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Horizontal-to-vertical spectral ratio-based seismic site characterization of the Agadir Oufella area, southwestern Morocco

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ABSTRACT

Seismic site effects induced by local geological and geotechnical conditions can significantly modify ground shaking and increase earthquake hazard in urban environments. This study aims to characterize near-surface seismic conditions in the Agadir Oufella area (southwestern Morocco) using ambient vibration measurements analyzed through the horizontal-to-vertical spectral ratio (HVSR) method applied at 31 measurement stations. The approach combines HVSR-derived fundamental resonance frequencies with simplified quarter-wavelength and two-layer velocity models to estimate sediment thickness and proxy shear-wave velocity (Vs30), providing a first-order spatial model of subsurface stiffness variations. The results show strong spatial heterogeneity in seismic site conditions, with fundamental resonance frequencies ranging from 2 to 15 Hz, corresponding to estimated sediment thicknesses between 3 and 21 m and proxy Vs30 values varying from 318 to 632 m/s. The southwestern sector consistently exhibits lower resonance frequencies, thicker unconsolidated deposits, and lower Vs30 values, indicating softer and more deformable subsurface conditions, while the northern and eastern sectors are characterized by higher frequencies, thinner sediment cover, and relatively stiffer near-surface materials. These patterns suggest a dominant control of bedrock morphology and sediment thickness on local seismic response. A key limitation of this study is the reliance on assumed shear-wave velocity values and simplified one-dimensional subsurface models, which introduce uncertainty into sediment thickness and Vs30 estimations. Additionally, the absence of borehole or active seismic validation restricts the calibration of the derived parameters. Nevertheless, the spatial consistency of the results provides a robust first-order approximation of site-condition variability. Practically, the findings offer valuable input for seismic risk assessment, land-use planning, and urban development strategies in the Agadir Oufella sector, particularly in identifying areas potentially prone to seismic amplification. The originality of this work lies in the first high-resolution HVSR-based seismic microzonation of the Agadir Oufella area, integrating spatial mapping of resonance frequency, sediment thickness, and proxy Vs30 within a structurally complex urban geological setting.

Keywords: HVSR, site response, ambient vibration, Vs30 proxy, seismic microzonation, Morocco.

INTRODUCTION

Local geological and geotechnical conditions can significantly modify seismic ground motion, leading to substantial amplification of earthquake shaking and increased seismic risk in urban areas. These local site effects are primarily controlled by the thickness, geometry, and mechanical properties of near-surface deposits overlying competent bedrock and are widely recognized as critical parameters in seismic hazard assessment and urban planning (Pierre-Yves et al., 1999; Bonnefoy-Claudet et al., 2006; Pilz et al., 2025).

Among passive seismic techniques, the horizontal-to-vertical spectral ratio (HVSR) method has become one of the most widely used approaches for rapid and cost-effective seismic site characterization. Originally proposed by Nogoshi and Igarashi (1971) and later popularized by Nakamura (1989), the HVSR technique enables reliable estimation of the fundamental resonance frequency of soil deposits from ambient vibration recordings. Owing to its operational simplicity and low implementation cost, HVSR has been extensively applied worldwide for seismic microzonation, sediment thickness estimation, and preliminary Vs30 assessment in urban areas lacking borehole or active geophysical data (Molnar et al., 2018; Molnar et al., 2022; Panzera et al., 2019; Janusz et al., 2025).

In Morocco, seismic microzonation studies based on ambient vibration measurements remain relatively limited despite rapid urban expansion in seismically exposed regions. This issue is particularly critical in the Agadir region, which was affected by the destructive 1960 earthquake (Mw = 5.9), one of the most damaging seismic events in Moroccan history. Despite the recognized seismic vulnerability of Agadir and its continued urban development, detailed investigations of local seismic site conditions remain scarce in several urban sectors, including Agadir Oufella, where pronounced geological and structural heterogeneities may generate significant variations in seismic site response.

The Agadir Oufella sector is characterized by variable-thickness superficial deposits overlying consolidated Upper Cretaceous formations and by fault-controlled structural compartmentalization inherited from regional tectonic activity. These geological conditions suggest strong potential for lateral variability in near-surface seismic behavior. Moreover, the sector currently undergoes important urban and tourism development, increasing the need for seismic site characterization to support risk-informed land-use planning and engineering design.

The present study aims to provide a preliminary seismic site characterization of the Agadir Oufella area using ambient vibration HVSR measurements. Despite the recognized seismic vulnerability of the Agadir region, no detailed HVSR-based investigation has previously been conducted in the Agadir Oufella sector, resulting in limited knowledge regarding the spatial variability of local seismic site conditions in this structurally complex urban environment. The study therefore seeks to fill this gap by providing a first-order spatial assessment of near-surface seismic properties based on ambient vibration analysis. The study assumes that lateral variations in sediment thickness and bedrock geometry exert a significant control on the spatial variability of seismic site response across the investigated area. In this context, the combined analysis of HVSR-derived resonance frequencies, sediment thickness estimates, and proxy Vs30 values is expected to provide useful insight into near-surface stiffness variability and potential zones of increased seismic amplification.

