213 Resonance between the soil and the building response increased the seismic demand of the structure,
214 which explains most probably the damage.

215

216 Figure 7

217

218 **CONCLUSIONS**

219 Through these examples, we illustrated how to use ambient vibration recordings in soil and structure
220 in post seismic survey. This approach helps to understand the possible causes of damaged zones
221 distribution. Moreover, ambient vibrations recordings are low cost and can be rapidly set up after an
222 earthquake.

223 With soil recordings, we investigated the possibility of soil to be prone to site effect. Link with damage
224 is however not straightforward: site effect only increases the seismic demand around the soil
225 resonance frequency. However, using both soil and structure recordings, the sensitivity of the
226 structure to the 1D linear soil resonance can be checked. Thus, conclusions can be made on the
227 possibility of having a resonance between soil and structure, which increases the seismic demand in
228 the building and can induce higher damage.

229 In the three study-sites, the free field ambient vibration recordings indicate the occurrence of site
230 effects. We found similarities between soil and structures resonance frequencies. It appears that
231 resonance played a role in damage distribution.

232 In the La Trinité hospital, the fundamental frequency suffered a shift of 15-20% during the earthquake.
233 Besides, the permanent frequency shift was related to a loss of stiffness of the structure that can be
234 associated to a damage grade 2 EMS 98. To analyse temporary frequency shift, structure permanent
235 monitoring is necessary.

236

237 According to this case study, we can make some recommendations for the use of these recordings in
238 post seismic survey. These recommendations should be adapted to the building importance, damage
239 level and the objectives of the recordings. In our experience, such post-seismic survey should be
240 focused on important buildings (importance class III and IV in Eurocode 8).

241

242 • Objective 1: Looking at potential concordance between soil and structure frequencies. In this
243 case only one recording at the top of the structure and one on the free field (in the same
244 geological context as the soil under the structure) are sufficient. Such measurements are
245 interesting to understand the sources of damage. Analysis of such measurements could be
246 used as one support (among others) to make decision on whether the building should be
247 retrofitted (so as the resonance frequency of the building is different from the soil one).

248

249 • Objective 2: Having the modal shape associated to the predominant frequency. It requires
250 simultaneous recordings at different storeys of the building. Such information could be very
251 useful to constrain the numerical simulation of the dynamic behaviour of the structure and to
252 test retrofitted solutions. Besides it can also be used to evaluate the evolution of the
253 damaged structure behaviour during the aftershock sequences.

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- Objective 3: Evaluate the stiffness loss of the structure and evaluate damage grade. It requires recordings at the top of the building before and after the earthquake. It is very useful in crisis management and is a support to emergency diagnosis of the building and visual screening of damages state. It is a quantitative measurement that is complementary to expert advises. Such measurements should be performed for high stake buildings of class IV in Eurocode 8.

For risk mitigation and to anticipate post earthquake crisis management, recordings of ambient vibrations should be performed in structures of high importance. Although permanent monitoring has a heavy cost, it should be considered for a small number of typical buildings.

