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Effects of Local Soil Profiles on Seismic Site Response Analysis

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Abstract
Local soil conditions play a significant role in the intensity variations of seismic waves during earthquakes. These variations can be either amplified or de-amplified depending on the specific soil conditions. This study aimed to assess the impact of different soil profiles on seismic site responses. The study considered four types of site profiles: sand (Sa), clay (Cl), sand overlying clay (SaCl), and clay overlying sand (ClSa) profiles. To simulate the ground motion, we selected seven sets of strong earthquake records from the European Strong-Motion Database. These records were selected according to Eurocode-8 with a peak ground acceleration (PGA) of 0.24 g, site class A using REXEL computer program. The records were then applied to the bedrock at a depth of 30 meters. Subsequently, a series of 1-D equivalent linear (EQL) response analyses were performed using the STRATA. Amplification factors (AFs) and surface acceleration time histories provided quantitative evaluations for our analysis results. The results demonstrated that site profiles with clay overlying bedrock (SaCl and Cl profiles) exhibited higher seismic amplification and peak ground acceleration in comparison to site profiles with sand overlying bedrock (Sa and ClSa profiles). The maximum median AF is calculated from the SaCl site profile, while the minimum median AF was calculated from the ClSa profile. The relative difference between the maximum and the minimum median AFs was about 33.7%. Based on these results, we can conclude that soft local soils have a pronounced effect on the amplification of seismic waves compared to stiff local soils.
Keywords
earthquake, amplification factor, local soil conditions, site response, STRATA

1 Introduction

Seismic ground motion is significantly influenced by local soil conditions [1–4]. Past earthquakes, such as the 1985 Mexico earthquake [5], the 1989 Loma Prieta earthquake [6], the 1995 Kobe earthquake [7], the 1999 Athens earthquake [8], the 2003 Lefkada earthquake [9], and the 2008 Achaia-Elia earthquake [10] have portrayed the importance of local soil conditions on seismic ground motion. Variations in soil conditions near the Earth's surface can cause large changes in seismic waves, leading to more pronounced ground motion on soft soil sites compared to stiff soil sites [11]. An estimated 250 people were killed in a magnitude 6.5 earthquake in Venezuela in 1967. This was mostly attributable to the high destruction rate of buildings on sites with substantial overburden, while sites with shallow overburden suffered essentially little damage [12]. In the 1989 Loma Prieta earthquake, significant damage was mainly caused by the amplification effect of soft soil sites [13, 14].

The effect of local soil condition on ground motion is commonly assessed through site response analysis. Site response is a function of the soil profile, and the distribution of the soil profile has a significant impact on the seismic site response [3]. The level of ground shaking changes depending on the layering, shear wave velocity (the speed at which shear waves propagate through the soil), modulus reduction (decrease in stiffness of soil under cyclic loading), and damping (the dissipation of energy during wave propagation) of the soil in the area.

To estimate the magnitude of amplification or de-amplification of seismic ground motions at a given location, site response analysis simulates seismic wave propagation from bedrock to the ground surface. This involves modeling the soil layers and their properties, as well as accounting for other factors such as topography and seismic source characteristics. By analyzing the interaction of seismic waves with different soil layers, site response analysis can

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provide valuable insights into how local soil conditions impact ground motion during an earthquake. These analyses quantify the effects of local soil conditions on shaking intensities and providing ground surface parameters required for geotechnical and structural design [15].

The 1-D equivalent linear (EQL) analysis method is widely used in geotechnical engineering to calculate ground motion due to its high computational efficiency, ease of obtaining parameters and excellent convergence performance [15]. This method involves modeling the shear modulus reduction (G/G_{max}) and damping (D) properties of soil layers as a series of springs and dashpots [16], with the dashpot and spring parameters computed based on the secant shear modulus and damping ratio for a given level of induced shear strain [17]. To perform EQL site response analysis, researchers frequently employ computer programs such as SHAKE [18–20], STRATA [21], and DEEPSOIL [22].

The main objective of this study is to investigate the impact of different soil profiles on seismic site response. Four distinct groups of site profiles were analyzed to achieve this objective. The assessment involved thorough examination and evaluation of response parameters generated for each profile. To calculate the response, we implemented the EQL analysis method for each site profile using STRATA.

