

# Seismic Site Characterization and Classification Using HVSR and MASW Analyses for Urbanization Suitability Assessment in the Azilal Urban Area, Central Morocco

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Article history: received March 14, 2026; accepted September 29, 2026

## Abstract

The Azilal urban area, located in the Central High Atlas and approximately 220 km from the 6.8 Mw Al Haouz earthquake epicenter, was investigated for seismic site effects using 24 Multi-Channel Analysis of Surface Waves (MASW) profiles and 99 Horizontal-to-Vertical Spectral Ratio HVSR. The Vs30 values derived from MASW inversion range from 500 to 1300 m/s, allowing the subdivision of the study area into three zones: central ( $Vs30 \leq 830$  m/s), northern ( $830 < Vs30 < 1300$  m/s) and southern ( $Vs30$  up to 1300 m/s). According to the Moroccan seismic design code (RPS 2000, version 2011), soils are classified into categories S1 (dominant) and S2, with S1 including the northern and southern zones formed by dense limestone and consolidated sandstone, and S2 corresponding to the central zone where karstified limestone and friable red clays dominate, while the NEHRP 2001 classified the study area into B and C classes. The amplification factor ranges from 1.0 to 1.5, indicating slight to moderate amplification. HVSR spectral analysis reveals natural frequencies between 0.5 and 2.3 Hz, with two main clusters: 1.38-1.69 Hz along the southeastern margin and 1.1-1.4 Hz in adjacent zones. These resonance zones correspond closely with the geomechanical boundaries, highlighting the critical role of subsurface geology in seismic response.

Keywords: Central High Atlas; Azilal; MASW; HVSR; Vs30 and Resonance frequency

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## 1. Introduction

Local site conditions are critical factors influencing seismic wave amplification and, consequently, the severity of damage during destructive earthquakes. Among these, shear wave velocity (Vs) and its depth variation are

fundamental parameters for predicting ground motion. Numerous studies have established correlations between  $V_S$  and ground motion amplitude (Boore, 2003; Boore et al., 2011; Park et al., 1998a; Stewart et al., 2003). In seismic design, building codes typically use a simplified representation of the  $V_S$  profile, namely the average shear wave velocity in the upper 30 m of soil ( $V_{S30}$ ), a parameter popularized by the National Earthquake Hazard Reduction Program (NEHRP) (Drake and Bachman, 1996).

Some researchers have proposed refining site classifications by incorporating fundamental frequency ( $f_p$ ) of the site, the inverse of the predominant period (TP). This frequency is considered an indirect indicator of soil stiffness and thickness (Weatherill et Burton, 2010). In recent years, site-specific geophysical investigations have advanced the assessment of seismic risk. Non-invasive methods such as MASW and HVSr have proven effective in mapping the spatial distribution of  $V_{S30}$ ,  $f_p$ , and related parameters (Carvalho et al., 2016; Livaoğlu et al., 2019; Rahman et al., 2018). Insights from past earthquakes underscore that site effects are especially significant in urban areas built over recent, unconsolidated sediments (Kawase et al., 2019). The MASW method offers several major advantages: it is

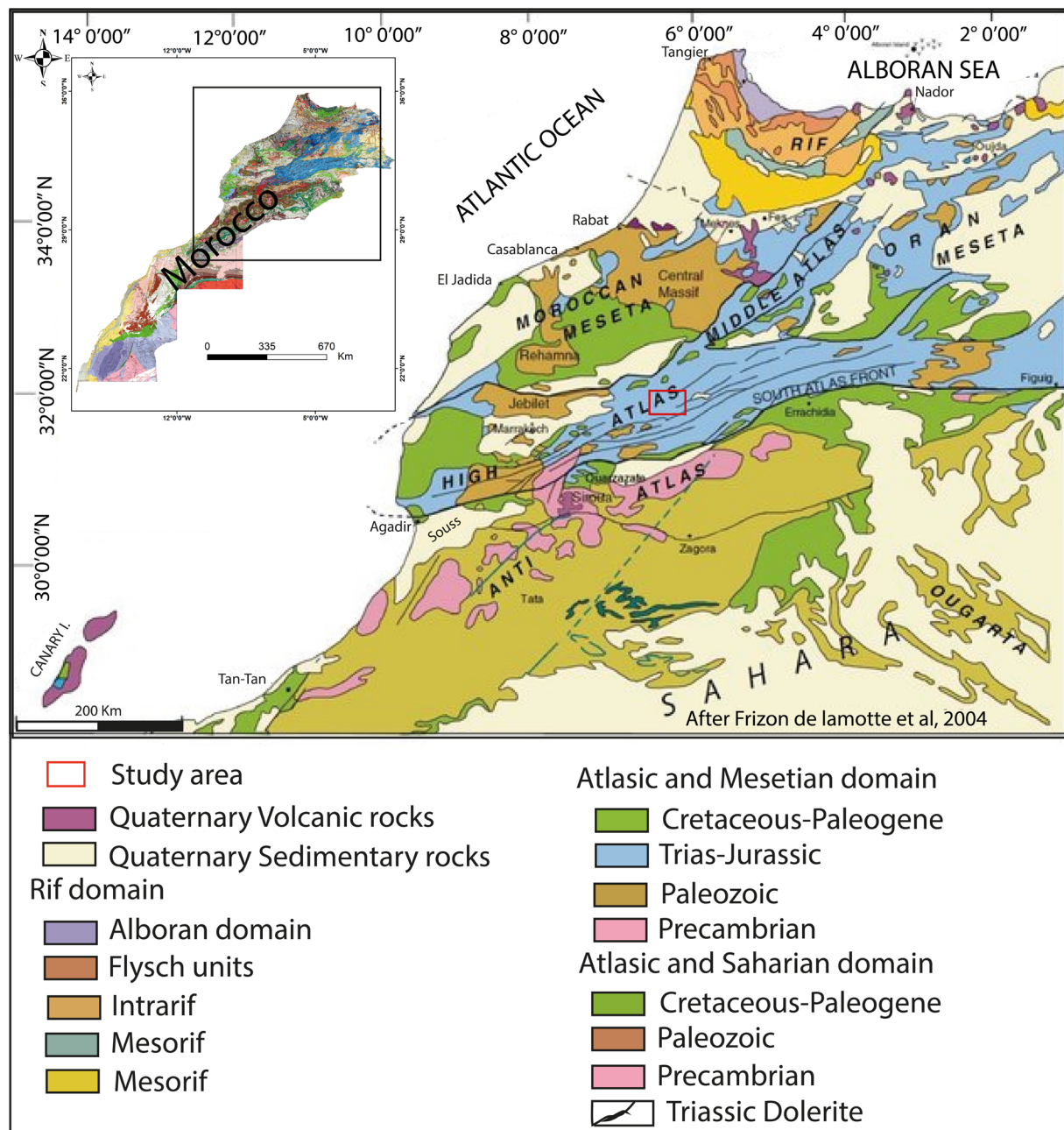


**Figure 1.** Geological location of the Azilal study area from the geological map of Morocco with 1:1,000,000 scale (Frizon de Lamotte et al., 2004).

non-invasive, cost-effective, suitable for urban environments, and provides reliable Vs profiles with high resolution in the shallow subsurface. It can reach investigation depths of several tens of meters and is particularly useful when combined with other methods such as HVSr or seismic refraction (Lin et al., 2004; Park et al., 1998, 1999). However, MASW also has limitations, including sensitivity to surface conditions, limited depth penetration (typically 20-30m), dependence on dispersion curve interpretation, and the assumption of horizontal stratification, which may not hold in tectonically complex environments (Hitouri et al., 2025b; Lin et al., 2004; Park et al., 1999, 1998). The HVSr spectral ratio method, by contrast, is passive, rapid, low-cost, and suitable for urban settings. It provides an estimate of site's fundamental resonance frequency ( $f_0$ ), which is key in assessing seismic site effects. HVSr excels in detecting strong impedance contrasts, though it lacks direct information on layer thickness or Vs values. Interpretation can be challenging in areas with 3D structures or multiple impedance contrasts, and the derived amplification factor ( $A_0$ ) remains debated due to uncertainties in influencing parameters (Borcherdt, 1994; Nakamura, 1989).

In Morocco, several studies have successfully applied MASW and HVSr methods to evaluate seismic site effects. Recent work by Hitouri et al. (2025b) in the Souss basin, the work by Essaied et al. (2025) in the Saïs Basin, Khadrouf et al. (2024) in the western Souss Plain near Agadir region, and El Hilali et al. (2022) in the Martil city's coastal zone have demonstrated the efficacy of these approaches. Their main objective was to determine the soil's resonance frequency to support earthquake-resistant building design. Therefore, urban areas underlain by soft sediments, such as found in Azilal, should be considered at increased seismic risk.

The city Azilal, located in the Central High Atlas about 80 km south of Beni Mellal at an elevation of 1674 m, presents a complex lithological and tectonic setting (Fig. 1). This elevation is attributed to tectonic uplift linked to the convergence of Africa and Eurasia plates since the Late Cretaceous (Amrhar, 2002; Froitzheim et al., 1988; Teixell et al., 2003), and to thermal anomalies due to mantle dynamics (Ayarza et al., 2005; Missenard, 2006; Teixell et al., 2005). The area lies within an active seismic zone, approximately 220 km from the Marrakech-Safi region, which was severely affected by the 2023 Amzmiz earthquake, from the 6.8 Mw Al Haouz earthquake epicentre, which located 71.8 km southwest of Marrakech in the rural commune of Ighil (Al Haouz province), caused extensive destruction (Carboni et al., 2025; Malusa et al., 2024).

The study aims to contribute to seismic hazard and risk evaluation and to support future urban planning. A detailed field campaign was conducted using MASW and HVSr methods, supported by borehole data, to develop geomechanical characterization of the area. The analysis includes the generalisation of soil amplification maps and seismic microzonation based on Vs30 and resonance frequency distributions. The results are intended to inform building design, highlight areas requiring special construction standards, and support early warning strategies in the event of future seismic event.

