

Effects of Engineering Bedrock Depth on Seismic Site Response in Thick Marly Deposits

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Abstract. The influence of local site conditions—particularly the properties and thickness of soil deposits overlying the engineering bedrock—on seismic ground motion is well established. Current seismic design codes generally account for these effects through simplified site classification schemes, most commonly based on the average shear-wave velocity in the upper 30 m (V_{s30}). While practical, this approach may prove insufficient in geological contexts characterized by thick and relatively stiff soil formations extending well beyond this depth, where deeper stratigraphic features can significantly affect the seismic response. The Algiers region provides a representative example of such conditions. A large part of the urban area is underlain by extensive deposits of fresh blue marls, whose thickness frequently exceeds 100 m before reaching the seismic bedrock. These marls exhibit a marked increase in stiffness with depth, with shear-wave velocities often exceeding 600 m/s at depths of 30 to 40 m. Consequently, in many site-specific studies, these formations are commonly considered as the engineering bedrock, despite their considerable thickness and internal heterogeneity. Detailed site modeling, supported in particular by ambient vibration measurements using the H/V spectral ratio method, highlighted a significant spatial variability across the study area. This variability concerns both the thickness of the superficial layers and the depth to the stiff marl formation that may act as engineering bedrock. Building on these observations, a series of additional stratigraphic models was developed by progressively increasing the thickness of the soil column, thereby simulating increasing bedrock depths. This study investigates the effect of engineering bedrock depth on seismic site response through one-dimensional equivalent-linear ground response analyses. A set of representative soil profiles was constructed by varying the depth to bedrock, with marl thicknesses ranging from approximately 30 m to more than 100 m. The results of the comparative analyses of free-surface ground motion indicate that increasing bedrock depth generally leads to a reduction in amplification levels, accompanied by a shift of dominant frequencies toward lower values. These findings highlight the limitations of V_{s30} -based classifications in such geological settings and emphasize the need to explicitly account for deep soil conditions in seismic hazard assessment and site-specific design.

Keywords: Accelerograms, Bedrock Depth, Marl, Amplification, Response Spectrum.

1 Introduction

In the context of earthquake-resistant design, engineers are required to reliably assess the response of a given site to seismic loading. While structural design relies on appropriate seismic analyses, these must be based on a rigorous characterization of local site conditions: the seismic hazard assessment and the analysis of the dynamic response of site.

The presence of heterogeneous near-surface formations, characterized by contrasts in stiffness, density, and mechanical behavior, can significantly modify seismic ground motion, particularly through amplification and resonance phenomena. The determination of local seismic response, typically through the transfer function of the soil profile, therefore represents a key step in evaluating site effects and in developing site-specific response spectra.

However, current code-based approaches, which rely primarily on simplified parameters such as the average shear-wave velocity over the upper 30 meters (V_{s30}), may prove inadequate in certain geological contexts. This is particularly the case in regions characterized by thick deposits of stiff soils, such as marls, where the depth to the engineering bedrock becomes a controlling factor in seismic response.

In the Algiers region, large areas are underlain by deposits of fresh blue marls, whose thickness may exceed 100 m, with stiffness increasing with depth. Under such conditions, identifying the engineering bedrock and properly accounting for its actual depth become critical issues for a reliable evaluation of site seismic response.

The present study aims to investigate the influence of engineering bedrock depth on the seismic response of sites characterized by thick marly deposits, through one-dimensional ground response analyses. The study is based on site modeling derived from geotechnical and geophysical data, enabling the assessment of the impact of bedrock depth variability on seismic amplification phenomena, and providing insights for earthquake-resistant design and seismic microzonation studies.

2 Geotechnical data and site investigations

As part of this study, a comprehensive geotechnical and geophysical investigation campaign was carried out to characterize the mechanical and dynamic properties of the in-situ formations. The program included nine core drilling boreholes, fourteen pressuremeter boreholes reaching depths of up to 40 m, as well as laboratory testing (soil identification and mechanical behavior). In addition, down-hole geophysical measurements were performed in three boreholes to determine seismic wave velocities.