The structure of the remaining part of this paper is as follows: Section 2 discusses on the site response simulation methods, including the equivalent linear analysis method, description of site profiles considered for the simulation, and selection of rock motion. In Section 3, a comprehensive discussion is presented on the results obtained from response analysis. Finally, Section 4 summarizes the main findings of the study and concludes by proposing recommendations for future research.

2 Response simulation

2.1 Equivalent linear analysis method

EQL site response analysis method uses frequency domain transfer function to model the 1-D, linear elastic vertically propagating horizontally polarized shear waves through layered soil deposits [23]. The analysis method estimates seismic response by adjusting the linear elastic properties of soils in accordance with induced strain level. It is suggested that for a given input earthquake motion, the ground response parameters should be computed for strain level approximately equal to 65% of the maximum strain in each layer [16]. The EQL site response analysis uses the iterative procedure, as illustrated in Fig. 1, to estimate G/G_{max} and D values. The procedures of setting the G/G_{max} and D values of soil in EQL site response analysis are as follow [21, 24]: (1) Set the initial G/G_{max} and D values of the soil, commonly taken as maximum G/G_{max} and minimum D, respectively, and perform response analysis. (2) After the analysis is completed, compute the new G/G_{max} and D values from the maximum strain level in each layer. (3) Use the newly calculated G/G_{max} and D values to perform the response analysis again and calculate errors until the errors converge to predetermined thresholds. Once the iterative section of the program is completed, the strain-compatible soil properties are used to calculate the site response.

2.2 Site profile

The effect of soil conditions on seismic site response is assessed through the evaluation of four distinct groups of site profiles (see Fig. 2). The analyzed site profiles comprise

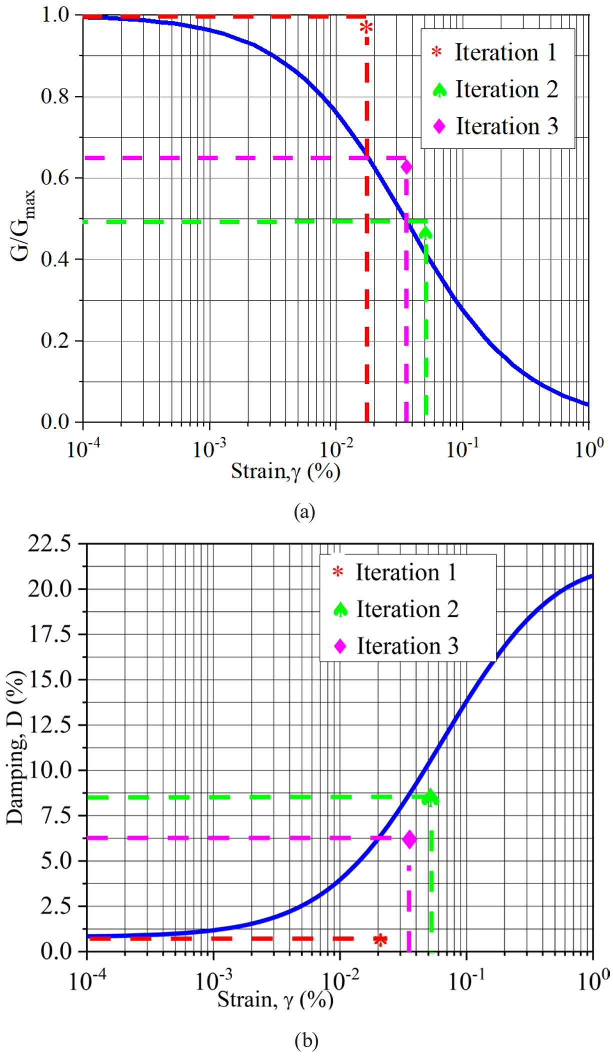

Fig. 1 EQL iterative procedure for (a) G/G_{max} and (b) D curve vs strain

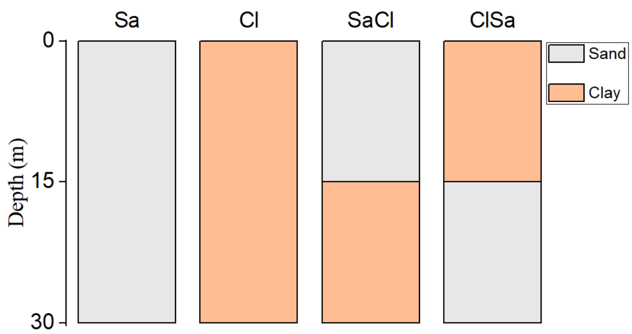

Fig. 2 Site profiles considered for seismic site response simulation

sand (Sa), clay (Cl), sand overlying clay (SaCl) and clay overlying sand (ClSa). We anticipated that the site profiles consist of stiff sand and soft clay soils. The material properties of each site profile, including shear wave velocity and unit weight of soil, were obtained from previously published works by Pass [25] and Dickenson [26]. Table 1 summarizes the soil data, including shear wave velocity and other relevant material properties, used in this study. The non-linear properties of soil, such as modulus reduction and damping properties, were also considered.