Accordingly, the research focuses on mapping the spatial distribution of fundamental resonance frequency, estimating sediment thickness and proxy Vs30 using simplified HVSR-based approaches, and identifying sectors exhibiting comparatively less favorable seismic site conditions in support of future seismic risk mitigation, urban planning, and land-use management strategies.

GEOLOGICAL AND SEISMOTECTONIC SETTING

The study area is located in the Agadir Oufella sector, in the northern part of Agadir city, southwestern Morocco, at the southern foothills of the Western High Atlas. This area belongs to the northern margin of the Souss Basin, an intramontane depression bounded by the Western High Atlas to the north and the Anti-Atlas to the south. The geological evolution of the basin is related to successive extensional and compressional tectonic phases associated with the opening of the Central Atlantic and subsequent Africa-Europe convergence (Ambroggi, 1963; Meghraoui et al., 1999).

At the local scale, the Agadir Oufella sector is characterized by consolidated Upper Cretaceous sedimentary formations unconformably overlain by Plio-Quaternary and Quaternary superficial deposits (Figure 1) (Mridekh et al., 2009). The consolidated substratum consists predominantly of competent carbonate and marly units forming the seismic bedrock of the investigated sector. The superficial cover is represented by discontinuous Plio-Quaternary and Quaternary deposits composed of unconsolidated to semi-consolidated materials filling local depressions and structurally controlled topographic lows.

Structurally, the study area is affected by several NE-SW to ENE-WSW trending faults associated with the western termination of the High Atlas structural front (Hafid et al., 2005). These

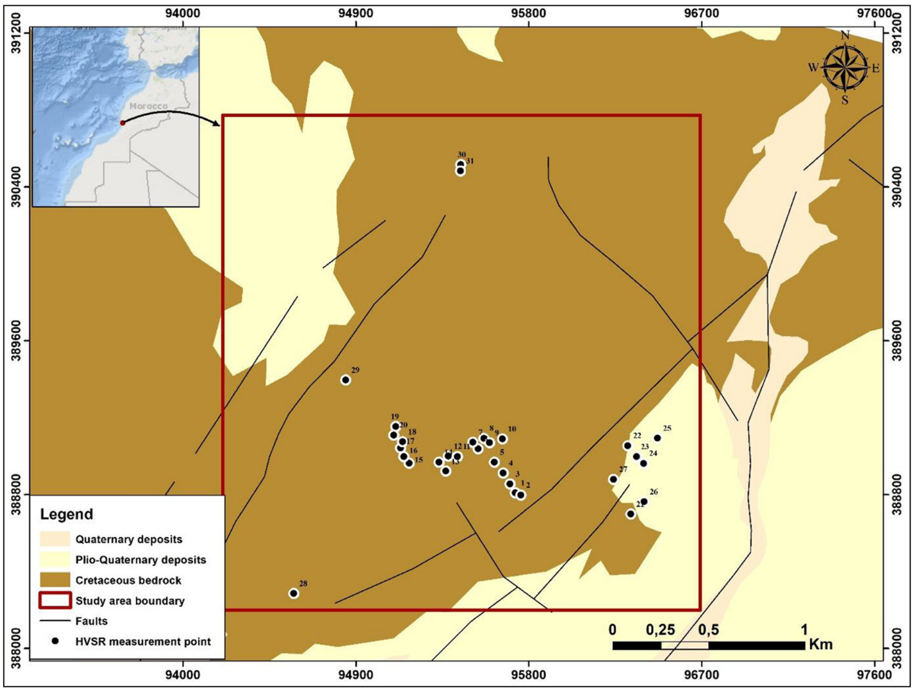

Figure 1. Simplified geological map of the Agadir Oufella area

inherited tectonic structures locally control topography, lithological boundaries, and sediment thickness distribution. The region is part of the seismically active Agadir area, which was affected by the destructive 1960 Agadir earthquake, emphasizing the importance of detailed seismic site characterization in this urban sector.

The combination of heterogeneous superficial deposits, competent bedrock, and active tectonic structures creates favorable conditions for significant lateral variations in local seismic response across the study area.

MATERIALS AND METHODS

HVSR data acquisition and processing

Ambient vibration measurements were carried out to determine the fundamental resonance frequency of the investigated sites using the horizontal-to-vertical spectral ratio (HVSR) technique. A total of 31 ambient noise measurements were acquired across the Agadir Oufella study area using a three-component short-period S3S2 seismic sensor (2 Hz geophones) connected to a 24-bit M.A.E. Vibralog acquisition unit (Table 1). Ambient vibrations were recorded simultaneously on two horizontal and one vertical component, and the geographic coordinates of each measurement point were determined using GPS. Each recording lasted approximately 15 min with a sampling frequency of 250 Hz, ensuring adequate signal duration for reliable spectral analysis. Measurements were preferentially conducted under relatively stable ambient noise conditions and away from transient anthropogenic disturbances such as heavy traffic or construction activities whenever possible.

