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ORIGINAL RESEARCH PAPER

2D equivalent linear ground response analysis for randomized site profiles

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ABSTRACT

Local soil conditions play a crucial role in shaping ground surface responses and impacting the intensity of ground shaking. In this study, the influence of different site profiles on computed ground motion was investigated using a 2D equivalent linear analysis approach. Four distinct site profiles: sand, clay, sand-clay-sand-clay, and clay-sand-clay-sand profiles were considered. The results were presented using multiple metrics, including surface acceleration, displacement, modulus decreasing ratio, and coherence analysis. Notably, the clay profile significantly influenced ground motion, while the sand profile exhibited relatively lower seismic activity. This suggests that softer sites significantly influence ground motion, leading to potentially high levels of shaking.

KEYWORDS

site response, earthquake, 2D equivalent linear, ground motion, random site profile

1. INTRODUCTION

Seismic site response analysis is a crucial technique for assessing the impact of local soil profiles on ground motion. The characteristics of local soil conditions including shear wave Velocities (Vs) profiles, soil layering, modulus reduction and damping properties have significant effect on amplitude of ground shaking. The impact of local soil nature on site response is often assessed using a 1D equivalent linear analysis approach. In this approach, the analysis results are commonly interpreted in terms of surface spectral acceleration, amplification factors, and surface acceleration time-histories [1]. The analysis assumes that the vertically propagating horizontally polarized seismic waves affect soil deposits. The nonlinear dynamic properties of the deposits (shear modulus and damping behavior) are approximated by an iterative procedures [2]. Several factors contribute to variability in seismic site response analysis, including variations in soil types and layering, changes in dynamic characteristics of soils, analysis approaches and differences in the intensity of seismic waves [3]. In the recent years, researchers have made attempts to incorporate these variations into site response analysis and evaluate their impact on computed ground motion [1, 4–9].

The characteristics of soil conditions have a significant impact on the amplitude of ground shaking during seismic events. Performing in-situ tests to investigate soil deposit characteristics may not be practical or economically feasible, except for a few critical facilities. Hence, it becomes imperative to include a wide range of soil types (e.g., soft clay to stiff sand) in site response analysis, to assess their impact on ground motion. Often, the variability of soil properties is modeled using specific probability distribution functions to capture the uncertainty inherent in soil characteristics. A great deal of previous researches have been conducted to examine how soil variability influence ground motion [10–13]. Bazzurro and Cornell [14] studied the influence of soil layering and uncertainty associated with layering on surface motion intensities. In addition to soil variability, the intensity of input rock motion

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characteristics may have considerable impact on level of ground shaking [15]. Proper characterization of soil layering and non-linear dynamic properties of soil layers is also important.

Site response analysis through 1D equivalent linear analysis technique simplifies the complex site response problems into one-dimensional soil column, where all boundaries are assumed horizontal and extend infinitely. Several software programs, including STRATA [16], DEEPSOIL [17] and SHAKE [18] have been developed to facilitate this process. However, there has been a lack of extensive research on the assessment of seismic site response problems employing a 2D finite element approach. The 2D equivalent linear seismic site response formulation requires characterization of soil layers including layer thickness, unit weight, soil dynamic properties (i.e., modulus reduction and damping curves with respect to dynamic shear strain) as well as maximum shear modulus G_{max}. At small strain levels, the relationship between $G_{\max}$ and shear wave velocity is as follow:

$$G_{\max} = \rho {V_s}^2, \tag{1}$$

where ρ is soil density and V_s is shear wave velocity. The non-linear behavior of soil under seismic loading is approximated within linear-elastic framework. The equivalent linear analysis approach involves solving the wave equation in the frequency domain using linear elastic soil properties. However, it is important to update these elastic properties based on the amplitude of induced effective shear strain [19].

The magnitudes of ground motion induced by incoming seismic waves are profoundly influenced by the unique properties of soil strata. In stratified soil deposits, the layering may involve the presence of softer layers (e.g., clay) sandwiched between stiffer layers (e.g., sand), or the alternation of sand layers within clay layers. These heterogeneous soil layers play a significant role in determining the amplitude of ground motion and should be carefully considered in site response analyses. Incorporating the complexities of stratified soil profiles is essential for a comprehensive understanding of how seismic waves interact with stratified soil deposits. The aim of this study is to evaluate the impact of stratified soil layers on amplitude of computed ground motion. For this purpose, four distinct types of soil profiles were evaluated using 2D equivalent linear analysis method. The results of the analyses were presented in terms of surface acceleration and displacement time-histories, shear modulus decreasing ratio and wavelet coherence analysis. The accuracy and reliability of the 2D equivalent linear analysis were cross-checked by comparing representative results obtained from the 2D equivalent linear method with the STRATA (1D) equivalent linear analysis.