## 2. Lithological and geological context

The study area, located within the boundaries of the city of Azilal, is situated in the Central High Atlas, bounded by latitudes 31°56'24"N and 31°58'48"N, and longitudes 6°32'24"W and 6°37'12"W. It is examined through a field lithostratigraphic analysis, along with a review of the detailed geological map of Azilal, and the hydrogeological boreholes (Figs. 2 to 4). The area is covered by five main geological formations belonging to the regional stratigraphy of the Central High Atlas:

- (i) The Pliensbachian Aganane Formation (approximately 190-183 Ma, Early Jurassic), exposed in the southeastern part of the area (Fig. 2), consists regionally of dolomites and biotrititic limestones, exceeding 600 m in thickness. Outcrops of this zone are among the most fractured and elevated in the study area. Borehole 527-45 shows alternating sandstones, marls, and laminated limestones (Septfontaine, 1986). This formation corresponds to Zone Z1, characterized by highly consolidated limestone and dolomitic units, representing the most competent and fractured sector of the study area.
- (ii) The Toarcian Azilal Formation (approximately 183-174 Ma, Early Jurassic) occupies the southern two-thirds of the study area and consists of red clays, and red-brown clays intercalated with thin sandstone layers (Jenny, 1983) (Fig. 2). This unit is documented in borehole 585-45, which shows alternating marly and fine sandstones overlying Domerian dolomitic limestones. Depending on the dominant lithology, this formation corresponds to two zones: Z2, composed of friable clayey deposits with interbedded consolidated sandstones, and Z3, composed of very consolidated sandstone and sandstone-clay sequences. The Aalenian Bin-el-Ouidane-1 Formation (approximately 174-170 Ma, Middle Jurassic), covering the northern third of the area, includes micritic

and bioclastic limestones with thin marl interbeds (Souhel, 1996 and Rais et al., 2021) (Figs. 2 and 3). Borehole 578-45 reveals thick limestone layers transiting into marl-limestone alternations and finally into marl-sandy deposits below 108 m. This unit corresponds to Zone Z4, characterized by very consolidated limestones and calcareous marl units, where karstification processes are suspected based on subsurface data.

- (iii) The Bajocian Bin-el-Ouidane-2 Formation (approximately 170-168 Ma, Middle Jurassic), present in isolated outcrops in the north part of the area, comprises alternating beds of micritic limestone and marl. Borehole 562-45 shows two total losses due to underground cavities, indicating active Karst processes (Jenny, 1983; Souhel, 1996) (Figs. 2 and 3). However, due to the limited extent and exposure of this formation, it was not assigned to any specific geomechanical zone.
- (iv) And finally The Quaternary terrace deposits, attributed to Rharbian-Soltanian (roughly equivalent to the Late Pleistocene to Holocene, i.e., ~126 ka to present), appear in the southwestern and northeastern parts of the area. These are divided into conglomeratic terraces with limestone clasts and a sandy-clayey-silty matrix, and silty terraces with reddish fine materials, and local micro-conglomeratic lenses (Rais et al., 2021; Souhel, 1996; Septfontaine, 1986) (Fig. 4). These recent formations are assigned to Zone Z5, characterized by lightly consolidated materials with low geomechanical competence.

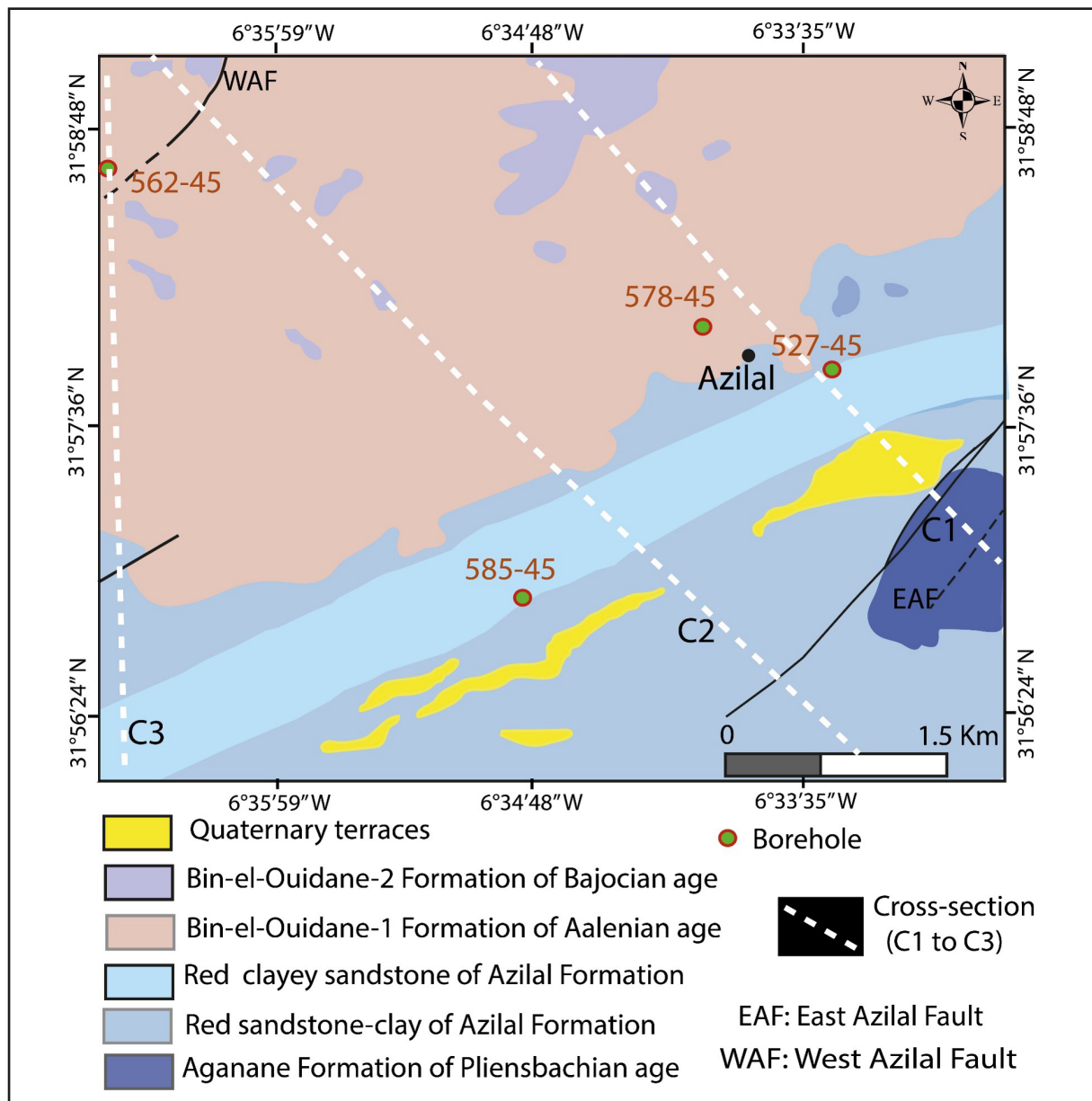


**Figure 2.** Geological map of study area.

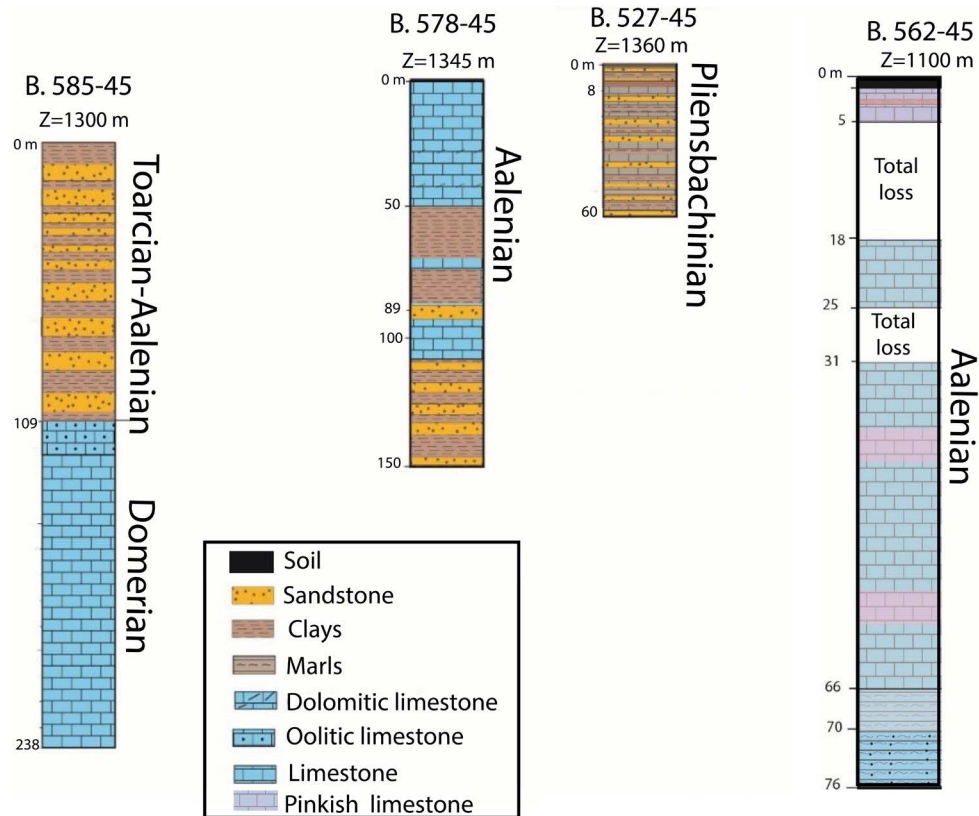


**Figure 3.** Lithostratigraphic columns of the hydrogeological boreholes drilled in the study area.



**Figure 4.** Photos illustrating the coarse silty-clayey conglomeratic facies that characterize the Quaternary terrace in the northeastern part of the study area.

## 2.1 Seismic and tectonic context

The seismotectonic networks and seismic activity of the study area are related to the tectonic framework of the Central High Atlas (Fig. 5), is an intracontinental mountain belt (Baudon et al., 2009; Bensalah et al., 2006; Louz et al., 2022). which has undergone several deformation phases due to the convergence of the African and Eurasian plates during the Late Cretaceous (Haddoumi et al., 2010; Mattauer et al., 1977; Rais et al., 2021). Subsequent tectonic fragmentation led to the formation of folds and troughs, facilitating the accumulation of thick marl-limestone sedimentary formations during the Lower Jurassic (Mattauer et al., 1977; Ouacha et al., 2016; Souhel, 1996). Indeed, three geological cross-sections were drawn across the study area in a NW-SE direction (Fig. 5).