The cored boreholes reveal a typical stratigraphic profile dominated by marly formations, organized as follows:

- a superficial layer consisting of fill materials and tuffs, with variable thickness;
- a layer of marly clays, sometimes weathered;
- a formation of grayish marls, locally friable or fractured;
- a deep layer of indurated gray to bluish marls, representing the stiffest horizon.

A pronounced lateral variability is observed across the site. In the western part, the indurated marls outcrop at shallow depth (<4m), whereas in the eastern part they are overlain by superficial formations reaching thicknesses of 20-25m. This configuration highlights a non-uniform geometry of the engineering bedrock (figure 1).

Laboratory test results indicate predominantly fine-grained soils (80–99% passing the 80 μm sieve), characterized by a liquid limit ranging from 45% to 99%, a plasticity index between 23 and 29, indicating medium to high plasticity soils and dry unit weights ranging from 1.52 to 2.17 t/m^3 .

Pressuremeter tests indicate a significant increase in stiffness with depth, with pressuremeter moduli (E_p) exceeding 200bars (figure 1a) and limit pressures (PI) greater than 20bars from approximately 12m depth (figure 1b), characterizing a firm soil profile.

Shear-wave velocity measurements show values ranging from 245 to 470 m/s in the superficial layers, exceeding 600 m/s in the indurated marls. A clear distinction is observed between the eastern part of the site, where velocities remain moderate over the first 20 to 25 m, and the western part, where high velocities are reached at shallow depths (blue line in figure 1c).

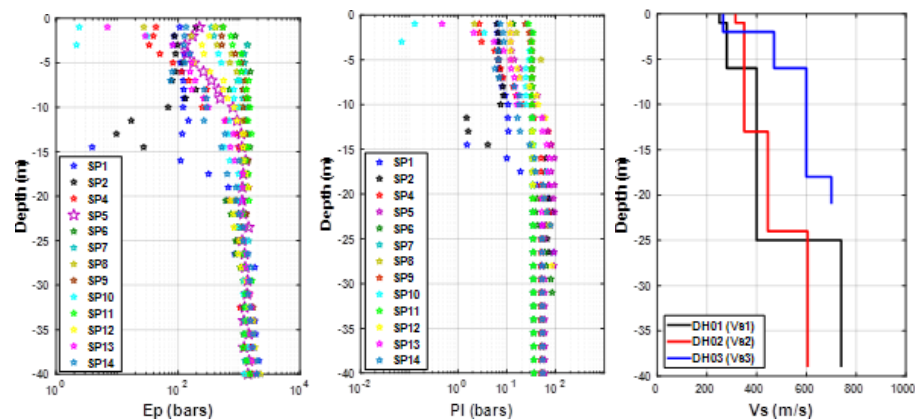


Fig. 1. Vs profiles obtained at the site

3 Ambient vibrations data and inversion

An ambient noise survey was conducted at the site using three-component seismometers, with 15-minute recordings acquired at more than 50 locations, including drilling and pressuremeter boreholes to ensure consistency with geotechnical data. The H/V spectral ratio analysis reveals a dominant fundamental frequency around 1.1 Hz, with secondary peaks between 2.6–3.8 Hz and occasionally higher than 10 Hz (figure 2a). Low-frequency peaks reflect the response of a very thick soil profile, while higher-frequency peaks are associated with shallow layers. The fundamental frequency is attributed to a thick indurated marl exceeding 150 m in thickness ($V_s \approx 700$ m/s), whereas the higher modes correspond to superficial deposits (tuffs and marly soils) with variable thicknesses up to about 25 m.