In this study, we utilized the Vucetic and Dobry [27] and Darendeli [28] nonlinear material models to accurately capture the nonlinear behavior of the soils (Fig. 3). The modulus reduction curve specifies the variability of the normalized shear modulus with respect to the shear strain, while the damping curve characterize the variation of the soil's damping nature with respect to the induced shear strain.

2.3 Input rock motion selection

The seismic site response analysis requires input rock motions in the form of acceleration time histories. The Fast Fourier Transform (FFT) is used to convert input acceleration-time histories into the frequency domain. The resulting Fourier amplitude spectrum (FAS) is multiplied by the transfer function that represents wave propagation to the ground surface, and the FAS at the surface is converted to an acceleration time histories using the inverse FFT [23].

In this study, the input rock motions were selected from European Strong-motion Database using REXEL [29] computer program. REXEL searches out suitable bins of earthquake records based on search parameters such as the size of the controlling earthquake, peak ground acceleration value, distance from the source to the site, and site class. Scaling techniques, which involve increasing or decreasing

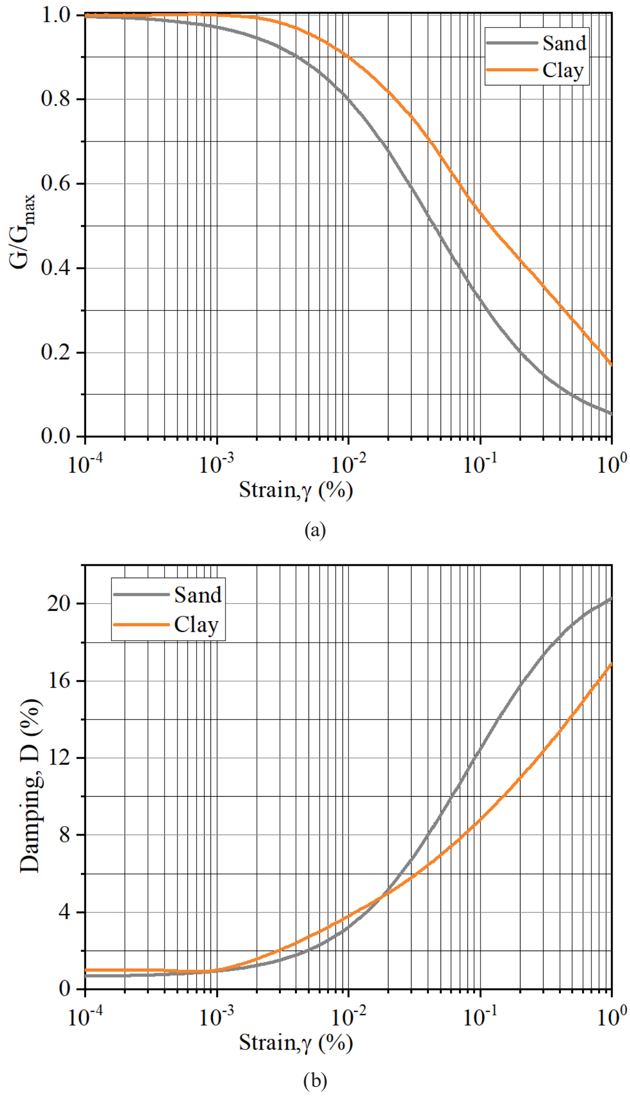

Fig. 3 Non-linear material models considered in this study (a) G/G_{max} (b) D (%) Vs strain, γ (%) (adapted from [27] and [28])

Table 1 Material properties used in this study(modified from [26, 27])