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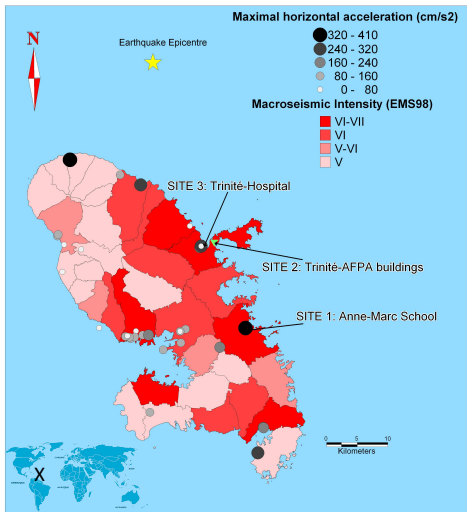
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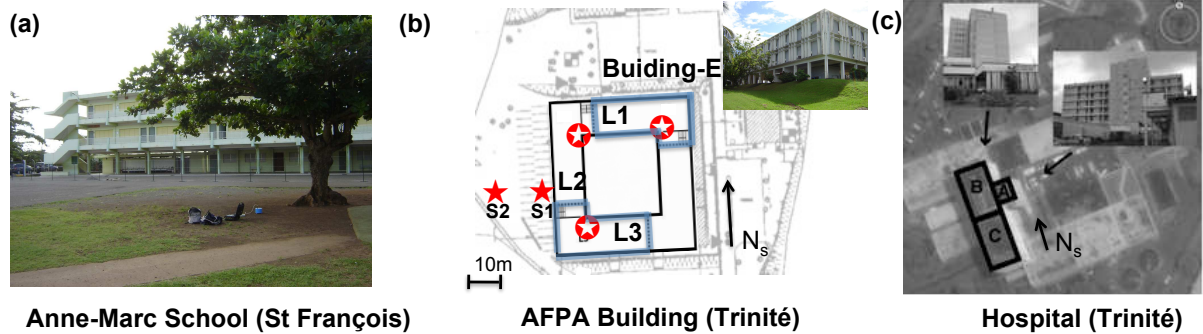
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353 **FIGURES**



354

355 Figure 1 Map of the macro seismic intensity at the Martinique island after the 28th November 2007
 356 earthquake. The circles indicate the position of the RAP stations that recorded the earthquake (size
 357 scale is function of the maximal PGA on the three components in cm/s^2), and location of the sites that
 358 were studied.



359

360

361 Figure 2: (a) Site 1- Location of the recordings performed at the Anne-Marc school in Le François. The
 362 building ambient vibration recording is performed at the second floor half length. (b) Site 2- AFPA
 363 Building E at the Trinité district. (c) Site 3 - The La Trinité Hospital site (aerial view) with study-blocks
 364 A, B and C. The Sensors were oriented in the transverse direction of the buildings (the N component
 365 of the sensors is called N_s)

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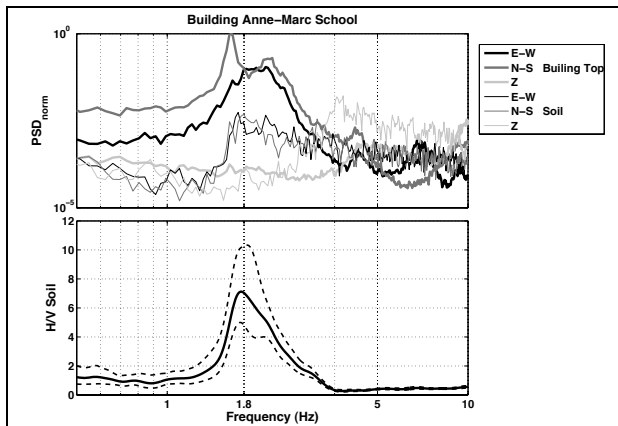


Figure 3: Site 1 – Top: Normalized Power Spectral Density of the recordings in the structure (solid lines) and the recordings in the soil (dashed lines) in the 3 directions East (E) North (N) and Vertical (Z). Bottom: HVNSR of the free field recording (mean, 16 and 84 percentiles).

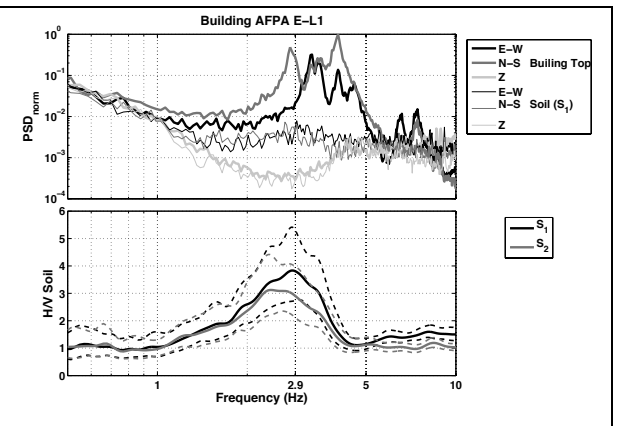


Figure 4: Site 2 - Top: Normalized Power Spectral Density of the recordings in the structure (solid lines) and the recordings in the soil (dashed lines) in the 3 directions East (E) North (N) and Vertical (Z). Bottom: HVNSR of the free field recording (mean, 16 and 84 percentiles).