Its subsurface configuration shows a slightly inclined monocline trending NW-SE, indicating that the area is affected by sub-vertical faults oriented NE-SW (Fig. 5), bounded the study area on to the northwest and southeast by two major faults; the West-Azilal Fault (WAF) and the Est-Azilal Fault (EAF) respectively (Figs. 2 and 5), consistent with the fault system identified through our geological investigations. The WAF is one of the few faults present on the Azilal Plateau, near the urban area. It extends over 7 km in a NE-SW direction and played a significant role during the Atlas compression, displaying a sinistral strike-slip movement with a vertical reverse component. The EAF, the second major structure mapped on the Azilal Plateau near, extends over 10 km along a NE-SW direction. It also experienced sinistral strike-slip. Their subsurface geometry of these faults similarly depicted in cross-section C2 (Figs. 2 and 5).

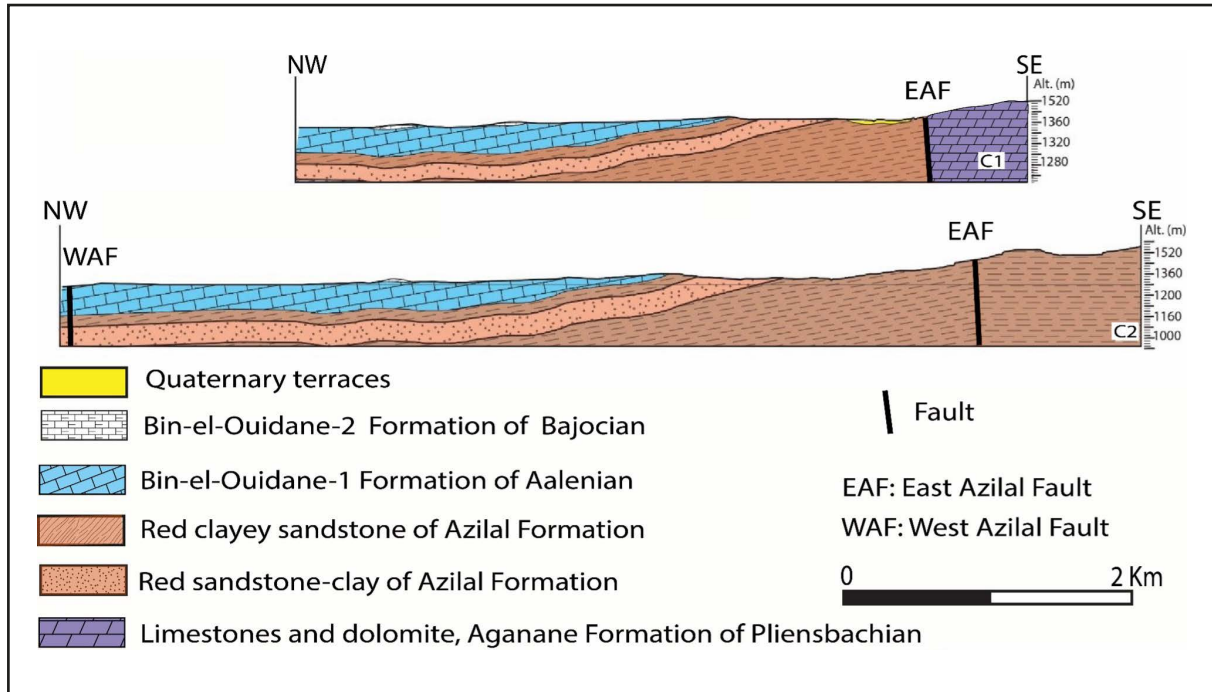


**Figure 5.** NW-SE geological cross-sections revealing the monocline structure of the study area (Fig. 2 for location).

### 3. Data and applied methodology

After conducting a detailed field study of the Azilal study area, primarily to identify and characterize the lithostratigraphic units in order to elaborate the geomechanical soil map, two geophysical techniques were employed.

#### 3.1 MASW acquisition and processing

The MASW method, which is based on the dispersion of Rayleigh-type surface waves (Park et al., 1998, 1999), was primarily used to determine the Vs30. This parameter represents the average shear wave velocity of the soil column to a depth of 30 m and is derived from the 1D velocity profiles obtained through MASW. Vs30 is a key factor in assessing site amplification during potential seismic events (Borcherdt, 1994; Dobry et al., 2000; Holzer et al., 2005). Indeed, MASW data were collected at 24 sites (Fig. 6) using a Geode seismograph from Geometrics, including 24 geophones with a 4.5 Hz frequency and an offset of 3 m geophones spacing. To minimize the impact of near-field and far-field effects, these sources were positioned at distances of 6, 18, and 36 m from both the first and the last geophones along each profile. To improve the signal to noise ratio, at least five impact tests with a 6-8 kg sledgehammer on a polyethylene plate were carried out. The sampling rate was set to 0.5 milliseconds, and the recording time for each measurement was 2 seconds.

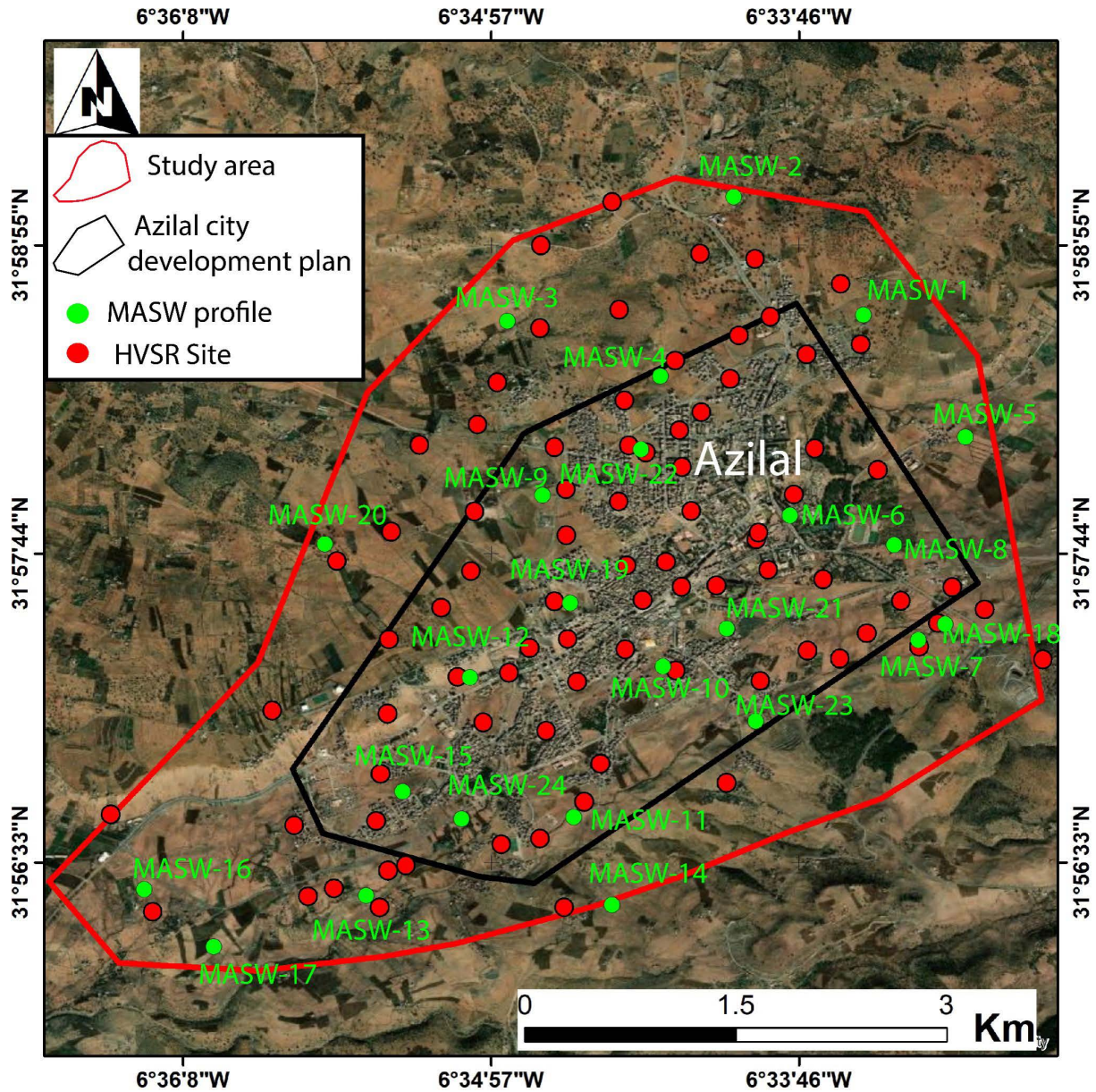


**Figure 6.** MASW and HVSR measurements sites and boreholes in the study area.

The MASW data were processed using ParkSeis software ([www.parkseismic.com](http://www.parkseismic.com)), which extracts dispersion curves through the phase shift method (Park et al., 1998). After several iterations, taking into account the physical properties as well as the number and thickness of the underlying layers, the software generates an experimental dispersion curve. The resulting 1D profile, where each layer is characterized by its shear wave velocity and thickness, is then used to construct a theoretical dispersion curve. When the theoretical curve closely aligns with the experimental curve, it is considered to represent the shear wave velocity profile that best fits the center of the geophones profile. During the surface wave acquisition of MASW data, low-frequency vertical geophones of at least 4.5 Hz are highly recommended to allow acquiring waves with greater wavelength, thus increasing the depth of the survey. The source offset to the first or the last array receiver is usually set to 1-4 times the distance between the geophones (dx). As mentioned before, three sources in this MASW survey were placed on each end of the receiver array at distances of 3, 18 and 36 m. These offsets are aimed at avoiding the near field effects and promoting the dominance of the M0 fundamental mode in the acquired data, as well as reducing the far field effects as the high frequency surface waves are significantly contaminated by reflected body waves. The root mean square (RMS) misfit values, computed directly by the ParkSeis inversion software, range from 1.8 to 2.5%. These relatively low RMS values indicate a good agreement between the observed and calculated dispersion curves, thereby confirming the reliability of the inverted shear-wave velocity ( $V_s$ ) profiles.

