

The H/V Spectral Ratio Technique for Dynamic Characterization of Existing Buildings in Morocco

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Abstract On September 8, 2023, Morocco suffered a severe earthquake in the Al-Houaz region, with a magnitude of 6.8 on the Richter scale. Some areas were more severely affected than others, with different degrees of damage observed on buildings of the same type. It appears that site effects, aging, and structural degradation are responsible for the increase in this damage. To understand these effects, the H/V spectral method provides useful information on the dynamic behavior of buildings using microtremor measurements. In this study, the frequencies and damping of a set of Moroccan buildings are derived from measurements of ambient vibrations and compared to those given by the Moroccan seismic code and research works. For this purpose, ambient vibration measurement is performed on 17 existing buildings, representing the seismic classification of the European Macroseismic Scale. This study shows that damping on different buildings is frequency-dependent, which can be explained by the effect of radiative damping when buildings are founded on flexible soils and is a possibility to take into account in seismic design. A comparison of the frequencies measured at the top with those on the soil indicates the risk of soil-structure resonance. Also, the variation in frequency between the regulatory state and the ambient vibrations shows a decrease in frequencies for all buildings of vulnerability classes A and B, while for buildings of classes C and D, no variation in frequency was

observed. This highlights a qualitative assessment of the damage and loss of rigidity of the buildings measured.

Keywords H/V Method, Ambient Vibrations, Nakamura Method, Soil-Structure Resonance, Seismic Vulnerability

1. Introduction

The convergence of the African and Eurasian plates makes Morocco exposed to seismic risk. On September 8, 2023, Morocco experienced a destructive earthquake in the High Atlas Mountains known as the Al Haouz earthquake, with a magnitude of 6.8 on the Richter scale and ranking as high as IX on the Mercalli Intensity Scale. Some areas of the Al-Houaz region were more severely affected than others, with different degrees of damage observed on buildings of the same type. This earthquake caused nearly 3000 deaths and 4661 injuries, having aggravated the fragile building stock with 59,674 collapsed buildings, of which 32% were completely destroyed and 68% partially damaged [1]-[4].

Most of the Moroccan building stock is not constructed in accordance with seismic code, and many buildings are subject to significant rehabilitation works and gradually

deteriorate during their service lives. In this context, while the definition of site effects becomes a priority in the prevention of a building's vulnerability, knowledge of its dynamic behavior is also necessary. These factors increase the aggressiveness of many earthquakes on buildings, thus causing human and economic losses [5], [6].

Building modeling can reproduce their dynamic behavior under known effects, but it becomes more complicated for some types of buildings. It is therefore necessary to measure the dynamic behavior of civil engineering structures, and the H/V method enables this behavior through in situ measurements. These evaluations are based on the measurement of building responses to non-damaging dynamic loads induced by human and natural activities [7], [8].

The H/V spectral ratio, also known as the Nakamura method, is used to estimate the resonance frequency of a site and to identify the fundamental frequencies and damping of existing buildings [9], [10]. It is based on the division of the spectrum of the horizontal component by the spectrum of the vertical component of the ambient vibrations. It was originally proposed by Nogoshi and Igarashi [11], [12] and later diffused by Nakamura in 1989 [13]-[16]. Many authors have published studies on the site effects obtained by this method [17]-[21], and other research concerns the characterization of dynamic construction behavior [22]-[25]. The dynamic behavior of a structure is defined by natural modes of vibration, whose frequencies and strains are determined by geometry, mass and stiffness distribution, and boundary conditions. Damages are related to the stiffness of the building and, consequently, to the frequencies and deformations. Identifying and comparing these dynamic characteristics with the regulatory ones provide an idea of the loss of stiffness. With regard to this, the H/V method is a non-destructive, fast, low-cost approach to identifying these characteristics.

The main objective of this paper is to exploit the results of the H/V method for the dynamic analysis of a set of buildings located in Morocco, presenting the seismic classification of the European Macroseismic Scale (EMS-98). The results make it possible to quantify the loss of stiffness due to damage based on frequency and damping variations and to assess the potential resonance of measured buildings with the soil. The first part gives a general overview of the principles and applications of the H/V method. The second one presents the buildings studied and the results obtained from the ambient noise vibration recordings. The last section compares and discusses these results for all the buildings measured and offers further suggestions for completing this work.

2. Description of the H/V Method

In 1971, Nogoshi and Igarashi presented the fundamental principles of the H/V method [11], [12]. Following Nakamura's article in 1989 [15], the H/V spectral ratio method became very popular worldwide. This technique estimates the ratio between the Fourier amplitude spectra of the horizontal and vertical components of the ambient vibrations recorded at the station [26]-[29].