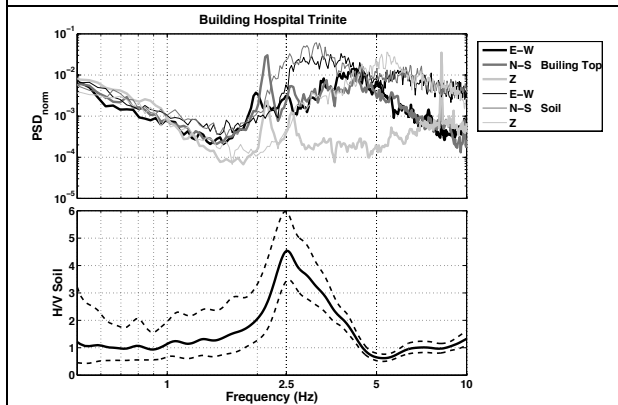
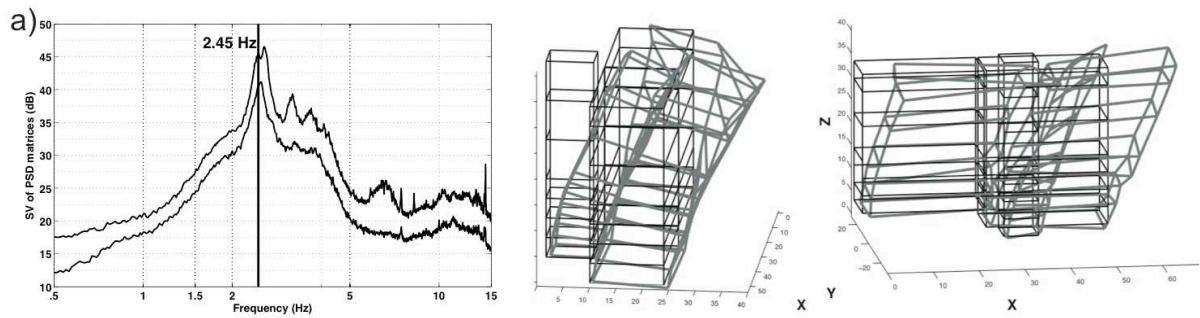


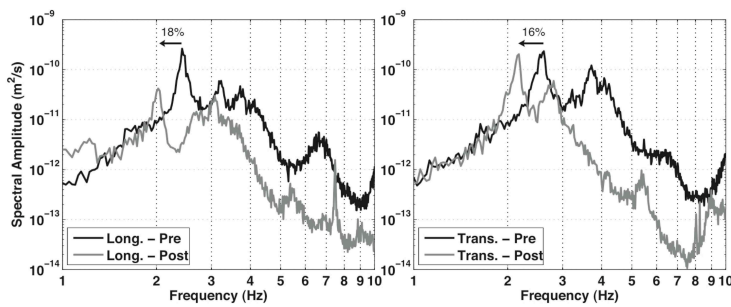
Figure 5: Site 3 - Top: Normalized Power Spectral Density of the recordings in the structure (solid lines) and the recordings in the soil (dashed lines) in the 3 directions East (E) North (N) and Vertical (Z) of the recording at the top of the block A. Bottom: HVNSR of the free field recording the mean, 16 and 84 percentiles.

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373 Figure 6: Site 3 - Pre-earthquake modal analysis results. a) FDD spectrum, b) Modal shapes of the
 374 first transverse and longitudinal modes at 2.56 and 2.45 Hz, respectively.



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377 Figure 7: Site 3 – Pre- and post-earthquake PSD spectra in block A in the longitudinal (left) and
 378 transverse (right) directions.