### 3.2 HVSR acquisition and processing

The HVSR method is widely used to identify sites that may amplify seismic ground motion in order to determine their resonance frequencies (Essaied et al., 2025; Hitouri et al., 2025b and Nakamura, 1989). This resonance frequency is then employed to calculate the thickness ( $H$ ) and shear wave velocity ( $V_s$ ) of the geological layers, using the following equation:

$$f_0 = \frac{V_s}{4H}, \quad (1)$$

where ( $f_0$ ) represents the resonance frequency, assuming the site under investigation has a one-dimensional and horizontal geometry of layers (Anbazhagan et al., 2019; Bonnefoy-Claudet et al., 2006; Delgado et al., 2000; Ibs-von Seht and Wohlenberg, 1999; Parolai et al., 2002).

In this study, ambient seismic noise was recorded at 99 sites across the entire study area (Fig. 6). The selection of measurement locations prioritized areas with varying building densities and diverse geological conditions. Data acquisition was carried out using three-component seismometers: two VelBox units and one GeoBox unit, all provided by Sara Electronic Instruments. Each recording lasted 20 minutes, a duration commonly recommended in the HVSR method to ensure the reliability and stability of the results. This duration captures a statistically representative sample of ambient noise, mitigates the effects of transient disturbances (e.g., traffic, wind), and enhances frequency resolution, particularly for low-frequency signals. This approach aligns with established scientific guidelines, such as those proposed by the SESAME project, and is considered a standard procedure in seismic microzonation studies aimed at assessing site effects. Recordings were taken in three orthogonal directions: vertical, north-south, and east-west. The instruments operate with a sampling frequency range of 1 to 600 samples per second and are equipped with GPS receivers to ensure accurate time synchronization during data acquisition.

The ambient noise recordings were carried out using a recording station coupled with a seismometer (cut-off frequency < 1 Hz). The HVSR data were processed using GeoExplorer software (<https://geoexplorer-hvsr.software.informer.com>), which features a powerful and user-friendly module that automatically checks compliance with the SESAME criteria (Table 1), particularly regarding the reliability of the HVSR curve and the clarity of

**Table 1.** Example of a verification table for the SESAME criteria placed at the end of the report generated by the Geoexplorer software.

| HVSR curve reliability criteria                             |                                              |    |
|-------------------------------------------------------------|----------------------------------------------|----|
| $f_0 > 10/L_w$                                              | 38 valid windows (length > 2,99 s) out of 38 | OK |
| $n_c(f_0) > 200$                                            | 3176.85 > 200                                | OK |
| $\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$                   | Exceeded 0 times in 37                       | OK |
| HVSR peak clarity criteria                                  |                                              |    |
| $\exists f^- \text{ in } [f_0/4, f_0]   A_{H/V}(f^-) A_0/2$ | 1.09345 Hz                                   | OK |
| $\exists f^+ \text{ in } [f_0, 4f_0]   A_{H/V}(f^+) A_0/2$  | 5.22953 Hz                                   | OK |
| $A_0 > 2$                                                   | 3.2 > 2                                      | OK |
| $f_{peak}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$        | 3.8% ≤ 5%                                    | OK |
| $\sigma_f < \varepsilon(f_0)$                               | 0.45061 ≥ 0.1672                             | NO |
| $\sigma_A(f_0) < \theta(f_0)$                               | 1.26119 < 1.58                               | OK |
| Overall criteria fulfillment                                |                                              | OK |

resonance peaks (Fig. 7). The SESAME project, a European initiative conducted between 2001 and 2004 under the EVG1-CT-2000-00026 program, aimed to establish a robust methodology for assessing seismic site effects using ambient noise, specifically through the HVSR spectral ratio method (Bard and the SESAME participants, 2004).

The first step of the processing phase involves identifying signal windows in each recording where the signal is as stationary as possible, and then cutting the signals from each of the three components into these stationary time windows. After calculating and smoothing the Fourier spectra of the three components for each selected window using the method proposed by Konno and Ohmachi (1998), the root mean square of the horizontal components is computed for each window. Finally, Nakamura's HVSR ratio is calculated for each window using the following equation:

$$\frac{H}{V} = \sqrt{\frac{(F_{NS}^2 + F_{EW}^2)}{F_D^2}} \quad (2)$$

where FNS, FEW, and FD represent the Fourier amplitude spectra in the N-S, E-W, and vertical directions, respectively.

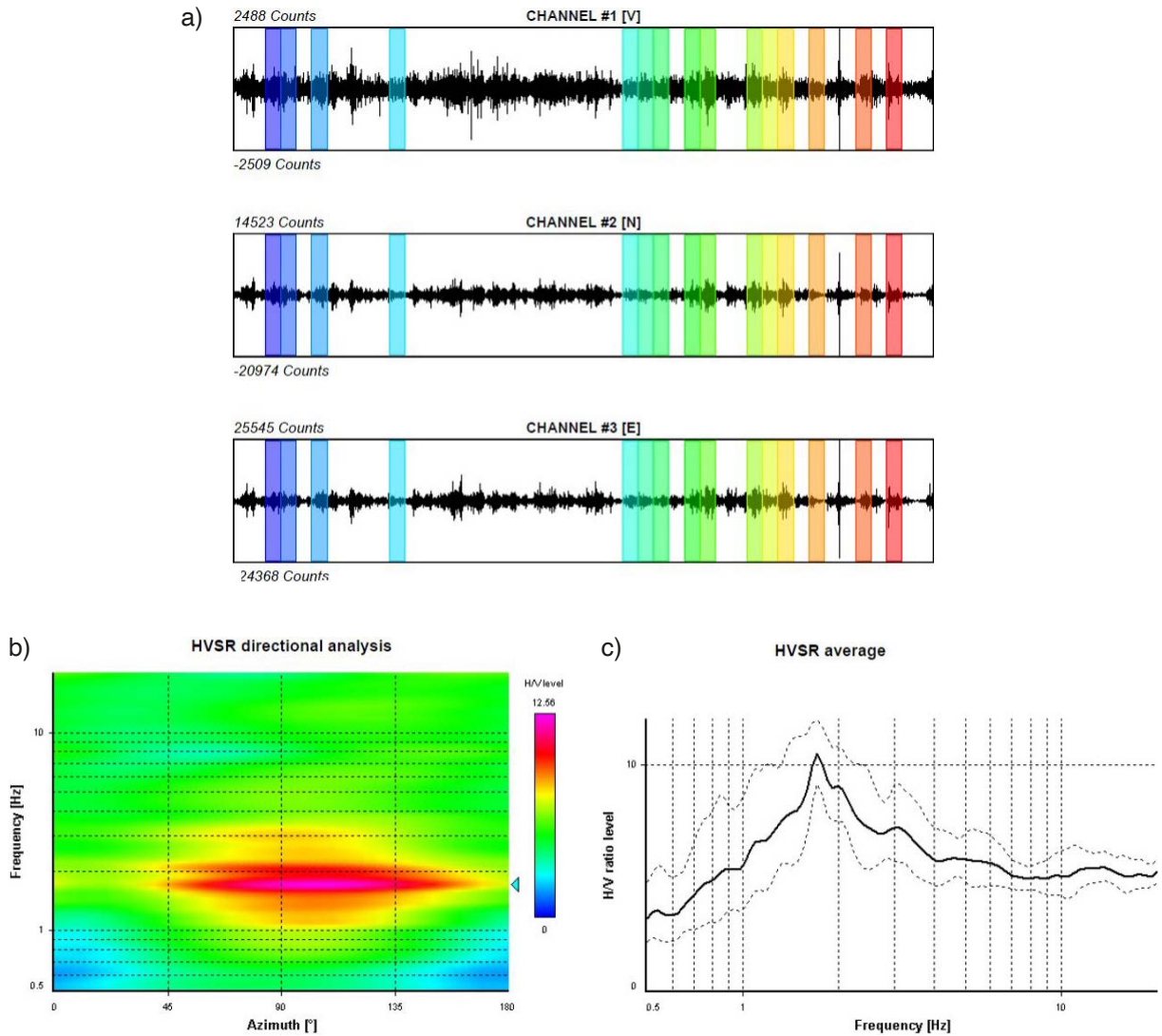


**Figure 7.** Illustration using recording H70 from the area of the different processing steps of HVSR data using geoxplorer software: (a) Selection and segmentation of stationary windows from the three recorded components, (b) directional analysis of the energy level of the HVSR ratio as a function of frequency and azimuth, and (c) HVSR curve calculated after computing and smoothing the fourier transforms of the three components.

After calculating the HVSR spectral ratios for all recording windows at a measurement point, the HVSR ratio for each specific point was obtained by averaging these spectral ratios. The fundamental frequency of the site was determined based on the peak observed in the HVSR spectral ratio, which corresponds to the fundamental to the first resonance frequency (Acerra et al., 2004; Field and Jacob, 1993; Sylvestre et al., 2006). The ratio of the horizontal and vertical Fourier spectra of ambient noise reveals distinct peaks (Fig. 10), provided there is a significant impedance contrast at depth (Bard, 1999; Bonilla et al., 1997; Boore et al., 1993; Haghshenas et al., 2008; Woolery and Street, 2002).

## **4. Results**

### **4.1 MASW measurement**

In order to identify sites with high risk of seismic amplification of soil movements in the study area during earthquake events, 24 MASW profiles were selected based on the analysis of the geological map of the study area as well as the results of the detailed lithostratigraphic study conducted as part of this research. In this study, we present four MASW profiles, each acquired in a different zone (Z2, Z3, Z4, and Z5). The interpretation of these profiles is based on field data and borehole information, allowing us to identify significant seismic velocity contrasts and their lithological causes:

The MASW-1 profile was acquired in zone Z5. Its interpretation is based on field data and borehole data from 578-45. The velocity range of this profile reveals two significant  $V_s$  velocity contrasts. The first seismic velocity contrast is located at a depth of approximately 5 m, where the velocity decreases from 900 m/s to 800 m/s. The second velocity contrast occurs at a depth of 64 m, where the velocity abruptly increases from 800 m/s to 1980 m/s before decreasing again through seven steps. These velocity units correspond to three lithological units of the Bin-el-Ouidane-1 Formation, of Aalenian age: U1 represents soil and marly limestones, U2 corresponds to massive limestones, sometimes dolomitic with clayey joints, and U3 consists of chocolate-colored marls (Figs. 6 and 11).