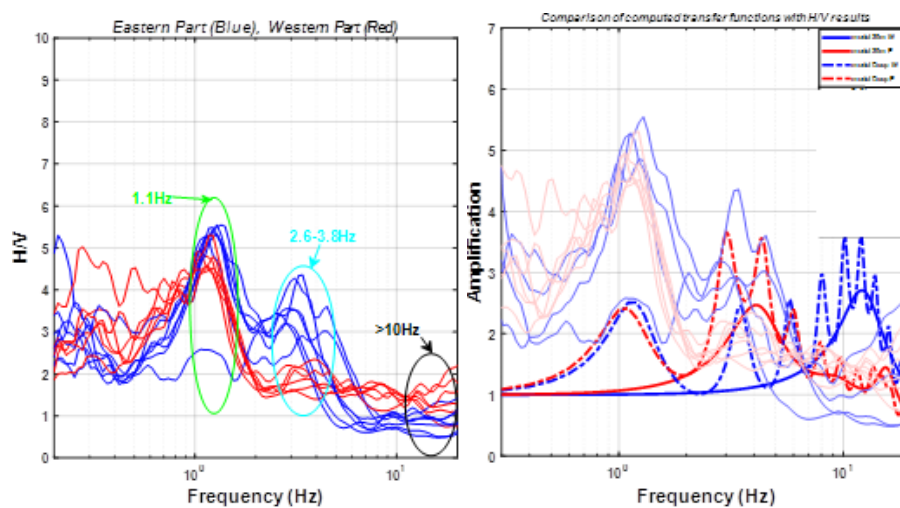


Fig. 2. H/V measurement results at the site

An inversion approach, developed at CGS, was applied to derive seismic soil profiles from ambient vibration (H/V) measurements around the cored boreholes where D-H tests were performed. The resulting best-fit profile highlights low-velocity superficial layers typical of soft materials, followed by a gradual increase in stiffness with depth and a marked velocity contrast reaching about 600 m/s between 23 and 180 m, interpreted as the seismic bedrock. This deep contrast likely explains the low-frequency peak around 1.1 Hz. The good agreement between theoretical and observed HVSR curves supports the validity of the proposed model.

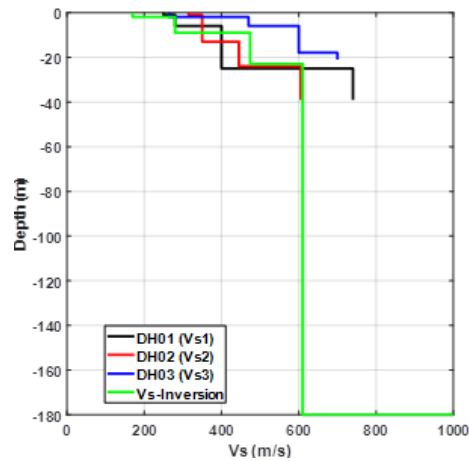


Fig. 3. Seismic profile obtained from inversion of HVSR results

4 Site modeling and stratigraphic profiles

The study area is characterized by heterogeneous near-surface deposits consisting of tuffs, marly clays, and locally soft marls, overlying a progressively stiffening marly formation that becomes indurated with depth.

Based on an integrated interpretation of borehole logs, pressuremeter results, shear-wave velocity (V_s) profiles from down-hole tests, and HVSR measurements, two representative one-dimensional stratigraphic models were developed for the eastern and western parts of the site. Shear-wave velocity profiles indicate a gradual increase in stiffness with depth, from approximately 170–280 m/s in the near-surface layers to 600–750 m/s in the indurated marls.

In addition to shallow configurations, deep soil models were developed by considering the full thickness of marly deposits, which may exceed 180 m according to geological evidence and HVSR interpretation. These models explicitly account for the depth to engineering bedrock and allow assessment of its influence on seismic site response, particularly at long periods where shallow-bedrock assumptions become inadequate.

The seismic response was evaluated using one-dimensional equivalent-linear site response analyses assuming vertically propagating shear waves in horizontally layered media. Each layer is defined by its thickness, density, shear-wave velocity, and damping ratio, while nonlinear soil behavior is represented through modulus degradation and damping increase as a function of shear strain. Seismic input motion is applied at the base of the model at the engineering bedrock level in the form of input accelerograms.



Fig. 4. Site profile models considered to account for the depth to engineering bedrock

Comparison of shallow and deep models (Figure 2b), in terms of transfer functions, clearly highlights the governing role of engineering bedrock depth in controlling the dynamic response of the site. While shallow models primarily reflect the influence of near-surface layers, deeper configurations exhibit pronounced low-frequency fundamental modes associated with the considerable thickness of marly deposits.

The transfer functions obtained for all models are presented in Figure 5a. A systematic decrease in both peak frequency and amplification is observed with increasing bedrock depth. At the same time, higher modes become increasingly involved in the amplification. The corresponding evolution of dominant frequency and amplification factors is illustrated in Figures 5b and 5c.