The wavelet coherence analysis was performed using R programming language [20] to gain insights into the complex interaction between different soil layers and seismic signals. The analysis was performed for pairs of ground surface parameters. In particular, the time-varying correlation between surface acceleration for site profiles (e.g., surface acceleration for Clay (Cl) and Sand (Sa) profiles) were analyzed. This analysis can help identify if the two signals share common features (response) and monitor changes in the behavior of the ground surface over time due to variability in soil profiles. The wavelet coherence proves to be a valuable technique for measuring the correlation between two time series, $x(t)$ and $y(t)$, both in time and frequency domain. It is defined using the following expression [21]:

$$R^2(\tau, s) = \frac{\left|S\left(s^{-1} W_{xy}(\tau, s)\right)\right|^2}{S\left(s^{-1}\left|W_x(\tau, s)\right|^2\right).S\left(s^{-1}\left|W_y(\tau, s)\right|^2\right)}, \tag{2}$$

where τ represents a translation parameter or time position, s represents the dilation parameter or wavelet scale, $W_x(\tau, s)$ and $W_y(\tau, s)$ represent continuous wavelet transform of x and y series, respectively and (.) is the smoothing operator. $R^2(\tau, s)$ represents squared coherency and takes values between zero (no coherence) and one (perfect coherence).

2. SITE PROFILES AND MATERIAL PROPERTIES

In this study, 2D equivalent linear site response analysis was performed using the MIDAS GTS NX commercial software [22]. The 2D equivalent linear seismic site response analysis requires soil profile data, material properties, and input ground motion in the form of acceleration time histories. The study considered hypothetical site profiles, including Sa, Cl, Sand-Clay-Sand-Clay (SaClSaCl), and Clay-Sand-Clay-Sand (ClSaClSa) profiles to evaluate influence of soil variability on computed ground response (Fig. 1). Seismic ground response is greatly affected by the dynamic properties of soils, specifically the normalized shear modulus reduction and damping curves. These curves define the variations of modulus reduction and damping of soils with induced shear strains. The MIDAS GTS NX software allowed the incorporation of different dynamic soil properties for each soil profile. The modulus reduction and damping curves for sands proposed by Seed and Idriss [23] were considered. Additionally, the modulus reduction and damping curves for clays (with plasticity indices of 30 and 50) proposed by Vucetic and Dobry [24] were considered. Figure 2 presents dynamic soil properties of site profiles considered for response analysis. Table 1 shows the unit weight, initial shear modulus, and dynamic soil properties (symbolized with the letter M) considered for the response analysis.

3. ROCK MOTION SELECTION

To perform site response analysis, seismic input loads in the form of acceleration time histories are required. These records are essential for assessing how a site's soil and geological conditions influence the behavior of seismic

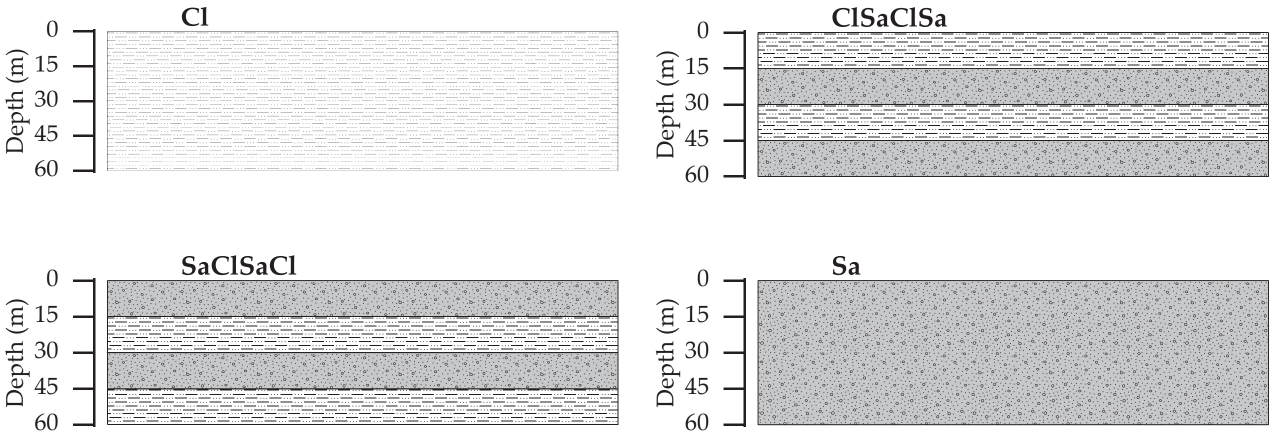

Fig. 1. Site profiles considered for response analyses (*Source*: Authors' result)