The MASW-5 profile (Fig. 8), acquired in Zone Z2, was interpreted using the available geological information and borehole 527-45 located near the profile. The velocity model is characterized by eight units with relatively constant shear-wave velocities and three velocity inversions. It also reveals two significant impedance contrasts. The first major velocity contrast occurs at a depth of approximately 10 m, where the shear-wave velocity increases abruptly from about 400 m/s to 1450 m/s before gradually decreasing through four successive layers. According to the borehole data, this contrast corresponds to Unit U1, which is composed of alternating red sandstone and clay layers. The second major contrast is observed at a depth of approximately 41 m, where the velocity increases from about 1200 m/s to 1750 m/s. This contrast corresponds to Unit U2, consisting of limestones interbedded with sandstones and marls. The limestone becomes progressively more competent toward the lower part of Unit U2, explaining the increase in shear-wave velocity. At greater depths, Unit U3 is composed of alternating marls, platy limestones, and clayey sandstones, resulting in a more heterogeneous velocity distribution.

Similarly, in the southwestern part of zone Z3, the interpretation of the MASW-16 profile data reveals two significant  $V_{s30}$  velocity contrasts. The primary seismic velocity contrast is located at a depth of approximately 5 m (Figs. 2 and 9), where the velocity abruptly increases from 400 m/s to 1750 m/s. The second contrast occurs at a depth of 41 m, where the velocity increases from 1100 m/s to 1850 m/s. Correlation of this velocity curve with the lithostratigraphic column from borehole 585-45, drilled 500 m southwest of the profile location, allows for the identification of the lithological causes of these contrasts. The borehole data indicate that the upper 5 meters of this area consist of red clay from unit U1, transitioning between 5 m and 41 m into alternating sandstone-clay deposits, where sandstone beds become progressively thinner downward, corresponding to U2. Below 41 m, the trend reverses, with sandstone beds becoming thicker and more frequent, marking the transition to U3 (Figs. 6 and 8).

The MASW-18 profile acquired in zone Z4 is interpreted based on field data and borehole 527-45. This interpretation reveals two strong  $V_s$  velocity contrasts at depths of 12 m and 41 m. The first velocity contrast, where the velocity abruptly increases from 400 m/s to 1700 m/s, corresponds to Quaternary terraces (U1). The second velocity contrast, where the velocity increases from 1700 m/s to 2150 m/s, corresponds to altered clays (U2) and red sandy clays with sandstone intercalations at the base of unit U3.

The detailed analysis of the inverted MASW profiles shows that the shallow seismo-lithological units have shear wave velocity values often greater than 360 m/s, indicating a good soil rigidity (Figs. 5 and 9). On the other hand, seismo-lithological units with shear wave velocities significantly higher than 760 m/s are observed at almost all

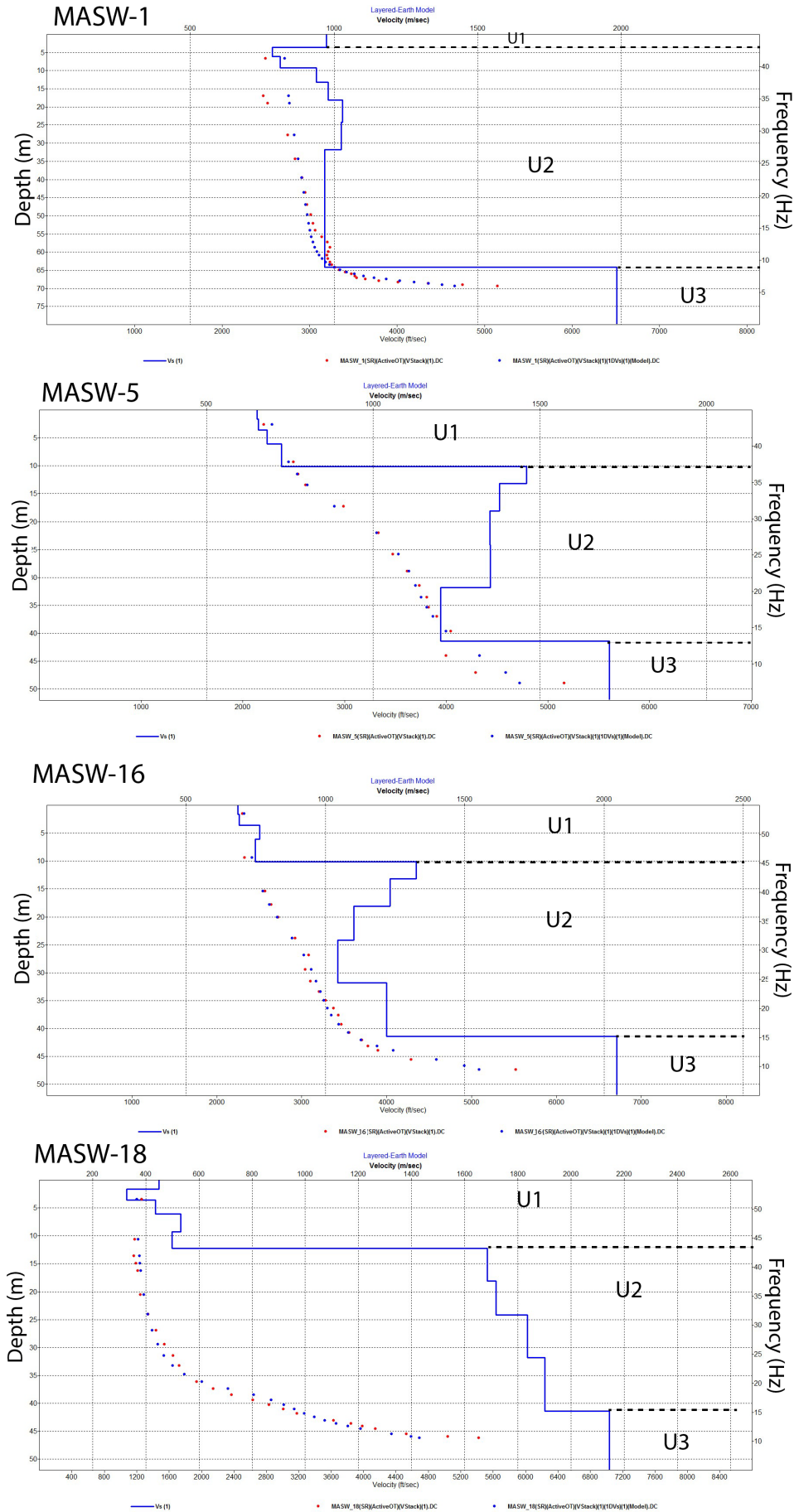


Figure 8. Interpretation of profiles MASW-1, MASW-5, MASW-16 and MASW-18.

sites at depths of less than 15 m (Figs. 5 and 9). In the study area, seismic interfaces with strong shear wave velocity contrasts are observed at shallow depths, not exceeding 10 m. Occasionally, during intense seismic events, it is these shallow seismic interfaces that could lead to the amplification of soil movements.

In general, the subsurface survey in the study area using the one-dimensional MASW method, as shown on the four exemplary profiles acquired from the four lithostratigraphic zones, reveals that the study area is characterized by sub-horizontal and parallel layers in the sub-surface, an absence of lateral lithological variations, and constant seismic velocities within the same layer (Fig. 9). However, some differences between the four zones were emphasized. Z3 and Z4 areas show more lateral homogeneity in terms of soil rigidity compared to Z2 and Z5 areas. The shear wave velocity in these two relatively homogeneous zones (Z3 and Z4) ranges from about 250 m/s in the shallow units to about 1500 m/s in the deeper units. In Z2 and Z5 areas, shear wave velocities increase with depth, reaching values of more than 1500 m/s (Fig. 9).

In this study, the generation of the distribution map of Vs30 values, based on the results of the VS-1D shear wave velocity profiles in the first 30 meters of depth, was done by interpolating the Vs30 values using the IDW method provided by the QGIS software (version 3.22). Thus two maps were elaborated using two different classification methods: a supervised classification based on the Vs30 class boundaries of the Moroccan RPS 2000 (Version 2011), and another supervised classification using 7 classes without considering the RPS 2000 (Fig. 9). The distribution map of Vs30 values, divided into 7 classes, shows that velocity varies from 571 to 1312 m/s, suggesting that the rocks in the study area exhibit significant rigidity. The analysis of this map reveals that the study area can be divided into three main zones: a central zone, a northern zone and a southern zone. The central zone is characterized by relatively low velocity values, ranging from 570 to 830 m/s (Fig. 9). The relative decrease in Vs30 values in this zone can be attributed to one of the following causes: (i) the absence of thick, compact Jurassic limestone formations within the first 30 m; (ii) the partial karstification of these limestone formations, if present; or (iii) the dominance of alternating layers of sandstone, marl, limestone slabs, and in particular, the friable red clays of Azilal formation. The two boreholes 527-45 and 585-45, support the last hypothesis. Specifically, the 585-45 borehole shows an alternation of marls and