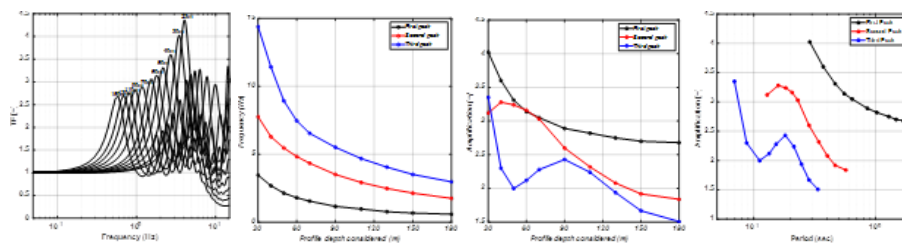


Fig. 5. Variation of transfer functions in terms of peak frequency and amplification for all considered models

5 Analysis of seismic responses

The seismic response at the free surface of the soil profiles was computed using selected input motions applied at the base, a key step in site response analysis (Idriss, 1993; NEHRP, 1997, 2003). Eleven input accelerograms (obtained in geological

contexts similar to the study site) were considered. The peak ground acceleration of the real records was scaled to 0.30g, consistent with the seismic hazard assessment of the site for a 475-year return period. The example of Keddara accelerogram is shown in figure 6.

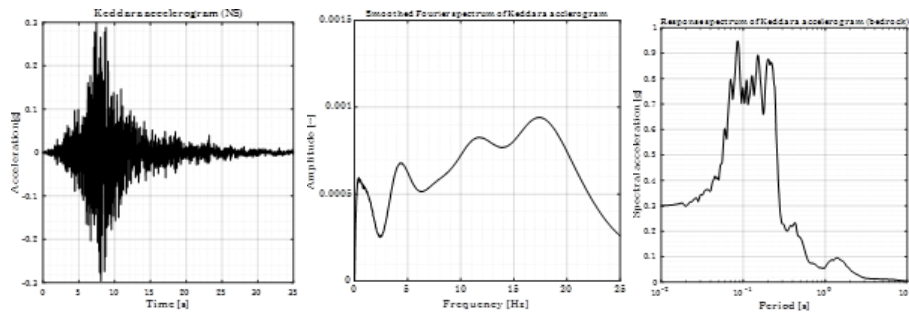


Fig. 6. N-S component of the Keddara accelerogram applied at the bedrock and its spectra

Figure 7 presents the seismic response in terms of response spectra for two extreme profile depths (30 m and 180 m). The results clearly show that deeper models lead to a more pronounced attenuation of spectral ordinates at short periods ($T < 0.5$ s), while simultaneously inducing a shift of the frequency content toward longer periods. For further insight, the peak accelerations at $T=0.0$ s are presented in Figures 7b and 7c. The results clearly indicate that increasing the depth to the engineering bedrock leads to a reduction in surface acceleration levels. Moreover, the western profile, characterized by thicker superficial soft layers, exhibits higher amplification compared to the eastern profile, where the stiff marl formation is encountered at a shallow depth.

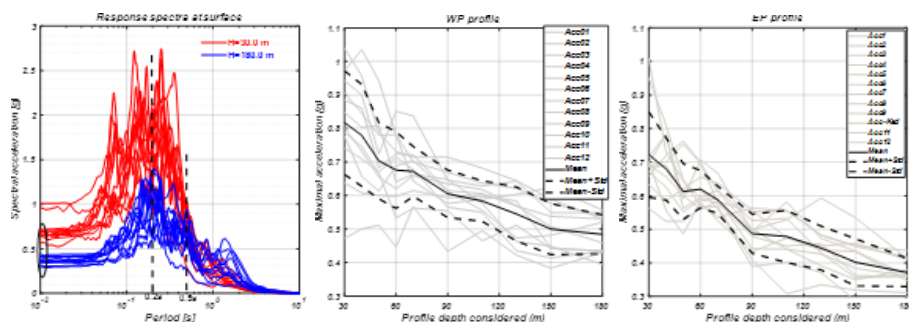


Fig. 7. Response spectra at the surface and variation of PGA with profile depth considered at East and West parts of the site.