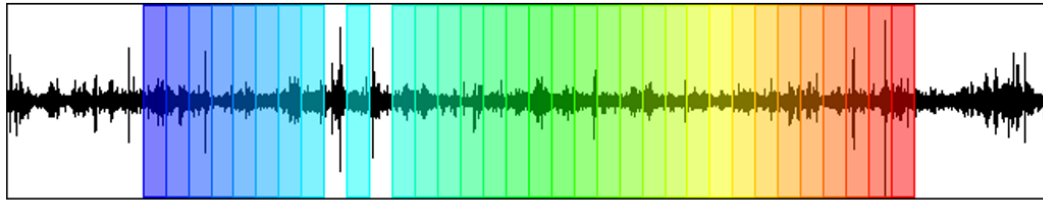
2.1. Importance of the H/V Method

Ambient vibrations are any solicitation, other than an earthquake, which generates vibrations in the soil. These solicitations may be natural or human-made and correspond to different frequency bands. At low frequencies (< 1 Hz), the sources are natural, such as ocean waves; at intermediate frequencies (between 1 and 5 Hz), the sources are natural or human activities; and at high frequencies (> 5 Hz), the sources are human activities, such as traffic or machinery [30], [31]. The amplitude of the ambient vibrations varied with the proximity and nature of the sources of the vibrations. The low amplitude of these vibratory solicitations ($10^{-7}g$ to $10^{-5}g$) makes it possible to describe the small deformation or linear behavior of structures [32]. Regulatory seismic calculations in Morocco generate accelerations of 0.04 g to 0.18 g [33], resulting in small to large deformation behavior and non-linear effects. These ambient vibrations have been used to assess the dynamic behavior of buildings, in particular their frequencies and risk of resonance. The transient decrease in frequency is permanent and is attributed to a decrease in the structure's rigidity, i.e., to damage that may not have been visually observed, referred to as structural aging. The H/V method makes it possible to monitor this parameter over time, thus quantifying the state of aging and damage to the structure.

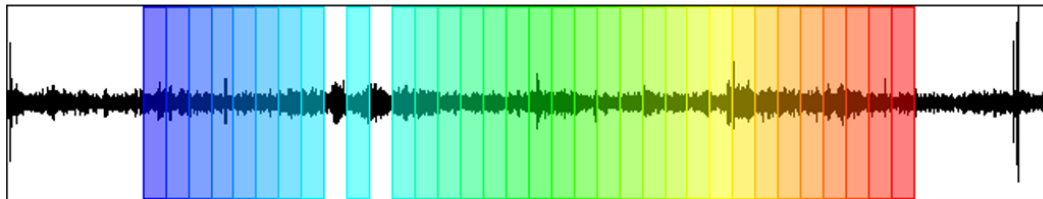
2.2. Computation of H/V Ratio

A detailed description of the experimental procedure of an ambient vibration recording to calculate H/V ratios and the limits of its field of application is one of the objectives of the SESAME European project (Site Effects Assessment Using Ambient Excitations) [35]. The principle of the H/V method is based on the recording of the ambient vibrations over a ten-minute duration according to the three components of displacement: vertical, horizontal North-South, and horizontal East-West [34]. Using this technique, the recorded signals are converted to the frequency domain, and then the characteristics of the peaks in the spectrum are examined [9], [36]. This procedure is shown in Figure 1 and is defined as follows:

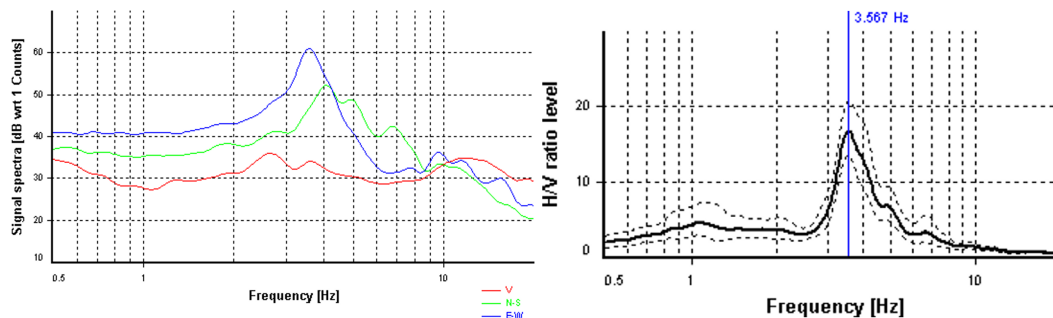
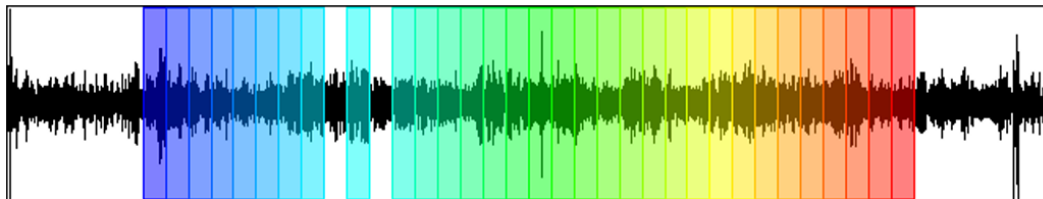
CHANNEL #1 [V]