The acquired ambient noise recordings were processed using HVLAB software associated with the Vibralog acquisition system. The signals were divided into stationary time windows selected according to signal stability, with the number of accepted windows ranging from 32 to 197 and individual window lengths varying between 4 and 22 s depending on signal quality. Time windows affected by transient disturbances or unstable spectral behavior were excluded from the analysis in accordance with the SESAME recommendations. For each selected window, the amplitude spectra of the three components were computed using Fast Fourier Transform (FFT). Spectral smoothing was subsequently applied using the Konno and Ohmachi (1998) smoothing algorithm to obtain stable spectral curves. The spectra of the two horizontal components were averaged and divided by the vertical component to compute the H/V spectral ratio for each window, from which the mean HVSR curve was derived for each

Table 1. Location and seismic site characterization parameters of the investigated measurement stations

Station	Latitude	Longitude	f_0 (Hz)	H (m)	Vs30 (m/s)
S01	30.4353	-9.6121	12.70	3.94	613
S02	30.4352	-9.6118	3.11	16.08	356
S03	30.4357	-9.6124	6.32	7.91	476
S04	30.4362	-9.6128	4.52	11.06	413
S05	30.4367	-9.6133	8.21	6.09	505
S06	30.4373	-9.6142	8.24	6.07	506
S07	30.4376	-9.6145	4.79	10.44	425
S08	30.4378	-9.6139	5.68	8.80	448
S09	30.4376	-9.6136	9.83	5.08	519
S10	30.4378	-9.6129	6.56	7.62	470
S11	30.4369	-9.6153	4.79	10.44	425
S12	30.4369	-9.6158	6.50	7.69	471
S13	30.4362	-9.6159	5.04	9.92	434
S14	30.4366	-9.6163	8.97	5.57	514
S15	30.4365	-9.6179	9.03	5.54	515
S16	30.4368	-9.6182	7.32	6.83	487
S17	30.4372	-9.6184	15.05	3.32	632
S18	30.4375	-9.6183	5.04	9.92	434
S19	30.4382	-9.6187	8.06	6.20	503
S20	30.4378	-9.6188	5.98	8.36	454
S21	30.4345	-9.6058	6.65	7.52	472
S22	30.4377	-9.6061	7.32	6.83	487
S23	30.4372	-9.6056	9.00	5.56	514
S24	30.4369	-9.6052	7.87	9.36	499
S25	30.4381	-9.6045	8.24	6.07	506
S26	30.4351	-9.6051	8.30	6.02	507
S27	30.4361	-9.6068	8.00	6.25	502
S28	30.4302	-9.6239	2.38	21.01	318
S29	30.4403	-9.6215	5.98	8.36	454
S30	30.4506	-9.6157	7.20	6.94	485
S31	30.4503	-9.6157	6.26	7.99	478

measurement point (Figure 2A). To ensure the reliability of the obtained resonance frequencies, data acquisition and processing were performed in accordance with the SESAME project recommendations (SESAME, 2004) (Figure 2B). Only well-defined and statistically stable HVSR peaks satisfying the SESAME reliability criteria were retained for interpretation. In particular, the reliability of the identified resonance frequencies was evaluated according to the SESAME criteria, including conditions such as $f_0 > 10/Lw$ and $nc(f_0) > 200$, ensuring the statistical stability of the H/V spectral peaks.

Sediment thickness estimation

The thickness of the superficial sedimentary cover overlying the seismic bedrock was estimated from the HVSR fundamental frequency using the quarter-wavelength approximation (Ibs-von Seht and Wohlenberg, 1999; Yang et al., 2025), which assumes a simplified one-dimensional horizontally layered subsurface. Under this approximation, sediment thickness H is related to the fundamental frequency according to:

$$H = \frac{Vs}{4f0} \tag{1}$$

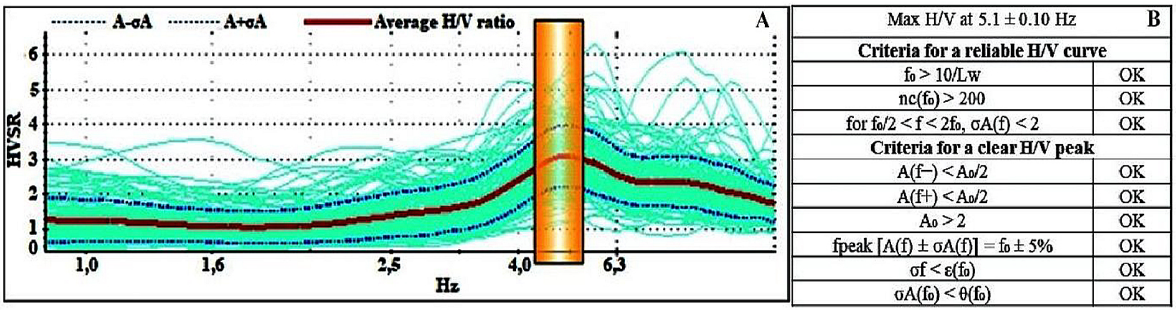

Figure 2. Example of HVSR results. (A) Average H/V spectral ratio curve (solid red line) with standard deviation (±σ, dashed lines); the vertical shaded band indicates the fundamental frequency (f_0). (B) SESAME criteria verification

where: f_0 is the fundamental frequency obtained from HVSR analysis and Vs is the average shear-wave velocity of the superficial sedimentary deposits.

In the absence of direct in situ shear-wave velocity measurements, a representative shear-wave velocity of 200 m/s was adopted as a first-order approximation for the unconsolidated superficial deposits. This value is consistent with typical shear-wave velocities reported for unconsolidated to weakly consolidated superficial sediments in comparable geological environments.

Estimation of Vs30

The average shear-wave velocity in the upper 30 m (Vs30) was estimated using a simplified two-layer velocity model consisting of a superficial sedimentary layer of thickness H overlying seismic bedrock. Vs30 was calculated according to:

$$Vs30 = \frac{30}{\frac{H}{Vs0} + \frac{30-H}{Vs1}} \quad (2)$$

where: H is the sediment thickness estimated from the HVSR results; $Vs0$ is the shear-wave velocity of the superficial sedimentary layer, fixed at 200 m/s; $Vs1$ is the shear-wave velocity of the seismic bedrock, fixed at 800 m/s.

The adopted bedrock velocity corresponds to the commonly accepted engineering threshold for stiff engineering bedrock used in seismic site classification frameworks such as Eurocode 8 (Rahman et al., 2016) and should be regarded as an engineering proxy rather than a directly measured bedrock velocity. Consequently, the estimated sediment thickness and proxy Vs30 values should be interpreted as first-order approximations of subsurface conditions rather than directly measured geotechnical parameters. The resulting Vs30 estimates were used to provide an engineering-oriented approximation of near-surface stiffness variations across the study area.

Spatial distribution maps of fundamental frequency, sediment thickness, and estimated Vs30 were generated using the inverse distance weighting (IDW) interpolation method within a GIS environment. The interpolation was performed using a power parameter of 2, a variable search radius, and 12 neighboring points.

RESULTS

Fundamental frequency distribution and HVSR characteristics

Representative HVSR curves show distinct morphologies across the study area, reflecting lateral variations in subsurface conditions (Figure 3). Most sites display a well-defined dominant peak, allowing reliable identification of the fundamental frequency and indicating that site response may be primarily influenced by a dominant impedance contrast between superficial deposits and the underlying substratum. Sharp peaks reflect strong impedance contrasts and relatively simple subsurface layering, whereas broader responses suggest more gradual mechanical transitions or local heterogeneity.

The HVSR analysis revealed marked spatial variability in fundamental frequency, with f_0 values ranging from 2 to 15 Hz (Figure 4). The lowest frequencies are concentrated in the southwestern part, particularly around station S28, where values below 5 Hz predominate, suggesting thicker superficial deposits. Intermediate