Soil profile No.	Soil description	Layer thickness (m)	Shear wave velocity (m/s)	Mass density (kg/m^3)	Modulus reduction model	Damping curve model
1	Sand	30	290	1800	Darendeli	Darendeli
2	Clay	30	290	1980	Vucetic & Dobry, PI = 30	Vucetic & Dobry, PI = 30
3	Sand/Clay	15/15	290/290	1800/1980	Darendeli & Vucetic & Dobry, PI = 30	Darendeli, Vucetic & Dobry, PI = 30
4	Clay/Sand	15/15	290/290	1980/1800	Vucetic & Dobry, PI = 30 / Darendeli	Vucetic & Dobry, PI = 30 / Darendeli

acceleration amplitude, are employed by REXEL to fulfill search parameters. Sufficient number of input motions that fulfil search parameters are required for the response analysis [30]. In this study, using Eurocode 8 [31] on soil class A, and peak ground acceleration (PGA) of 0.24 g as the target spectrum, REXEL returned seven sets of input rock motions shown in Table 2. Fig. 4 displays the seven selected input rock motions that were scaled by factors ranging from 0.71-11.507, along with the median of the scaled rock motions and the target spectrum. The input rock motions were applied to the bedrock, with unit weight 25 kN/m³, shear wave velocity1000 m/s, and the damping ratio of 1% at a depth of 30 m.

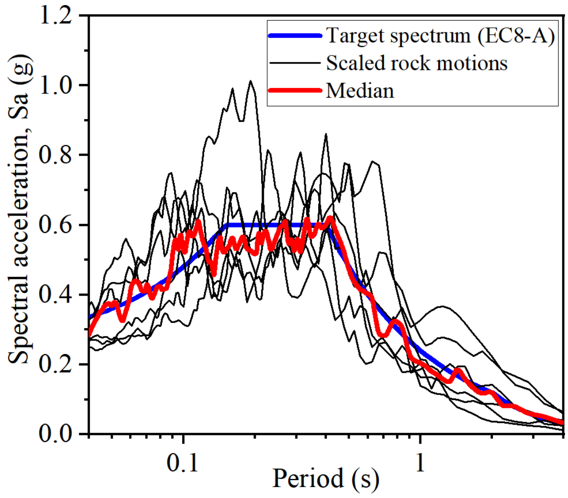

Fig. 4 Seven scaled input rock motions along with EC8-A target spectrum

3 Simulation results and discussion

1-D EQL site response analysis was conducted for each site profile using STRATA. Each site profile was subjected to similar input rock motions. The results of the analyses are evaluated using surface acceleration time histories, surface response spectrum (*SRS*), rock response spectrum (*RRS*), and the site amplification factors (*AF*s) at each period (*T*). The *AF* is computed using Eq. (1) [33]:

$$AF(T) = \frac{SRS(T)}{RRS(T)}, \tag{1}$$

where T is the predominant natural period of the multi-layered soil profile and it is calculated as follow [32]:

$$T = 4\left(\sum_{i=1}^{n} \frac{h_i}{(V_s)_i}\right) \tag{2}$$

In Eq. (2), $(V_s)_i$ represent shear wave velocity of layer i and h_i represent layer thickness.

Fig. 5 presents analysis results for each site profile. For each site profile, the left figures represent the surface response spectrum (SRS), the middle figures represent the rock response spectrum (RRS), and the right figures represent the amplification factors (AFs). The blue lines represent the values of individual analysis while the solid thick red line represents the median SRS, RRS and AF. The horizontal red arrows mark peak median SRS, RRS and AF values while the vertical arrow mark predominant spectral periods. At the top of each figure, the maximum median values of SRS, RRS, and AF at their peak period are displayed. These results demonstrated that the seismic waves were amplified by the site profiles by median AFs ranging from 2.08 to 2.78.

Fig. 6 represents the median analysis results of each site profile. The left figure represents median surface response spectrum (SRS), the middle figure represents the median rock response spectrum (RRS), and the right figure represents the median amplification factors (Afs). The horizontal arrow lines on top of Afs figures mark median peak amplification factor values for each site profile while the vertical arrow lines mark the predominant spectral periods.