CHANNEL #2 [N]



CHANNEL #3 [E]



HVSr curve reliability criteria		
$f_0 > 10 / L_w$	32 valid windows (length > 2.8 s) out of 32	OK
$n_c(f_0) > 200$	4566.03 > 200	OK
$\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$	Exceeded 0 times in 75	OK
HVSr peak clarity criteria		
$\exists f \text{ in } [f_0/4, f_0] \mid A_{H/V}(f) < A_0/2$	3.1331 Hz	OK
$\exists f^+ \text{ in } [f_0, 4f_0] \mid A_{H/V}(f^+) < A_0/2$	4.4559 Hz	OK
$A_0 > 2$	16.8 > 2	OK
$f_{\text{peak}}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$	0% <= 5%	OK
$\sigma_f < \varepsilon(f_0)$	0.17771 < 0.17836	OK
$\sigma_A(f_0) < \theta(f_0)$	1.24166 < 1.58	OK
Overall criteria fulfillment		OK

Figure 1. Illustration of the H/V method processing steps: (a). Windowing of a 3-component microtremor signal. (b). Calculation and smoothing of the Fourier amplitude spectra for the 3 components. (c). Root-mean-square of the two horizontal components and selection of the peak frequency f_0 marked by the vertical line. (d). Assess the reliability of the H/V curve and the selected peak with SESAME criteria

Step 1: Selection of the three components (V: Vertical, HN-S: North-South, HE-W: and East-West) of an ambient vibration signal.

Step 2: Calculation and smoothing of the Fourier amplitude spectra for the 3 components.

Step 3: Root-mean-square of the two horizontal components for each window.

Step 4: Calculation of the H/V ratio expressed by Equation 1 and selection of the peak frequency:

$$H/V = \sqrt{\frac{H_{N-S}^2 + H_{E-W}^2}{2 V^2}} \quad (1)$$

Where:

H_{N-S} : Fourier amplitude spectra of the North-South component.

H_{E-W} : Fourier amplitude spectra of the East-West component.

V: Fourier amplitude spectra of the vertical component.

Step 5: Assess the reliability of the H/V curve and the selected peak with SESAME criteria.

In this study, all ambient vibration recordings are measured using seismometers with a natural frequency of 1 Hz (Figure 2). All types of external noise disturbance and transient noise must be eliminated before measuring the ambient vibrations in the field to obtain good signal quality and good accuracy in predicting natural soil and building frequencies. The conditions under which each recording is made are based on the model proposed in SESAME. H/V data are processed using Geoxplorer software; this software has a module that automatically checks the SESAME criteria.

3. Ambient Vibrations Measurements of Buildings Selected

3.1. Description of Buildings Selected

In total, 17 ambient vibration recordings were made on different building typologies. The set of buildings measured was selected from four different building

typologies representative of buildings in Morocco, as developed in the article [37], presenting the seismic classification of the European Macroseismic Scale (EMS-98) as illustrated in Figure 3 [38]-[41]. The sensors are located on the soil and at the roof level of each building.

The different buildings measured are presented in Figure 4.

3.2. Ambient Vibrations Results

The treatment of H/V data makes it possible to quantify the loss of stiffness due to damage based on frequency and damping variations and to assess the potential resonance of measured buildings with the soil. Figure 5 shows the peak frequencies identified on the spectral amplitudes for 4 buildings in their longitudinal and transversal directions with ambient vibration records computed at the roof (a) and on the soil (b). Table 1 details the different dynamic characteristics obtained from the ambient vibration recordings for all the instrumented buildings.