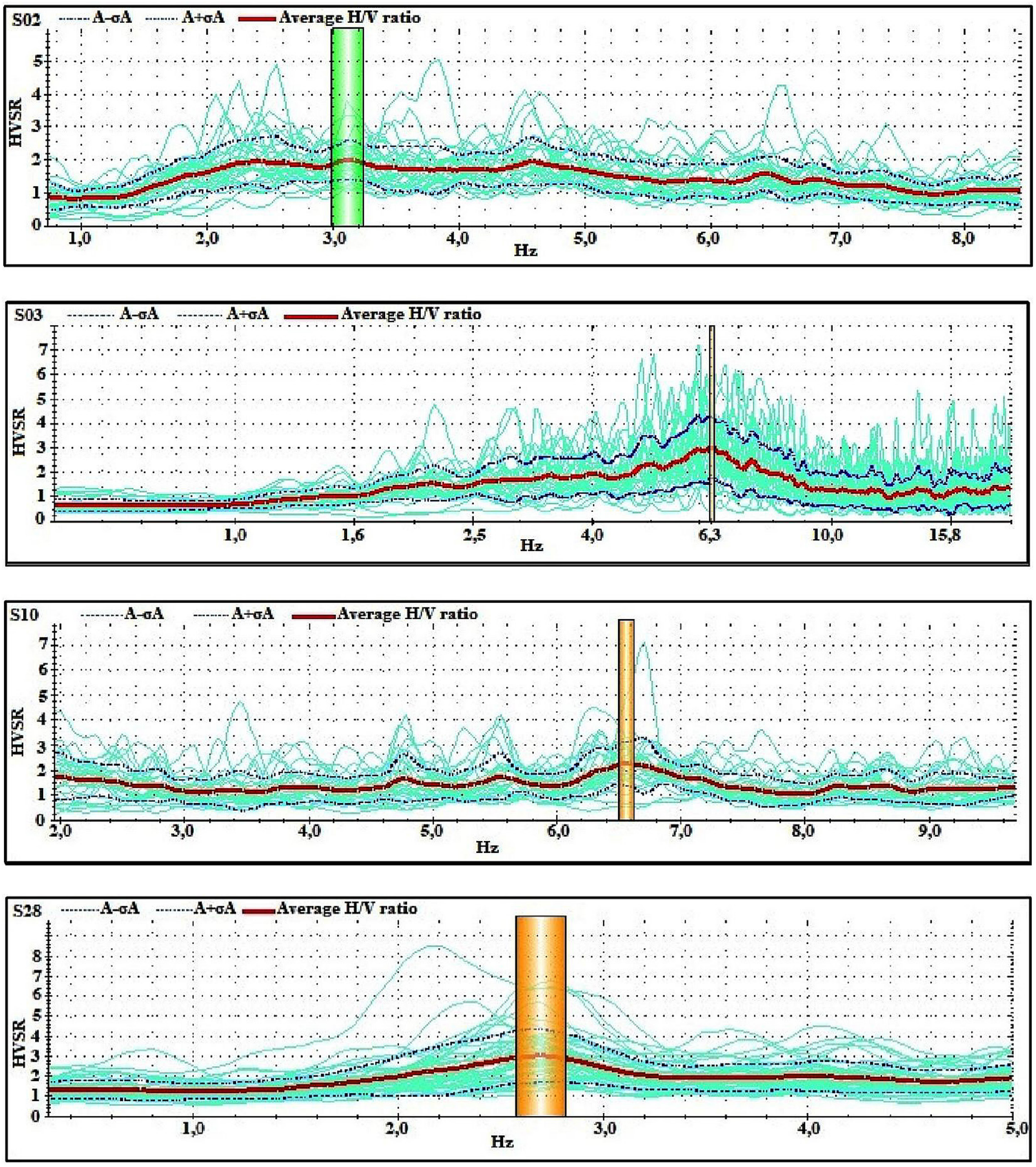

Figure 3. Representative HVSR curves for selected measurement points illustrating the main response typologies observed across the study area

frequencies between 5 and 8 Hz characterize much of the investigated area and suggest moderate sediment thicknesses. Higher frequencies exceeding 8 Hz occur locally in the central and eastern sectors, consistent with shallower bedrock conditions. A localized high-frequency anomaly reaching 15 Hz is observed at station S17, consistent with the presence of very shallow competent bedrock.

Sediment thickness distribution

The estimated sediment thickness across the study area ranges from 3 m to 21 m (Figure 5). The highest thickness values, locally exceeding 16 m, are confined to a limited zone in the southwestern part near station S28, indicating a localized zone of increased sediment accumulation. Sediment thicknesses between 8 and 12 m are mainly distributed in the central and southern-central parts indicating moderate development of superficial deposits above the seismic bedrock.

In contrast, the northern, northeastern, and eastern sectors are characterized by thinner sedimentary cover, generally less than 8 m, consistent with shallower bedrock conditions. The overall sediment-thickness pattern closely follows the spatial distribution of the fundamental resonance frequency, as expected from the adopted quarter-wavelength approximation. These lateral