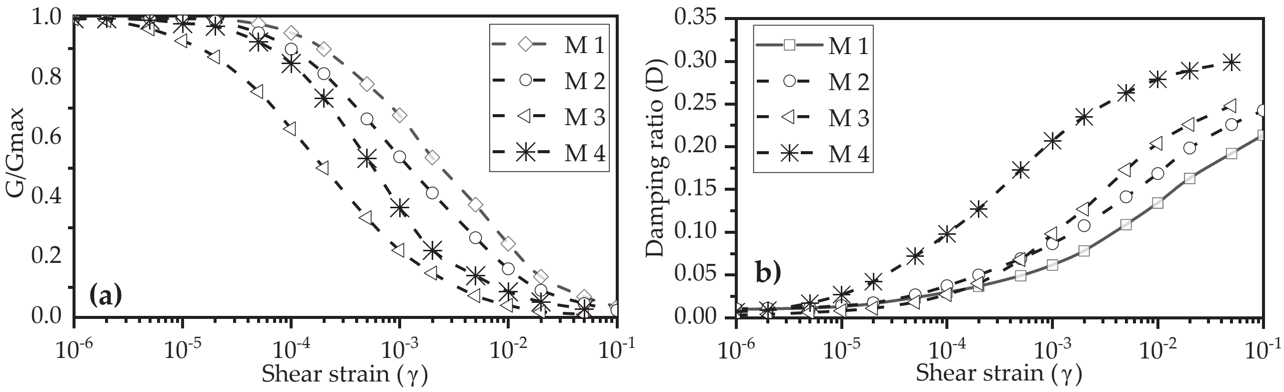

Fig. 2. a) Modulus reduction, b) damping ratio with respect to shear strain (*Source*: on the basis of [23, 24] plotted by the Authors)

Table 1. Material properties for each profile

Profiles	Unit weight, γ (kN m^{-3})	G_{max} (MPa)	Dynamic soil properties (M)
Cl	19	20	M2
ClSaClSa	18, 20, 19, 21	15, 40, 20, 50	M1, M3, M2, M4
Sa	20	40	M3
SaClSaCl	20, 18, 21, 19	40, 15, 50, 20	M2, M1, M4, M3

waves. In most cases, geotechnical engineers select real earthquake records based on the seismic hazard level specific to the site [25]. These records represent the ground motion characteristics that the site may experience during an actual seismic event. Several databases compile real seismic records from monitoring stations worldwide [26, 27]. Synthetic ground motion can also be generated to perform seismic site responses [28].

In this study, records from the 1989 Loma Prieta Earthquake, characterized by magnitude of 6.93 recorded at an epicentral distance of 74 km was chosen from Pacific Earthquake Engineering Research (PEER) strong motion database center [26]. Figure 3 illustrates the earthquake records and its spectral acceleration considered for response simulations. The peak acceleration and time interval of the recorded data were 0.276 g and 0.01 s, respectively (Fig. 3a). The record was applied at the base of each site profile and allowed to propagate through the soil to evaluate responses at the ground level.

4. 2D EQUIVALENT LINEAR SEISMIC SITE RESPONSE ANALYSIS

The 2D equivalent linear site response analysis was conducted using MIDAS GTS NX software [22], as previously indicated. It employs an equivalent linear analysis approach to simulate dynamic properties of soil under cyclic seismic loads. The soil layer is simplified as layers in a horizontal plane with different properties (e.g., shear modulus and damping). Transmitting boundary conditions available in