Figure 2. Ambient vibration instrument

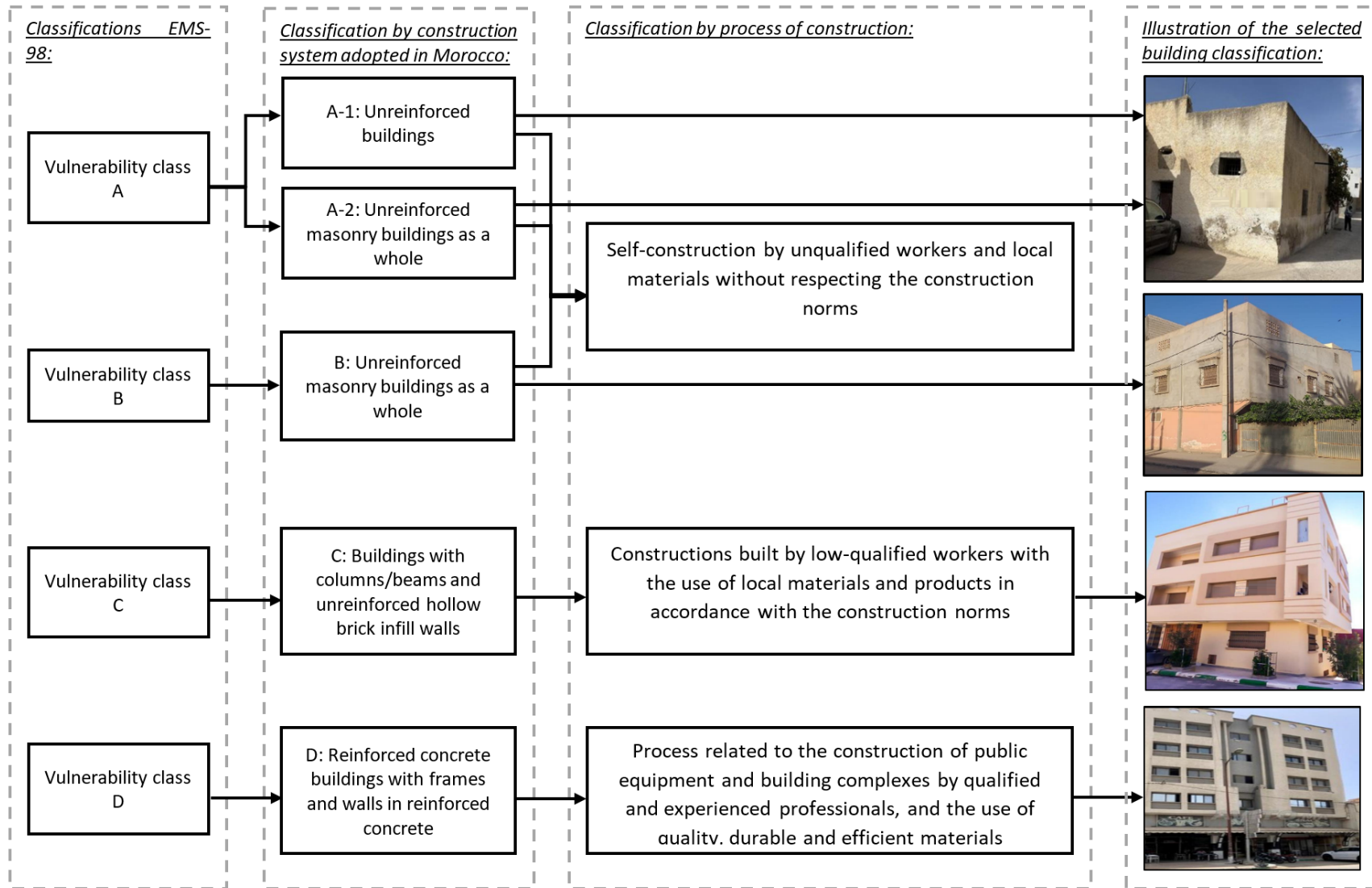
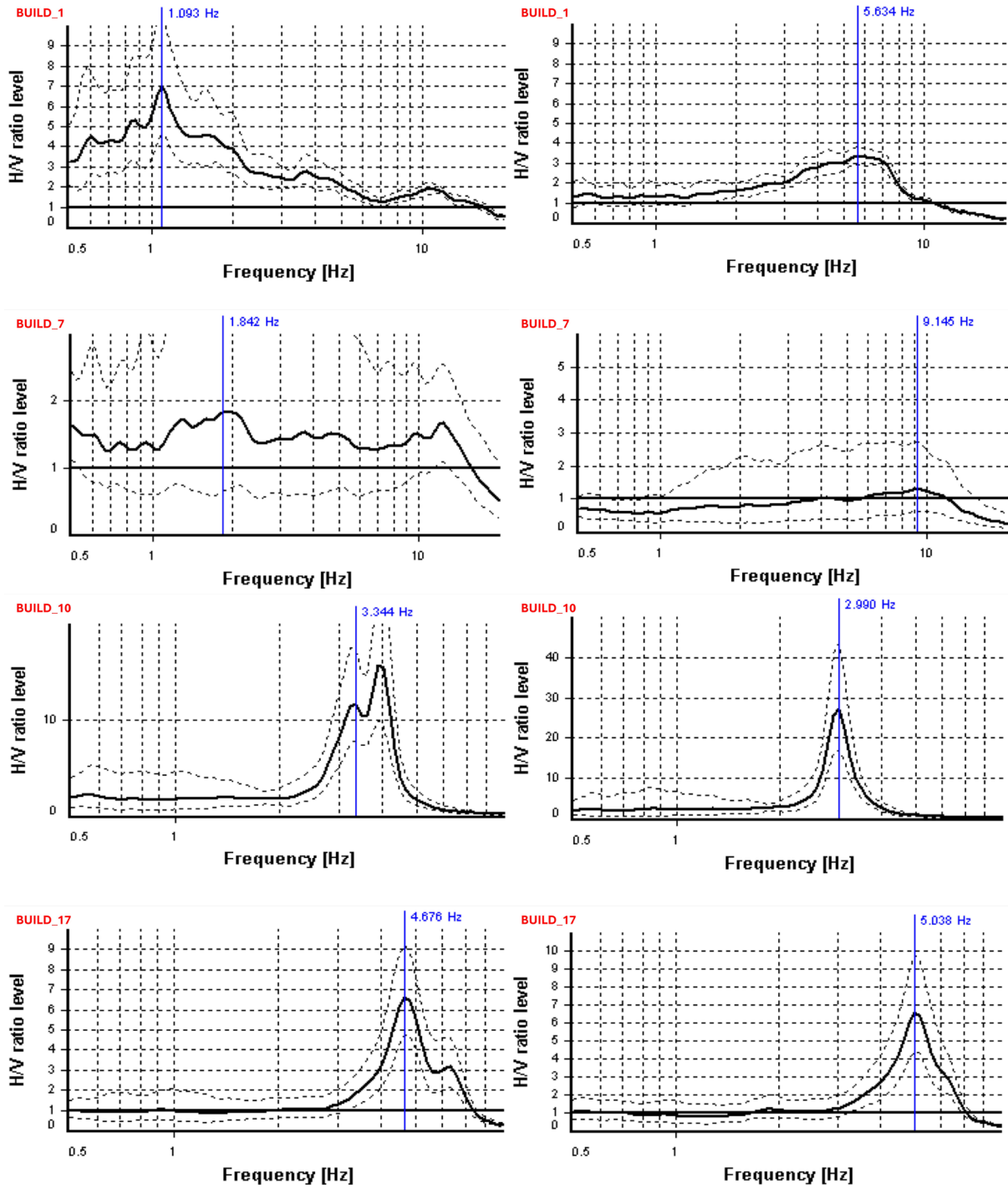