Table 2 Input motion returned by REXEL on the basis of user search criteria

Earthquake ID	Earthquake Name	Date	M	Fault Mechanism	Epicentral Distance (km)	PGA_X (m/s²)	PGA_Y (m/s²)	Scale Factor	EC8 Site class
146	Campano Lucano	11/23/1980	6.9	normal	25	0.5878	0.5876	4.006	A
1885	Kalamata	10/13/1997	6.4	thrust	61	0.2046	0.2014	11.507	A
2309	Bingol	5/1/2003	6.3	strike slip	14	5.0514	2.9178	0.807	A
2142	South Iceland (aftershock)	6/21/2000	6.4	strike slip	14	1.7476	1.1423	2.062	A
87	Tabas	9/16/1978	7.3	oblique	12	3.316	3.7789	0.710	A
34	Friuli	5/6/1976	6.5	thrust	23	3.4985	3.0968	0.760	A
1635	South Iceland	6/17/2000	6.5	strike slip	29	3.1176	3.3109	0.755	A

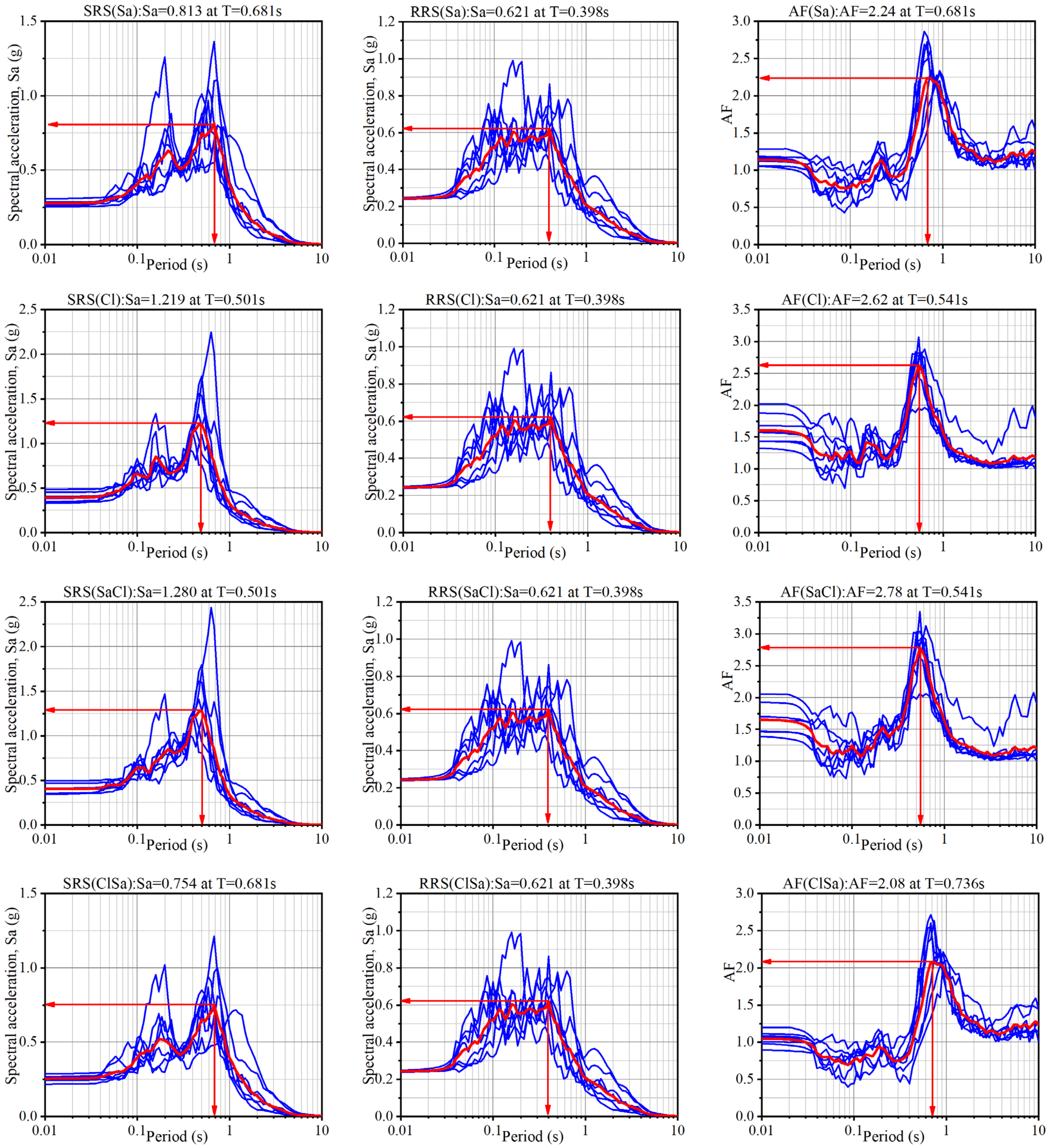

Fig. 5 Site response analysis results for each site profile (Sa-ClSa)