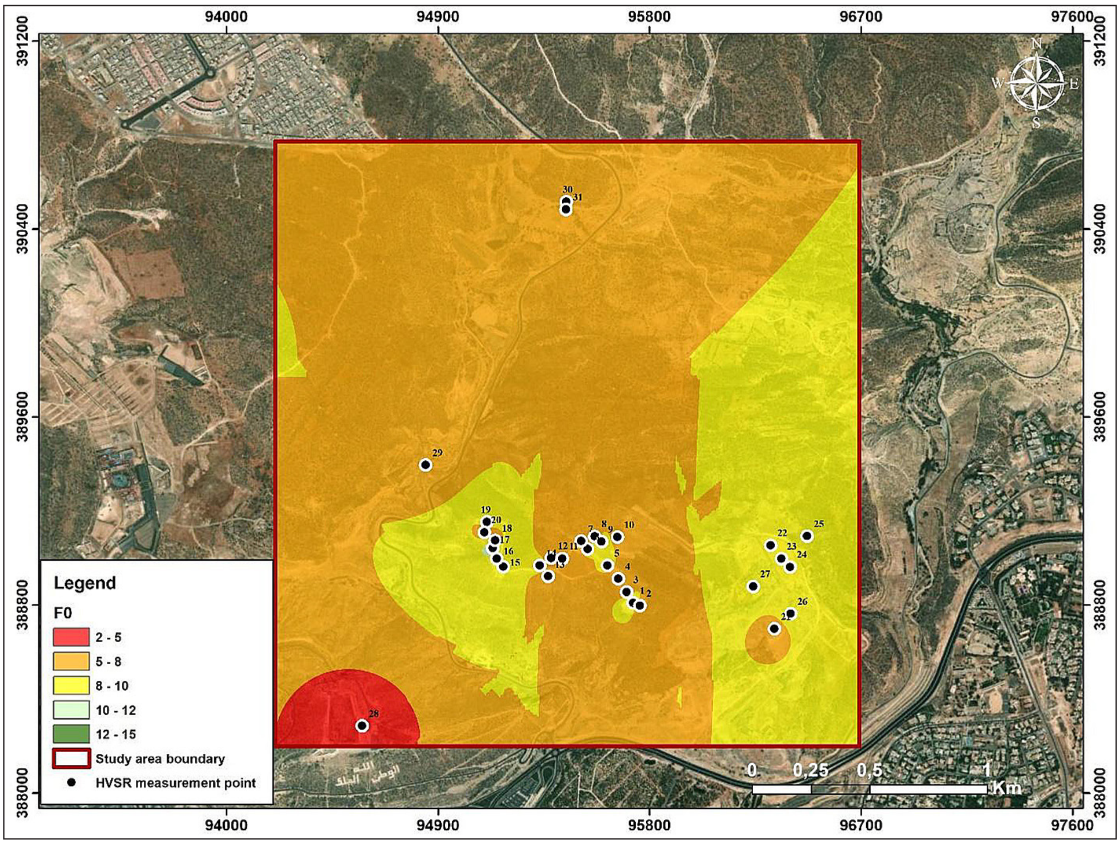

Figure 4. Spatial distribution of the fundamental frequency f_0

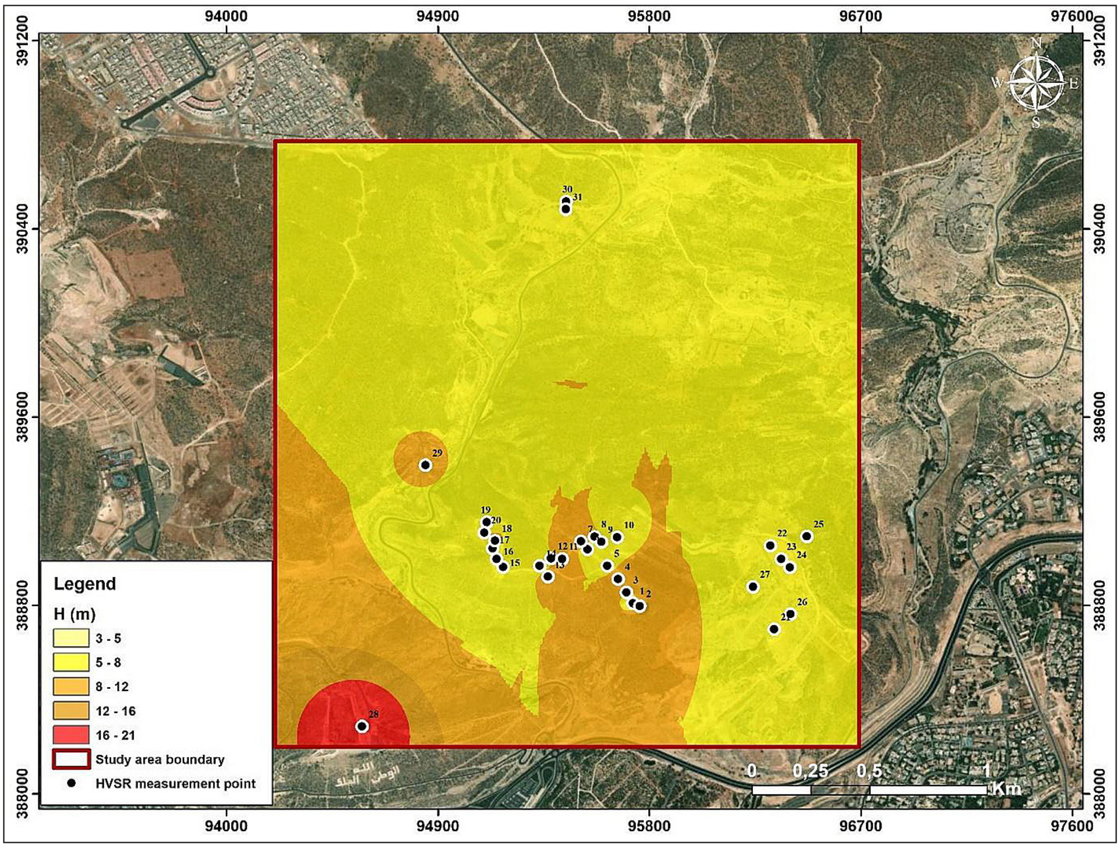

Figure 5. Spatial distribution of estimated sediment thickness

variations may reflect the combined influence of depositional heterogeneity, local topographic effects, and fault-controlled bedrock morphology.