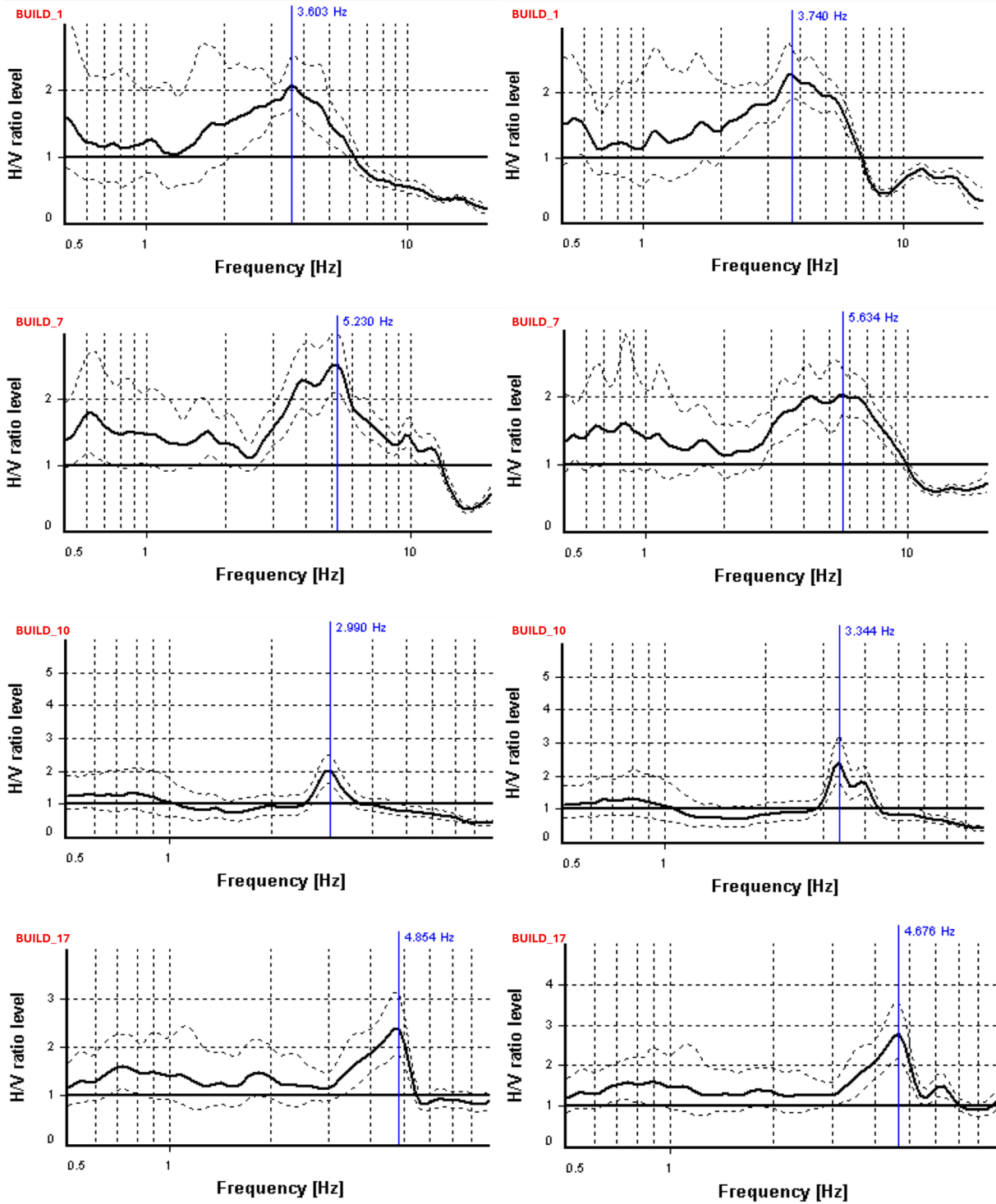
Figure 3. Synthetic schema of the classification of buildings in Morocco