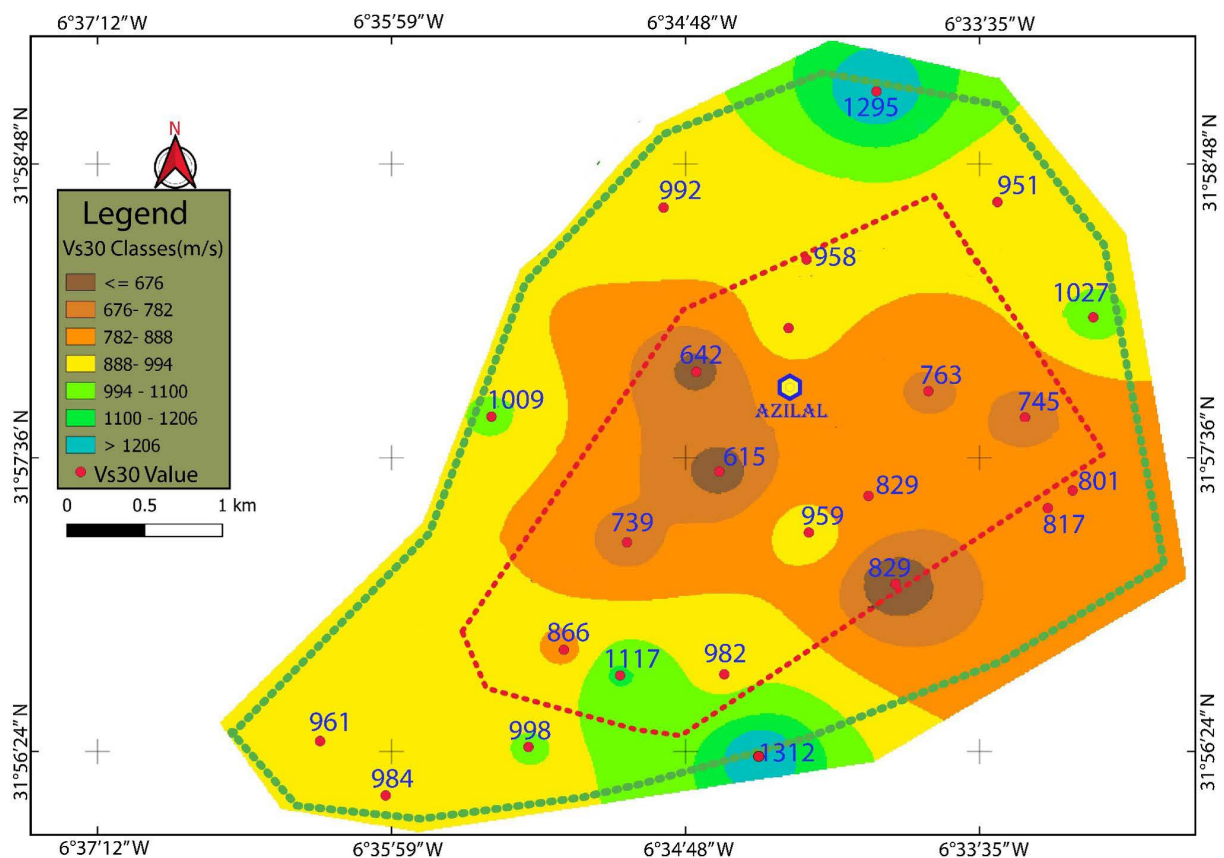


**Figure 9.** Spatial distribution of Vs30 over the Azilal study area without considering the Vs30 boundaries of RPS 2000, version 2011.

sandstones in the first 100 m, while the 527-45 borehole reveals a slab-like structure of the limestone horizons (Fig. 2). This structural characteristic further affects their rigidity, consequently leading to the decrease in  $V_{s30}$  values.

The northern and southern zones exhibit  $V_{s30}$  values exceeding 900 m/s. These velocity values generally increase from the central zone toward the north and south, reaching higher values of over 1300 m/s (Fig. 9). In the southern part, the uplift of highly consolidated sandstone and sandstone-clay formations, structured as a monocline (Fig. 5), could explain this increase in velocity. Furthermore, the Quaternary formations, which outcrop irregularly and run parallel to the southern boundary of the study area, indicate significant geomechanical rigidity. Their presence in these areas does not reduce velocity values; instead, it further enhances them.

The classification of  $V_{s30}$  values, based on the boundary criteria of RPS 2000 (version 2011) as outlined in Table 2, enables the establishment of a geotechnical zonation with respect to the  $V_{s30}$  parameter. The resulting map indicates that the study area comprises five sites classified as S2 class, while the remaining 19 sites belong to S1 class (Fig. 9). With the exception of four small S2 zones, the S1 class dominates almost the entire study area. This dominance can be attributed to the presence of very dense seismic bedrock of Z4 area limestone in the northern part of the study area, which outcrops as compact slab with almost no porosity or permeability, as well as the uplift of a relatively consolidated sandstone ridge of the Azilal formation in Z3 to the south. The limited areas of S2 class seem to be associated with the Bin-el-Ouidane-1 formation and the sandstone and sandstone-clay formations of Z3. The decrease in  $V_{s30}$  at these sites, which are limited to Z2 and Z3 and have minimal effect on Z4, may be due to two additional factors as the karstification phenomenon in the Bin-el-Ouidane-1 carbonate formation of Z4 or the impact of friable clay layers in the limestones and dolomites of Z2.

**Table 2.** Soil classes according to the Morocco seismic building code (RPS 2000, Version 2011).

| Site Class | Description                   | Shear wave velocity $V_s$ (m/s) | Standard penetration resistance $N_{60}$ | Undrained shear strength $S_u$ (kPa) | Soil factor (RPS 2011) |
|------------|-------------------------------|---------------------------------|------------------------------------------|--------------------------------------|------------------------|
| S1         | Rock                          | $V_s > 760$                     | Not applicable                           | Not applicable                       | 1                      |
| S2         | Very dense soil and soft rock | $360 < V_s < 760$               | $N_s > 50$                               | $S_u > 100$                          | 1.2                    |
| S3         | Stiff soil                    | $180 < V_s < 360$               | $15 < N_s < 50$                          | $50 < S_u < 100$                     | 1.4                    |
| S4         | Soft soil                     | $180 < V_s$                     | $N_s < 15$                               | $S_u < 50$                           | 1.8                    |

In addition, the NEHRP classification system based on  $V_{s30}$  values is widely used to assess seismic site response by evaluating the average shear-wave velocity in the upper 30 m of the subsurface (Table 3). This parameter is essential for estimating local seismic amplification and for defining site conditions in seismic design codes (Dobry et al., 2000; NEHRP, 2001). The NEHRP system classifies sites into six categories (A, B, C, D, E, and F) according to specific  $V_{s30}$  thresholds, as summarized in the following table (NEHRP, 2001). Based on this classification, the study area is primarily categorized as class B and class C.

In conclusion, based on the two maps of the spatial distribution of  $V_{s30}$  elaborated in this study, along with the soil classification according to the Moroccan anti-earthquakes building guidelines, it can be stated that the local geological conditions will have minimal to no impact on the amplification of seismic waves motion. Consequently, the site effect phenomenon is unlikely to pose a significant risk of increased amplitude during a seismic event. To further validate this conclusion regarding the absence of lithological site effects, a supplementary analysis will be conducted using the Midorikawa (1987) Eq. (3).

$$A = 68 V_{s30}^{-0.6} \quad \text{for} \quad V_{s30} < 100 \text{ m/s} \quad (3)$$

Although the HVSR method has proven effective in estimating the predominant frequency ( $f_0$ ), uncertainties remain regarding the accuracy of its associated amplification factor ( $A_0$ ) (Bard, 1999). This equation relates the amplification

**Table 3.** Classification the soil of NEHRP, 2001.

| NEHRP Class | Vs30 (m/s) | Description                                                                  |
|-------------|------------|------------------------------------------------------------------------------|
| A           | >1500      | Hard rock                                                                    |
| B           | 760-1500   | Rock                                                                         |
| C           | 360-760    | Very dense soil and soft rock                                                |
| D           | 180-360    | Stiff soil                                                                   |
| E           | <180       | Soft soil (e.g., soft clays, loose sands)                                    |
| F           | —          | Soils requiring site-specific investigations (e.g., liquefiable soils, peat) |

factor (A) to Vs30 (Midorikawa, 1987). However, it is crucial to note that soil amplification is also influenced by other factors, such as the soil profile, soil types (sand/silt/clay), shear modulus, and damping ratio. Therefore, the results from this equation serve as an initial approach for creating a preliminary map of soil amplification of the study area. The map generated by interpolating the results of this equation, based on Vs30 values derived from the inverted MASW profiles, indicates that the amplification values range from 1 to 1.5 (Fig. 10). On this map, the highest amplification factors, around 1.5, are concentrated in two small areas located at the center of the study area, approximately 500 m from the municipality of Azilal. The relatively low amplification observed can likely be attributed to two factors: the karstification phenomenon in the limestones of the Bin-el Ouidane 1 formation and

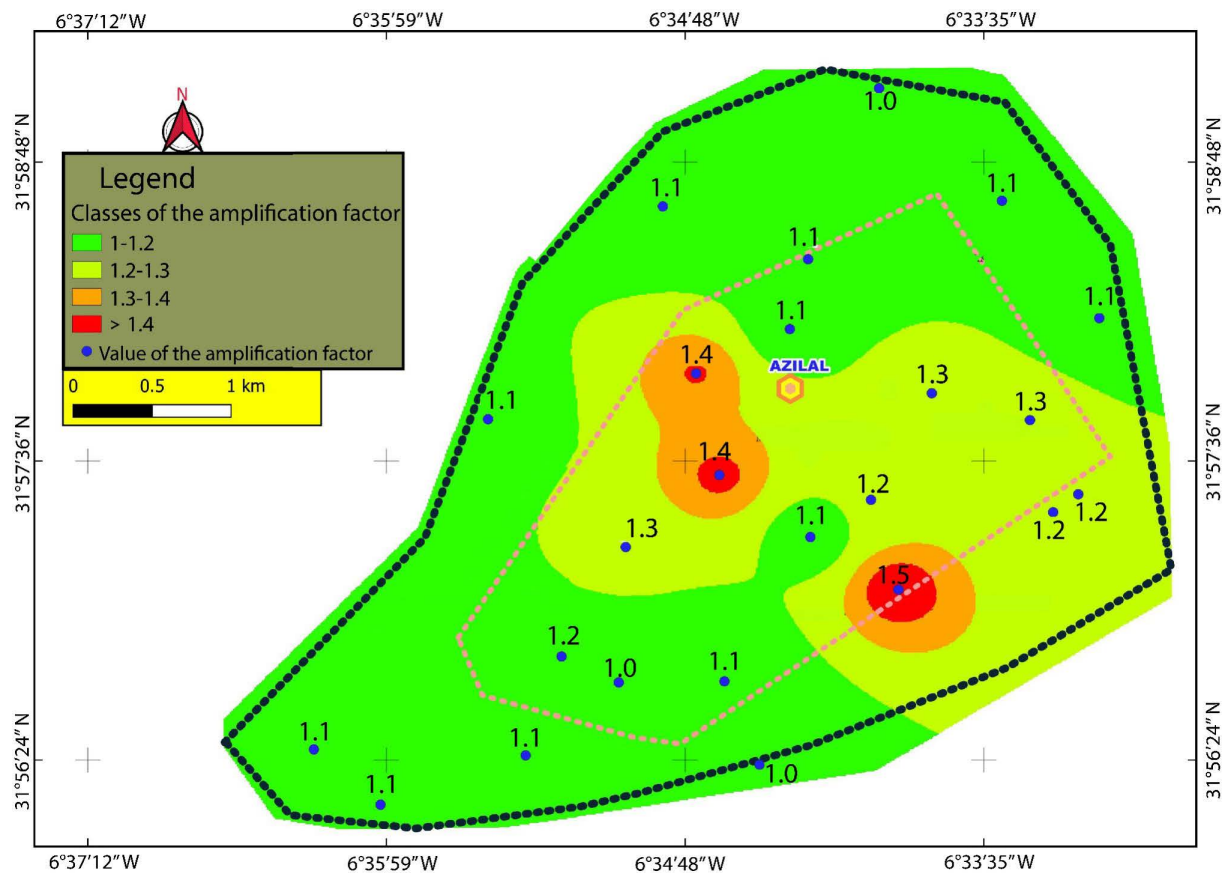


**Figure 10.** Soil amplification map of Azilal study area.

the influence of the red clays of Azilal formation. Therefore, this preliminary amplification map suggests that the study area may experience low to moderate seismic soil amplification during a future earthquake.