Spatial distribution of estimated Vs30

The estimated Vs30 values range from 318 m/s to 632 m/s (Figure 6), indicating moderate to relatively high near-surface stiffness conditions overall. The lowest Vs30 values below 360 m/s are confined to a localized zone in the southwestern part of the study area near station S28, corresponding to areas characterized by thicker superficial deposits and lower resonance frequencies.

Intermediate Vs30 values between 360 and 480 m/s dominate the central part and reflect moderately stiff subsurface conditions. Higher Vs30 values exceeding 480 m/s are mainly observed in the northern and eastern sectors, indicating shallower competent bedrock and reduced thickness of superficial deposits.

The spatial distribution of estimated Vs30 is consistent with the previously identified patterns of fundamental frequency and sediment thickness, indicating comparatively softer subsurface conditions in the southwestern part of the study area. Based on the estimated Vs30 values, most of the study area corresponds to Eurocode 8 site class B, with localized class C conditions restricted to the southwestern sector.

DISCUSSION

Geological interpretation of site response variability

The spatial distribution of HVSR-derived parameters highlights substantial lateral heterogeneity in near-surface seismic conditions across the Agadir Oufella area, reflecting the combined influence of sediment-thickness variability, bedrock geometry, and structural controls. The progressive transition from lower fundamental frequencies, greater sediment thicknesses, and lower estimated Vs30 values in the southwestern sector toward higher frequencies and stiffer conditions in the northern and eastern sectors suggests a general shallowing of the competent substratum from southwest to northeast. This pattern indicates that seismic site response is primarily governed by

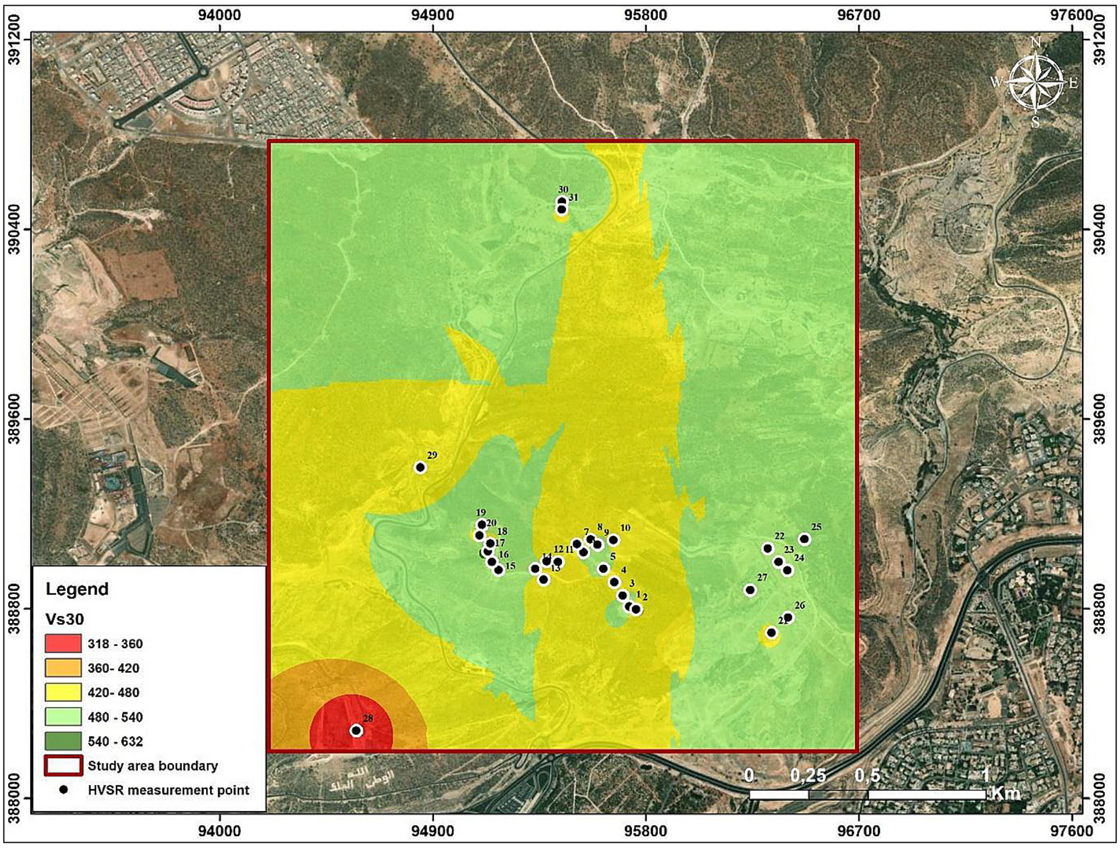

Figure 6. Spatial distribution of Vs30

variations in the thickness and stiffness of superficial deposits overlying the seismic bedrock.