Figure 4. List of the instrumented buildings using the H/V technique



(a)



(b)

Figure 5. The H/V spectral ratio of four buildings with ambient vibration records computed at the roof (a) and on the soil (b)

Table 1. Dynamic characteristics of the 17 buildings with ambient vibration records

Ref.	Building type	Vulnerability class	Height [m]	Plan dimensions		Selected frequency f_0 [Hz]			
				Long. [m]	Trans. [m]	Soil		Roof	
						Long.	Trans.	Long.	Trans.
Build_1	Residential building	A	3.5	4	5	3.6	3.74	1.09	5.63
Build_2	Residential building	A	4.5	5	5.5	0.5	0.5	3.4	1.18
Build_3	Residential building	B	10.5	8	14	8.49	8.49	2.04	3.25
Build_4	Residential building	B	10.5	8	9	5.63	4.68	5.85	6.79
Build_5	Residential building	B	11	8	10	8.18	8.18	9.85	8.81
Build_6	Residential building	B	7	10	10	5.04	5.04	2.99	7.31
Build_7	Residential building	B	12	8	12	5.23	5.63	1.84	9.15
Build_8	Residential building	C	8	8	10	1.05	1.05	3.2	5.04
Build_9	Residential building	C	8	7	12	4.18	4.18	4.2	5.23
Build_10	School building	C	12	15	15	2.99	3.34	3.34	2.99
Build_11	Administrative building	D	12	13	13	3.34	3.47	6.79	3.74
Build_12	Administrative building	D	10	10	10	1.99	2.78	2.88	2.88
Build_13	Hospital building	D	10	16	20	2.39	2.39	4.01	3.98
Build_14	Industrial building	D	12	12	12	4.03	3.88	4.02	3.7
Build_15	Residential building	D	16	16	12	0.91	0.91	3.6	3.1
Build_16	Residential building	D	14	14	12	5.43	5.43	4.85	5.23
Build_17	University building	D	17	16	16	4.85	4.68	4.68	5.04

4. Fundamental Period and Damping Evaluation of Buildings Using Codes Seismic

Fundamental period and damping ratio are the principal factors in seismic design. To estimate the period of vibration of buildings rapidly, the Moroccan seismic building code offers empirical formulas for estimating the period of a building based on its horizontal and vertical dimensions [33]. Following the Moroccan seismic code, these empirical formulas are applicable under specific conditions. For reinforced concrete frames, it can be estimated using Equation 2:

$$T = 0.075 H^{3/4} \quad (2)$$

Where T is the fundamental period of vibration, H is the building height.