## 5. HVSR measurements

A total of 99 HVSR measurement sites were distributed across the study area, taking into account the lithological variability of the geological formations. The recorded ambient vibration data were processed to extract the characteristic HVSR spectra for each site. Spectra significantly affected by transient anthropogenic noise were carefully filtered by removing contaminated time windows prior to the estimation of the fundamental resonance frequency, following the SESAME guidelines.

Among the 99 recordings, only two sites exhibited flat or nearly flat HVSR curves, indicating the absence of a significant impedance contrast and, consequently, the absence of a reliable fundamental resonance frequency. Nine sites did not display any peaks satisfying the SESAME reliability criteria. Thirteen sites showed a single well-defined resonance peak corresponding to the fundamental frequency, whereas the remaining sites (approximately 76%) exhibited two or more resonance peaks. Most of these secondary peaks did not satisfy the SESAME reliability criteria and were therefore excluded from the interpretation.

The HVSR77 measurement site, belonging to the 0.77-1.07 Hz frequency class, is representative of the single-peak response (Fig. 11a). This site is located within the Aalenian Bin El Ouidane Formation (Middle Jurassic, approximately 174-170 Ma), which occupies the northern part of the study area and consists predominantly of micritic and bioclastic limestones interbedded with thin marl layers. The observed resonance frequency is consistent with the local geological setting and is corroborated by the MASW-18 velocity profile, which reveals a pronounced shear-wave velocity contrast at a depth of approximately 12 m, corresponding to the contact between two lithological units. The good agreement between the HVSR and MASW results confirms that the observed resonance is primarily controlled by the subsurface geological structure.

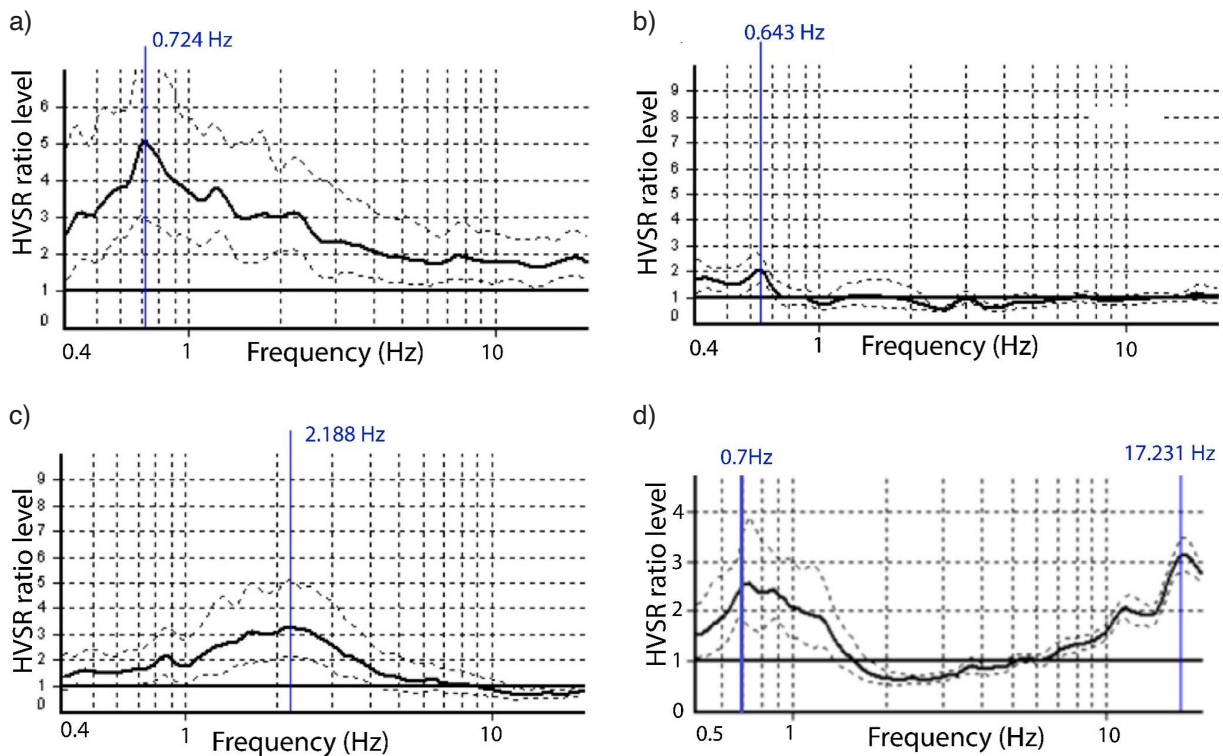


**Figure 11.** Four types of HVSR spectra highlighted in the study area: (a) HVSR curve at the measurement point AZL-HV 77-Z4 in Azilal showing a well-defined peak at 0.72 Hz, (b) HVSR curve at the measurement point AZL-HV 91-Z3 at the city-center of Azilal with very low amplification amplitude at 0.6 Hz, (c) HVSR curve at the measurement point AZL-HV 38-Z3 showing a wide peak and (d) HVSR curve showing two peaks at 0.7 Hz and 17.2 Hz.

The HVSR curves shown in Fig. 11 illustrate several types of spectral responses, including single-peak, broad-peak, flat or nearly flat, and multiple-peak curves. Single, well-defined peaks (Figs. 11a and 11c) generally indicate a significant impedance contrast between the superficial deposits and the underlying seismic bedrock. The relatively low fundamental frequencies (0.724 and 0.643 Hz) suggest thick unconsolidated or weakly consolidated deposits overlying the bedrock, whereas the higher resonance frequency (2.188 Hz) reflects either a thinner sedimentary cover or a shallower impedance contrast.

Conversely, the nearly flat HVSR curve observed in Fig. 11b, characterized by amplitudes close to unity over the investigated frequency range, indicates the absence of a significant impedance contrast and is typical of sites underlain by exposed or very shallow competent bedrock.

The multiple-peak HVSR curve illustrated in Fig. 11d exhibits two distinct resonance frequencies at approximately 0.70 Hz and 17.23 Hz. Such multiple-peak responses are generally associated with the presence of several impedance contrasts within the subsurface, reflecting layered geological sequences with contrasting shear-wave velocities. They may also result from the excitation of higher resonance modes or from complex geological conditions involving lateral heterogeneities and two-dimensional or three-dimensional basin effects. Consequently, these sites cannot be adequately characterized by a single resonance frequency and require joint interpretation with the MASW velocity profiles and the geological information to identify the origin of the different resonance peaks.

Overall, the predominance of broad-peak and moderate-amplitude HVSR curves across the study area suggests gradual impedance contrasts rather than sharp lithological boundaries. Such responses are commonly associated with consolidated sedimentary sequences overlying competent bedrock and generally imply moderate site amplification during strong earthquakes (Bonnefoy-Claudet et al., 2008; Konno and Ohmachi, 1998). In contrast, flat spectra, typically observed over hard-rock sites, are indicative of negligible local seismic amplification, whereas broad peaks may also reflect progressive increases in shear-wave velocity with depth or the influence of two-dimensional and three-dimensional geological structures.

### **5.1 HVSR peak amplitude ( $A_0$ )**

The frequency spectra analysis of the HVSR data reveals two distinct classes. Class 1 includes spectra with amplified frequencies between 0.5 Hz and 2.3 Hz, characterized by wide peak/band shapes. On the other hand, class 2 features spectra with high-frequency peaks ranging from 10 Hz to 20 Hz (Fig. 12). The low-frequency peaks are typically associated with deeper velocity contrasts and are generally not due to surface layer resonance. In contrast, high-frequency amplification is linked to a velocity contrast in a relatively shallow layer, resulting in a spectrum with two distinct peaks (Fig. 12).

As only one site (H92) exhibits a high-frequency peak, classed as class 2, we created the resonance frequency spatialization map for sites in class 1 only. The resulting map reveals a frequency zone dominated by frequencies ranging from 1.38 Hz to 1.68 Hz, located along the southeast side of the study area. This is followed by a zone with frequencies ranging from 1.1 Hz to 1.4 Hz. To the northwest, lower frequencies under 1.1 Hz are observed. The contours of these three zones generally follow a NE-SW direction, parallel to the geological formation boundaries of the study area (Fig. 12). The comparison between the resonance frequency spatialization map for Class 1 and the geomechanical map of the study area reveals a striking similarity between the boundaries of the geomechanical units on one hand, and the frequency zone boundaries, which generally follow a NE-SW direction, on the other hand.

Notably, a positive correlation can be observed between the frequency zone  $> 1.4$  Hz (brown) and the geographic boundaries of the Z2 unit on the geomechanical map of Azilal. This zone consists of rocks made up of clays and sandstones of Azilal formation, which extends across much of the southern and southeastern parts of the study area (Fig. 6). The relatively high frequencies in this zone reflect the fact that the hard, compact rocks of Z2 are found at shallow depths in the southeast, compared to the areas (yellow and green) to the northwest. In fact, the three geological cross-sections through the urban area of Azilal clearly show that the 'bird's-eye' limestones of the Jurassic Bin-el-Ouidane-1 formation (Fig. 5), which extensively outcrop in the northwestern half of Azilal urban area and its surrounding regions, thicken toward the northwest, revealing the existence of a slope as these formations are part of a monocline dipping to the north.