The concentration of thicker sedimentary accumulations in the southwestern part likely reflects localized depositional depressions related to bedrock topography and structural compartmentalization. Given the tectonically controlled setting of Agadir Oufella, inherited fault systems may have contributed to the development of shallow depressions favoring preferential sediment preservation and thicker superficial cover in structurally lower zones. Similar fault-controlled sediment-thickness variability has been documented in several urban environments affected by active or inherited tectonic structures, where shallow bedrock morphology exerts a first-order control on seismic site response (Akin and Sayil, 2025) (Panzera et al., 2019).

The inverse relationship observed between fundamental frequency and estimated sediment thickness is consistent with the expected behavior of resonance in layered media and agrees with previous HVSR-based investigations performed in geologically heterogeneous urban settings (Ibs-von Seht and Wohlenberg, 1999; Parolai et al., 2004; Vijayan et al., 2022; Yang et al., 2025). Although the sediment thickness and Vs30 values derived in this study rely on simplified assumptions, the spatial coherence of the mapped parameters and their agreement with the geological framework support the plausibility of the interpreted subsurface model.

From an engineering perspective, the southwestern sector emerges as the least favorable zone in terms of seismic site conditions. This area combines lower resonance frequencies, thicker unconsolidated deposits, and reduced estimated Vs30 values, all of which are commonly associated with enhanced amplification potential during seismic shaking (Bonnefoy-Claudet et al., 2006; Bard et al., 2010). In the context of the historical seismicity of Agadir and the ongoing urban development of the Agadir Oufella, these findings underline the importance of integrating site-condition variability into future urban planning and seismic design considerations.

Limitations and uncertainties

Despite the overall consistency of the results, several limitations should be considered when interpreting the derived sediment thickness and Vs30 distributions. First, sediment thickness estimation is based on the quarter-wavelength approximation, which assumes a one-dimensional horizontally layered subsurface and homogeneous sediment properties. In structurally complex environments such as the Agadir Oufella area, these assumptions may not fully account for local three-dimensional effects or abrupt lateral lithological variations.

Second, both sediment thickness and Vs30 estimations rely on assumed shear-wave velocity values for the superficial deposits and seismic bedrock rather than direct in situ geophysical measurements. Consequently, the computed values should be regarded as first-order approximations of subsurface conditions rather than absolute geotechnical parameters. Furthermore, the adopted two-layer velocity model represents a simplified approximation of the subsurface structure and may not fully account for local lateral heterogeneity or complex stratigraphic variations. In addition, the absence of direct geophysical or borehole validation data limits the calibration of the estimated sediment thickness and proxy Vs30 values. Similar uncertainty sources have been highlighted in recent assessments of HVSR-based sediment thickness estimation and passive seismic site characterization methodologies (Molnar et al., 2018; Perret et al., 2024).

In addition, interpolation of discrete HVSR measurements may introduce localized artefacts, particularly near peripheral areas where station density is lower and spatial control is reduced. Therefore, the interpolated maps should be interpreted as indicative of regional trends in site-condition variability rather than exact representations of subsurface geometry.

However, the spatial consistency of the derived parameter distributions, together with their agreement with the geological framework of the area, suggests that the proposed seismic site characterization provides a robust first-order assessment of local site-condition variability.

CONCLUSIONS

This study presents a seismic site characterization of the Agadir Oufella area based on ambient vibration measurements using the HVSR method. The analysis of 31 measurement points enabled the spatial mapping of fundamental resonance frequency, sediment thickness, and estimated proxy Vs30 values, providing new insights into near-surface seismic properties in this urban sector. The results reveal marked lateral variability in seismic site conditions, with fundamental resonance frequencies ranging from 2 to 15 Hz, approximated sediment thicknesses from 3 to 21 m, and estimated proxy Vs30 values from 318 to 632 m/s. The southwestern sector is characterized by lower resonance frequencies, thicker superficial deposits, and lower estimated proxy Vs30 values, indicating comparatively softer subsurface conditions than the northern and eastern sectors.

The overall spatial coherence between the mapped parameters highlights the dominant influence of sediment thickness and bedrock geometry on local seismic site response. Although the sediment thickness and Vs30 estimates rely on simplified assumptions, the results provide a robust first-order assessment of site-condition variability and identify the southwestern sector of the area potentially most susceptible to local amplification effects. These findings provide valuable information for seismic risk mitigation, urban planning, and future geotechnical investigations in the Agadir Oufella sector. Further investigations integrating active geophysical surveys and borehole data are recommended to refine the subsurface model and validate the estimated geotechnical parameters.

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