Taking into account the presence of infill walls, the Moroccan seismic code proposed the following empirical expressions:

$$T = 0.09 H/(L)^{0.5} \quad (3)$$

$$T = 2N(N + 1)/(M/k)^{0.5} \quad (4)$$

Where T is the fundamental period of vibration, N is the number of floors, L is the length of the wall in the

direction of the seismic action, and M/k is the ratio of mass to stiffness per level, respectively.

L'euocode 8 proposed the empirical formula given by Equation 5 for the estimation of the fundamental period:

$$T = C_t H^{3/4} \quad (5)$$

Where C_t is a numerical coefficient that depends on the type of bracing system. For reinforced concrete frames, its value is 0.075, identical to the formula proposed by the Moroccan seismic building code. For buildings with concrete or masonry shear walls, the numerical coefficient C_t can be calculated using the Equation 6:

$$C_t = 0.075/\sqrt{A_c} \quad (6)$$

Where A_c is the total effective area of the shear walls in the first storey of the building.

However, the Eurocode 8 and the Moroccan seismic building codes do not define empirical formulas to estimate the damping ratio for seismic design; the standard damping recommended by this code for ordinary buildings is 5%. The treatment of H/V data has also made it possible to estimate the damping of the buildings studied in the longitudinal and transverse directions. Lagomarsino proposed a damping predictor for ordinary buildings and steel structures, and the statistical analysis of Lagomarsino has shown that the only parameter on

which the damping depends is the fundamental frequency, a formula based on Rayleigh's damping law [42], [43]. The proposed forecast formula is:

$$\xi_{Lag} = 0.7238/f_0 + 0.7026 f_0 \quad (7)$$

5. Discussion

Based on building heights and the classification illustrated in Figure 3, it can be concluded that the frequency of buildings of Vulnerability Class A takes values between 3.71 Hz and 6.71 Hz. For buildings of vulnerability class B, the fundamental frequency ranges from 2.07 Hz to 3.99 Hz. For buildings of vulnerability classes C and D, the fundamental frequency is between 0.61 Hz and 3.48 Hz. From ambient vibration measurements, it was observed that the frequencies of buildings of vulnerability classes A and B show a distribution between 1 and 12 Hz. Reinforced concrete buildings of vulnerability classes C and D have frequencies between 2 and 7 Hz, which correlate well with those derived from the Moroccan seismic code standard formulas.

The comparison of these measured frequencies at the top with the estimated ones by formulas of the Moroccan seismic code underlines, for all the buildings of vulnerability class A, a decrease in frequencies is about 80% and around 40% for the majority of class B buildings, thus putting forward the effects of ageing and degradation of the studied buildings. In contrast, there was no change in frequency for buildings in vulnerability classes C and D. For some buildings, due to reinforcement and rehabilitation work carried out on the buildings studied, a considerable increase in frequencies was noted.

In some buildings, the frequencies measured at the top in the longitudinal and transversal directions are identical. This can be explained by several causes: approximately symmetrical distribution of mass and stiffness in the two directions, the modal deformation measured corresponds to a torsional mode, or the effects of foundations and soil.

The damping of buildings corresponds to the quantity of energy dissipated in one way or another during their vibration under applied loads. In seismic codes, damping

is considered constant and independent of frequency. Since the phenomenon of soil-structure interaction leads to energy loss from the building into the soil by wave radiation, a loss that increases with frequency, there is thus a relationship between damping and frequency. This dependence is more marked in the case of soft ground (lower S-wave velocity). Taking the movement of the building in terms of wave propagation, it's clear that as frequencies increase, the wavelength decreases, meaning that waves are diffracted by small heterogeneities such as mass or stiffness contrasts between bracing and floors. As a result, the energy measured at the top of the building is not equivalent to the energy of an entire wave front traveling back and forth between the top and bottom of the building but to the energy of waves that have been diffused throughout the building, giving a damping at the top of the building composed of three types of energy loss: intrinsic structural damping, wave radiation, and internal diffraction. These observations indicate the need to introduce damping-frequency dependency into seismic codes.