It is evident that a 100% correlation between frequency distribution and geology is not possible, as geology represents surface observations with interpolations at depth, while frequencies measured using the HVSR method reflect the soil vibrational characteristics, which can vary rapidly on a lateral scale. Consequently, several lateral

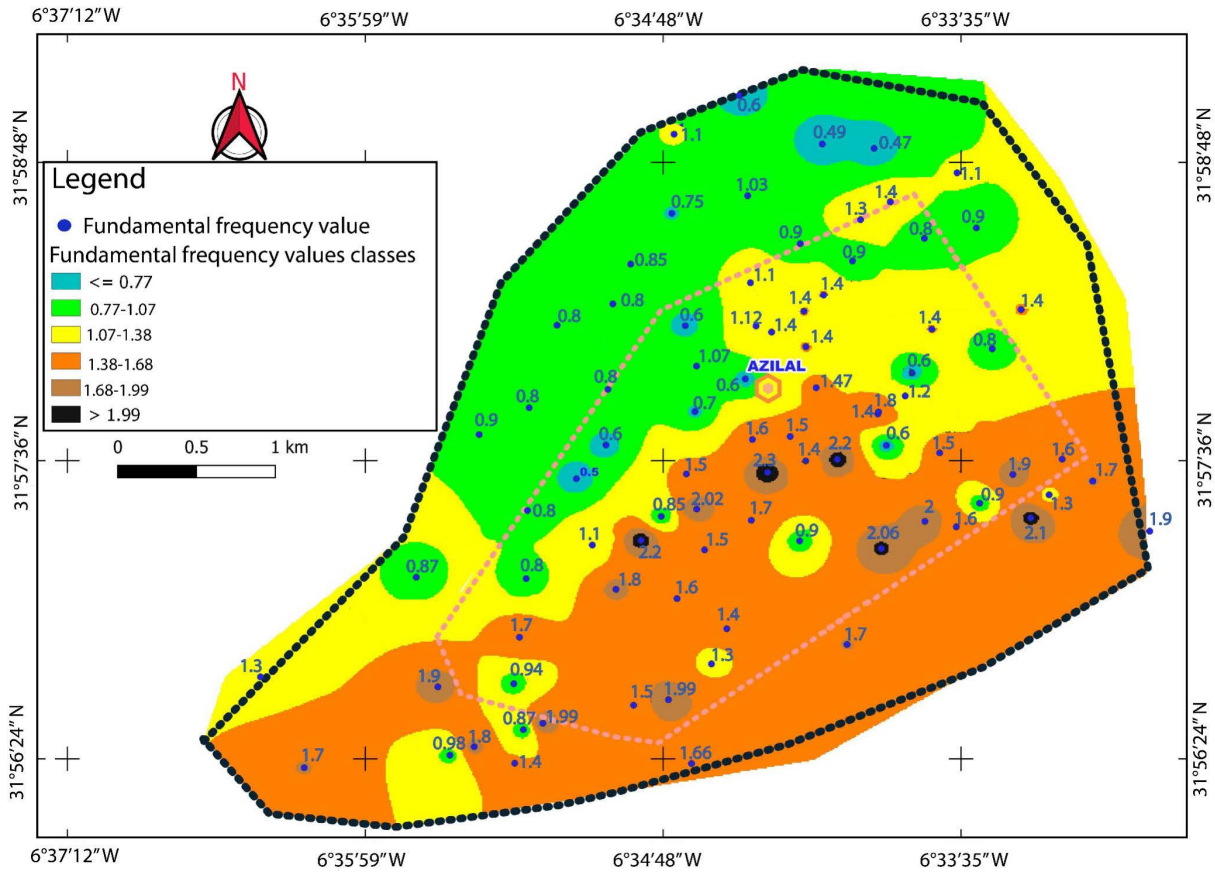


**Figure 12.** Contours of the resonance frequencies for class 1. Note that the contours follow a NE-SW direction, parallel to the directions of the geological formation boundaries in the Azilal study area.

variations (small anomalies or patches) in frequencies are observed, caused by the heterogeneity of the superficial loose layers. In conclusion, the distribution of natural frequencies obtained through the HVSR method appears to be significantly influenced by the geological environment of the study area, spanning zones Z1 to Z5.

## 6. Discussions

The spatial distribution map of Vs30, derived from the analysis and interpretation of the MASW profiles, indicates that Vs30 values range from 676 to 1312 m/s across the study area. Comparable Vs30 values have been reported in the nearby Ghabt Admin area (Agadir, western Morocco, Souss Basin) by Khadrouf et al. (2023) and in the Sais Basin by Essaied et al. (2025).

The subsurface is characterized by tabular, subhorizontal layers with limited lateral lithological variations and relatively uniform seismic velocities within each geological unit. Based on nearly equal intervals of approximately 100 m/s, the Vs30 map allows the study area to be divided into three main zones: central, northern, and southern. The central zone is characterized by relatively low Vs30 values, ranging from 676 to 830 m/s. These lower velocities are attributed to the absence of thick, competent Jurassic limestone within the upper 30 m or to the effects of partial karstification of these limestone formations. In contrast, the northern and southern zones exhibit Vs30 values generally exceeding 900 m/s, locally reaching more than 1300 m/s. This increase is mainly associated with the monoclinical structure of a ridge composed of highly consolidated sandstone and clayey sandstone formations, as illustrated in the geological cross-section shown in Fig. 5.

The signal amplification map, with amplification factors ranging from 1.0 to 1.5, indicates that the highest amplification is concentrated in two small areas located in the central part of the study area. The relatively low amplification values are probably related to the partial karstification of the Bin-el-Ouidane-1 limestone formation and the influence of the red clay deposits of the Azilal Formation.

The resonance frequency map shows that the dominant frequencies are mainly distributed between 0.5 and 2.8 Hz (Fig. 13). According to the RPS 2000 seismic code (Version 2011), the HVSR curves can be classified into three categories. Class 1 includes frequencies ranging from 0.47 to 2.8 Hz and represents the majority of the investigated sites (78%), most of which exhibit two resonance-frequency peaks. Class 2 consists of a single site characterized by a high dominant resonance frequency of 16.4 Hz. Class 3 includes two sites exhibiting flat HVSR curves without a clear dominant resonance frequency. It is noteworthy that several Class 1 HVSR curves also display secondary peaks within the frequency range of Class 2.

Finally, the analysis of the Vs distribution derived from the MASW profiles across the different geological zones revealed a pattern that is generally consistent with the HVSR results. The MASW-derived shear-wave velocity models corroborate the site classification and subsurface characterization inferred from the HVSR analysis. Furthermore, MASW surveys conducted in the vicinity of boreholes proved particularly effective for characterizing the dynamic properties of subsurface materials and identifying weak or weathered layers. The comparatively low Vs values observed locally within the massive limestone unit (U2) are interpreted as the result of partial karstification and fracturing, which reduce the effective stiffness of the rock mass despite its competent lithology. The combined interpretation of MASW, HVSR, borehole data, and geological observations therefore provides a robust framework for understanding the lateral variability of the subsurface and improves the reliability of the geological and geotechnical interpretation.

In fact, some studies conducted in Morocco and in authors countries, further support this observation. Several studies have addressed seismic site characterization and microzonation in Morocco and neighboring regions using a variety of geophysical, geotechnical, and modeling approaches. Essaied et al. (2025) conducted a study in Meknes (Morocco) using the HVSR method to perform seismic microzonation, successfully classifying seismic site types based on HVSR curve analysis. In the Ghabt administrative area of Agadir, Khadruf et al., 2024b combined HVSR, MASW and geotechnical data to establish seismic microzonation aimed at ensuring safe urban expansion, identifying stable zones suitable for development. Similarly, Khadruf et al. (2024a) applied MASW and near-surface geophysical methods in eastern Agadir to improve geotechnical zoning, achieving enhanced zoning accuracy through integrated geophysical surveys.

In northeastern Morocco, Chaaraoui et al. (2021) used ambient noise HVSR analysis in the Nador area to assess seismic site effects, revealing significant spatial variability in site conditions. El Hilali et al. (2021) focused on the Martil region, where geotechnical investigations were employed to map liquefaction susceptibility, identifying zones with a high risk of liquefaction. In a subsequent study, El Hilali et al. (2023) analyzed the vulnerability of existing buildings in Tetouan through structural and seismic analyses, highlighting the high vulnerability of older masonry structures.

At a broader scale, Razzouk et al. (2023) investigated soil-structure interaction across various regions of Morocco using numerical modeling, emphasizing the strong influence of soil type on the optimal bracing design of reinforced concrete buildings. Hamdache et al. (2022a) applied stochastic modeling techniques in Al Hoceima to analyze aftershock sequences, successfully reproducing realistic aftershock scenarios. In northern Algeria (Hamdache et al., 2022b) conducted probabilistic seismic hazard modeling, incorporating uncertainty into seismic hazard maps to improve hazard assessment reliability.

## 7. Conclusion

This study demonstrates the effectiveness of integrating MASW and HVSR geophysical methods with detailed geological investigations to characterize seismic site effects and support urban planning in the Azilal urban area. The combined approach provided a reliable assessment of subsurface conditions and their influence on local seismic response. This study represents the first analysis of ambient noise measurements in the area city to estimate Vs30 velocity and to develop a seismic microzonation map. Indeed, the obtained Vs30 values indicate that most of the study area is characterized by relatively rigid geological formations, with only the central sector exhibiting comparatively lower shear-wave velocities due to the presence of weathered and less consolidated lithological units. Consequently, the study area is mainly classified as S1 and B according to the Moroccan Seismic Code (RPS 2000, version 2011) and the NEHRP classification, respectively, while the central zone locally corresponds to S2 and C classes. The estimated amplification factors (1.0-1.5) suggest generally low to moderate site amplification, indicating relatively favorable ground conditions for future urban development. Additionally, the HVSR analysis revealed predominantly low fundamental frequencies (0.5-2.3 Hz), controlled mainly by deep impedance contrasts rather than

shallow resonance effects. The spatial distribution of resonance frequencies closely follows the regional lithological boundaries, highlighting the strong influence of geological conditions on seismic site response. These findings confirm the complementary nature of MASW and HVSR methods for seismic microzonation studies.

From an engineering perspective, the produced Vs30, soil classification, amplification, and resonance frequency maps constitute valuable tools for seismic hazard assessment and land-use planning in the Azilal region. They provide essential information for the design of earthquake-resistant structures and for identifying areas requiring particular attention during future urban expansion. Although the study provides a robust characterization of local site effects, further investigations combining borehole data, ambient noise array measurements, and numerical site-response modeling would improve the understanding of three-dimensional subsurface conditions and refine seismic hazard assessments in the region.

This study initiated geotechnical engineering research in the urban area of Azilal to improve seismic risk management and reduce the vulnerability in the region. The use of complementary methods, such as seismic refraction, and the geotechnical data and boreholes, is valuable for the characterization of the city.

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