The maximum median AF of 2.78 was obtained from SaCl profile at predominant period of 0.541 s while minimum median AF of 2.08 was obtained from the CLSa profile at predominant period of 0.736 s. The maximum median Afs calculated from Cl and Sa profiles were 2.62 and 2.24, respectively. Site profiles with clay soil overlying bedrock (SaCl and Cl profiles) generated higher Afs compared to those with sandy soils overlying bedrock (Sa and ClSa profiles). The maximum Afs for the Sa and ClSa profiles were calculated at predominant spectral periods of 0.681 s and 0.736 s, respectively. The maximum median Afs for the Cl and SaCl profiles were calculated at the same predominant spectral period of 0.541 s. A shift in the peak period of the Afs was observed for each site profile. Despite the natural period of all the sites being 0.414 s (calculated using Eq. (2)), the peak period of the Afs increased to higher values for all sites.

The shift in the predominant period of each site is due to changes in material non-linear behavior with an increase in the intensities of ground shaking. As the amplitude of shaking increases, soil stiffness decreases which in turn can lead to a decrease in shear wave velocity. Additionally, as the amplitude of shaking increases, damping increases, resulting in a shift in the predominant period.

Fig. 7 shows a sample ground surface acceleration time histories for each site profile, with the peak ground acceleration marked on each graph. Consistent with Afs, the SaCl and ClSa profiles generated the highest and the lowest peak ground acceleration, respectively. Specifically, the maximum peak ground acceleration values for SaCl and ClSa are 0.49 g and 0.28 g, respectively. Furthermore, Sa and Cl sites generated peak ground acceleration of 0.308 g and 0.486 g, respectively.

4 Conclusions

During an earthquake, the intensity of seismic waves can vary significantly based on local site conditions. The amplitude of these waves may be amplified or de-amplified depending on local soil conditions.

This study aims to investigate the impact of different site profiles on seismic site responses. Four distinct groups of site profiles were analyzed, including sand (Sa), clay (Cl), sand overlying clay (SaCl), and clay overlying sand (ClSa) profiles. To accurately model the behavior of these soils,

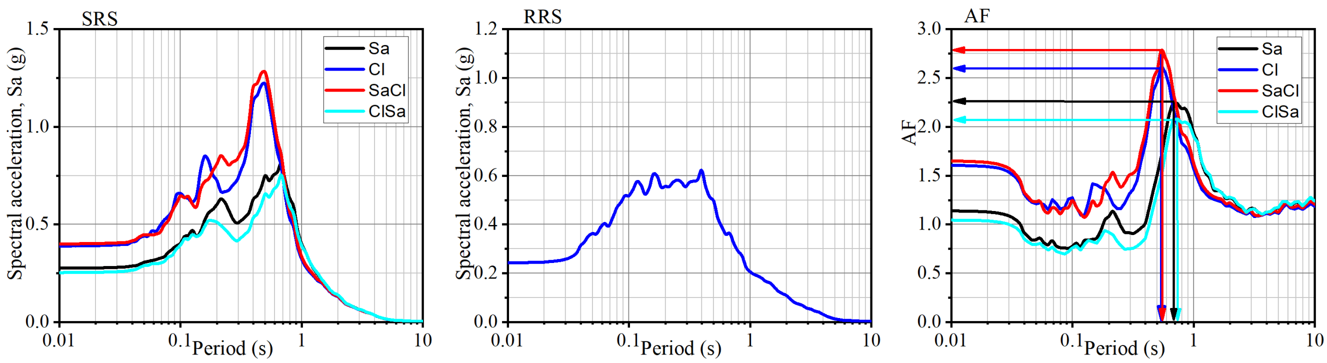

Fig. 6 Median response analysis results for each site profile (Sa-ClSa)