By comparing Lagomarsino's predictor to the standard damping recommended by Eurocode 8 and Moroccan seismic building codes, it can be observed that all the damping computed was lower than that of the codes. A comparison of the frequencies measured at the top with those on the soil indicates the risk of soil-structure resonance. Table 2 summarizes all dynamic characteristics identified using the H/V spectral ratio, the fundamental frequency values estimated using the Moroccan seismic code, and the resonance risk of the different buildings measured.

This article presents one of the engineering techniques used to assess the seismic vulnerability of buildings. Combining engineering and architectural techniques, using resistant materials and earthquake-resistant design, can minimize seismic damage and protect human life and material assets. Scientific and technical evolution in the field of earthquake engineering has also highlighted the importance of a technical revision of the Moroccan seismic code. The revision, based on an international benchmark of recently updated seismic codes, introduces recent techniques for the dynamic characterization of constructions and updating the seismic zone map.

Table 2. Dynamic characteristics and resonance risk of the different buildings measured

Ref.	Longitudinal direction				Transversal direction				Resonance risk	
	f_0 at soil [Hz]	f_0 at Roof [Hz]	ζ_{Lag} [%]	F [Hz]	f_0 at soil [Hz]	f_0 at Roof [Hz]	ζ_{Lag} [%]	F [Hz]	Long.	Trans.
Build_1	3.6	1.09	1.43	6.35	3.74	5.63	4.08	7.10	No risk	No risk
Build_2	0.5	3.40	2.60	5.52	0.5	1.18	1.44	5.79	No risk	With risk
Build_3	8.49	2.04	1.79	2.99	8.49	3.25	2.51	3.96	No risk	No risk
Build_4	5.63	5.85	4.23	2.99	4.68	6.79	4.88	3.17	With risk	No risk
Build_5	8.18	9.85	6.99	2.86	8.18	8.81	6.27	3.19	No risk	With risk
Build_6	5.04	2.99	2.34	5.02	5.04	7.31	5.24	5.02	No risk	No risk
Build_7	5.23	1.84	1.69	2.62	5.63	9.15	6.51	3.21	No risk	No risk
Build_8	1.05	3.20	2.47	3.93	1.05	5.04	3.68	4.39	No risk	No risk
Build_9	4.18	4.20	3.12	3.67	4.18	5.23	3.81	4.81	With risk	No risk
Build_10	2.99	3.34	2.56	3.59	3.34	2.99	2.34	3.59	With risk	With risk
Build_11	3.34	6.79	4.88	3.34	3.47	3.74	2.82	3.34	No risk	With risk
Build_12	1.99	2.88	2.27	3.51	2.78	2.88	2.27	3.51	No risk	With risk
Build_13	2.39	4.01	3.00	4.44	2.39	3.98	2.98	4.97	No risk	No risk
Build_14	4.03	4.02	3.00	3.21	3.88	3.70	2.80	3.21	With risk	With risk
Build_15	0.91	3.60	2.73	2.78	0.91	3.10	2.41	2.41	No risk	No risk
Build_16	5.43	4.85	3.56	2.97	5.43	5.23	3.81	2.75	With risk	With risk
Build_17	4.85	4.68	3.44	2.61	4.68	5.04	3.68	2.61	With risk	With risk

6. Conclusions

The treatment of H/V data for building frequencies and damping variations provides reliable information in relation to their dynamic behavior. It therefore seems worthwhile to integrate these measurements as an aid to seismic design, seismic diagnosis, and seismic vulnerability studies. From the study, the following conclusions can be drawn:

1. The comparison of the frequencies measured at the top of the ambient vibrations with those recorded on the soil indicates the risk of soil-structure resonance.
2. The variation in frequency between the regulatory state and the ambient vibrations shows a decrease in frequencies for all buildings of vulnerability classes A and B, while for buildings of classes C and D, no variation in frequency was observed.
3. The variation in frequency between the regulatory state and the ambient vibrations gives a qualitative judgment of the damage and loss of stiffness of the buildings measured. In the case of building reinforcements, these pre-reinforcement and post-reinforcement measurements can be used to verify the efficiency of the work carried out.
4. The damping observed on different groups of buildings systematically shows an increase in frequency. This dependence is explained by radiative

damping when buildings are built on soft ground and could be considered for inclusion in seismic codes.

These results also allow for applying different methods, such as the N2 Method Pushover or incremental dynamic analysis, for quantifying the vulnerability of existing buildings and proposing different seismic reinforcement interventions.

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