The peak accelerations at $T=0.2$ and 0.5 s are presented in Figures 8 in the case of Keddara accelerogram. A clear decreasing trend in acceleration is observed at $T=0.0$ s for both the eastern and western parts of the site. However, at $T=0.5$ s, the spectral

accelerations appear to be only marginally affected by variations in the assumed bedrock depth. More generally, as illustrated in Figure 7a, for periods greater than 0.5 s, the spectral response tends to increase with increasing bedrock depth. This suggests that bedrock depth has a strong attenuating effect at short periods, while exerting an opposite influence—enhancing the response—at longer periods.

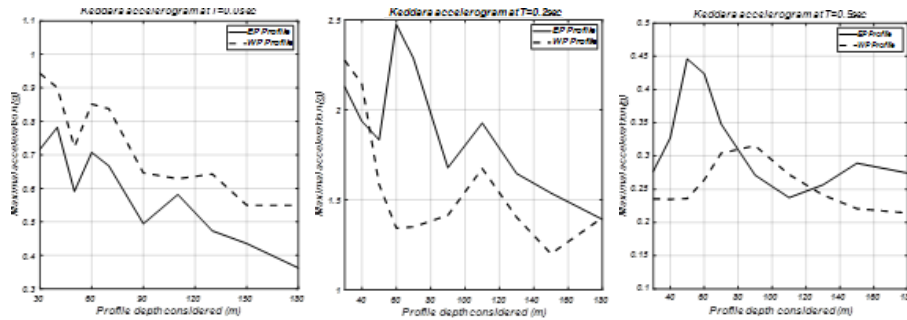


Fig. 8. Variation of spectral acceleration with profile depth considered at East and West parts of the site.

6 Effects of superficial layers characterized by low vs

Superficial layers with relatively low shear-wave velocities play a key role in amplifying seismic waves, particularly at high frequencies. It is therefore of practical interest to mitigate these effects through excavating and backfilling. Figure 9 further illustrates that, for a deep site configuration ($H=180\text{m}$), decreasing the thickness of the superficial layers (h) systematically results in lower surface amplification. In the case of a deep model without low- V_s superficial layers ($h = 0\text{ m}$), the surface response spectra closely approach the input motion spectrum at the base.

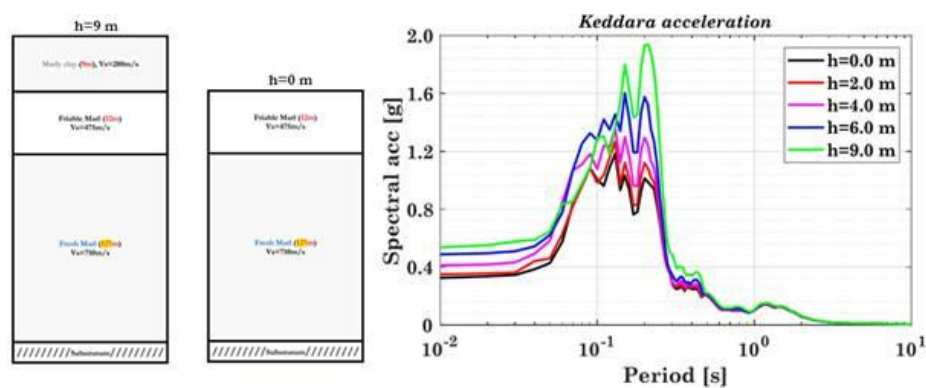


Fig. 9. Site profile models considered to account for the depth to engineering bedrock

7 Conclusion

In summary, deep layers tend to act as energy absorbers (dampers) of seismic waves, whereas superficial layers behave as amplifiers. It was also shown that extending the site model beyond 30 m depth to reach the actual bedrock ($V_s > 800$ m/s), as in the case of marly formations, leads to a reduction in amplification. These findings support the recommendation to extend the depth of the site model used for seismic response analysis down to the engineering bedrock ($V_s > 800$ m/s) in deep marly sites such as those encountered in Algiers, and to mitigate superficial layers through excavating and backfilling, particularly for critical structures.

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