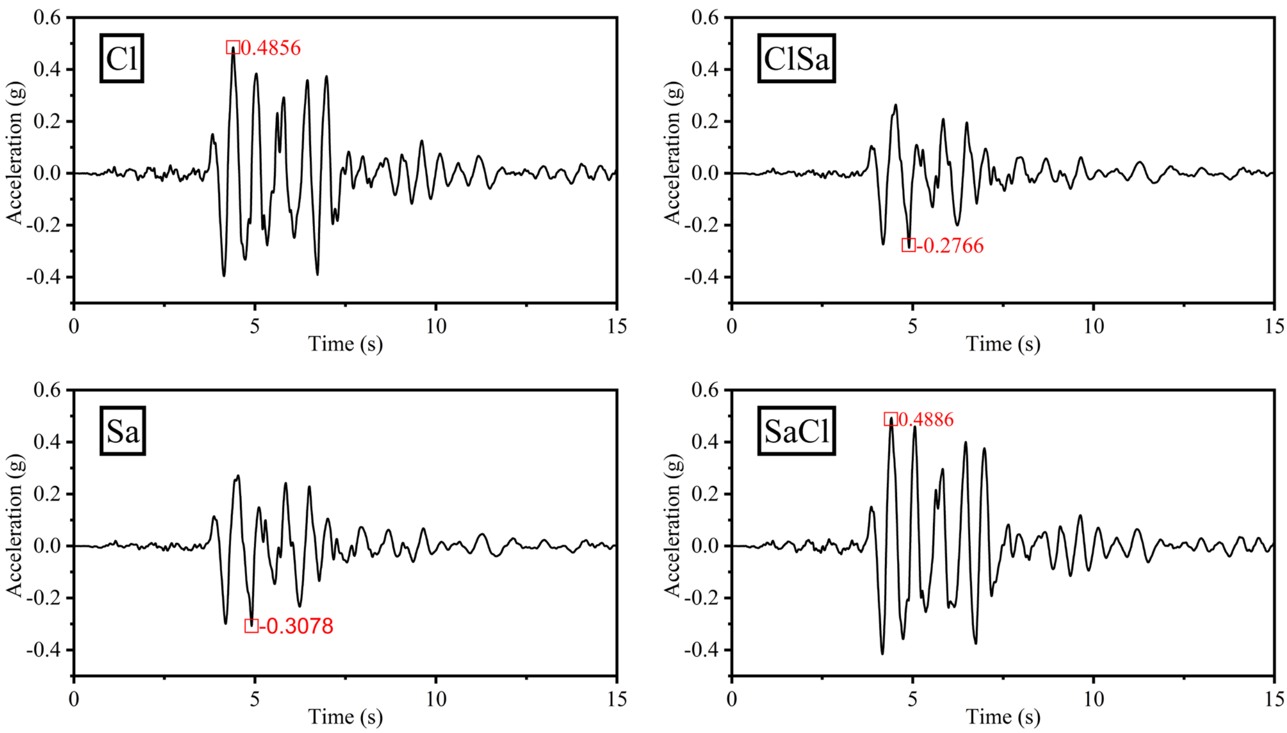

Fig. 7 Surface acceleration time histories for each site profile

we utilized the Darendeli and Vucetic and Dobry non-linear material models for sand and clay profile soils, respectively. To simulate realistic ground motions, we selected seven sets of strong rock motion records with a PGA value of 0.24 g on soil class A according to Eurocode-8 using REXEL. These records were then applied at the bottom of each site profile at a depth of 30 m.

To evaluate the response parameters for each site profile, we performed a series of 1-D EQL response analyses using STRATA. This method allowed us to accurately calculate the amplification factor and surface acceleration time histories for each site profile. Based on our analyses results, the following conclusions can be drawn:

- Site profile with clay overlying bedrock (SaCl and Cl profiles) produced higher AFs and acceleration time histories compared to profiles with sand overlying bedrock (Sa and ClSa profiles).
- The maximum median AFs for SaCl and Cl profiles were 2.78 and 2.62, respectively, obtained from the profiles at predominant periods of 0.541 s.
- The maximum median AFs calculated from sand overlying bedrock profiles (Sa and ClSa profiles) were 2.24 and 2.08, respectively.
- The SaCl site profile generated the highest median AF, while the Sa site profile generated the lowest. The relative difference between the highest and lowest median AFs is about 33.7%.
- The maximum surface acceleration time histories for all site profiles range from 0.277–0.489 g. The SaCl site produced maximum acceleration time histories of 0.489 g while ClSa produced the maximum acceleration time histories of 0.277 g.
- To better understand the effect of local site conditions on seismic wave amplifications/de-amplification, the future research could focus on the incorporation of a wide range of input rock motion intensities and site profiles into similar response analyses.

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