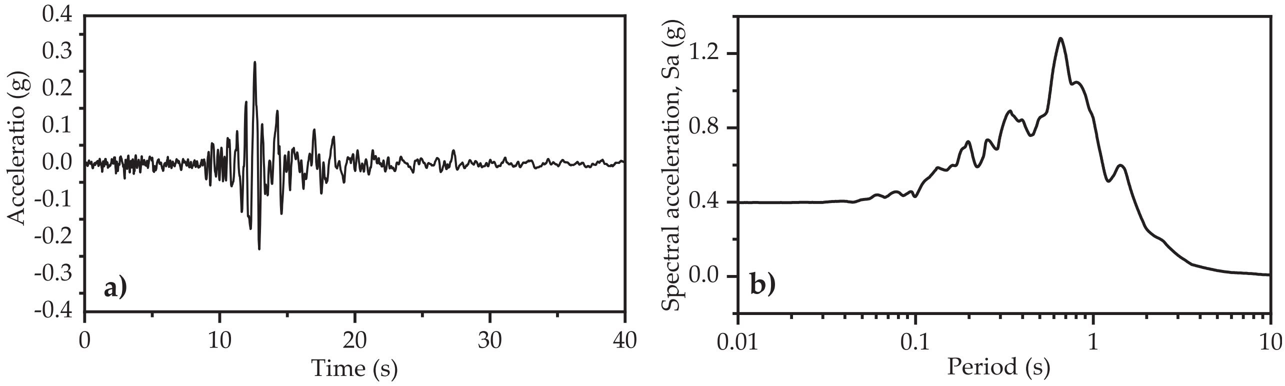

Fig. 3. The 1989 Loma Prieta Earthquake, a) Acceleration time histories, b) spectral acceleration (*Source*: on the basis of [26] plotted by the Authors)

MIDAS GTS NX library are considered to minimize reflection effects on vertical boundaries [29]. The transmitting boundary conditions typically assume that the horizontal properties of each ground layer are equal. Figure 4 depicts the meshed finite element model representing the ClSaClSa profile, created using MIDAS GTS NX software. Each profile has overall dimensions of 200 m by 60 m. The meshing process involved a rigorous evaluation of various element sizes to assess their impact on the analysis outcomes. After thorough assessment, it was determined that an element size of 2 m yielded optimal results. By selecting this element size, the analysis results remain reliable while maintaining computational efficiency.

In the equivalent linear analysis approach, the nonlinear dynamic properties of soil are approximated by equivalent linear models. This involves updating the shear modulus and damping as a function of the shear strain during the seismic event. Typically, the values of modulus reduction and damping are estimated at 65% of maximum shear strain, commonly referred to as effective shear strain [30]. The equivalent linear analysis follows an iterative procedure, as outlined in [2, 10]:

1. Start with the initial assumption of shear modulus and damping values (commonly low-strain values are considered);
2. Compute the ground response using these initial values;
3. Compute the effective shear strain for each layer (65% of maximum shear strain induced within each layer);

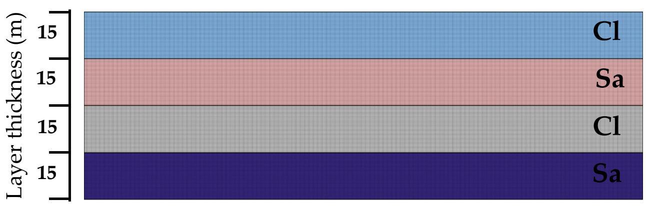

Fig. 4. 2 D finite element model mesh grid of ClSaClSa soil profiles (*Source*: Authors' result)

4. Select new shear modulus and damping values based on computed effective shear strain;
5. Repeat steps 2 to 4 until the difference between estimated values in two successive iterations falls below predetermined threshold value, typically ranging from 5 to 10%.

5. RESULTS AND DISCUSSIONS

2D seismic site response analyses were conducted for all site profiles under identical rock motion intensity using MIDAS GTS NX. The simulation results are recorded at the ground surface for each soil profile and are presented in terms of time histories for surface acceleration and displacement. Furthermore, modulus decreasing ratio and wavelet coherence analysis were evaluated. The maximum surface acceleration and displacement were recorded from Cl profile while the minimum peak acceleration and displacement were recorded from Sa profile (Fig. 5). The relative difference between the maximum and minimum acceleration and displacement were 80% and 64%, respectively. The maximum acceleration and displacement computed from SaClSaCl profile are very close to those computed from ClSaClSa profile. Figure 6 display samples of simulation results for peak ground acceleration and displacement obtained from the Cl profile. The maximum ground acceleration and displacements are indicated in the legend (left of each image).

Furthermore, the evaluation of the results involved assessing the shear modulus decreasing ratio, a parameter representing ratio of change in shear modulus to initial shear modulus (Eq. 3),

$$Modulus\ decreasing\ ratio = \frac{(G_{initial} - G_{converged})}{G_{initial}}. \qquad (3)$$

Color gradient was used to visualize the shear modulus decreasing ratio. Figure 7 illustrates the variation of shear modulus decreasing ratio across different layers of the site profiles. Sa profile exhibits lower seismic action as indicated

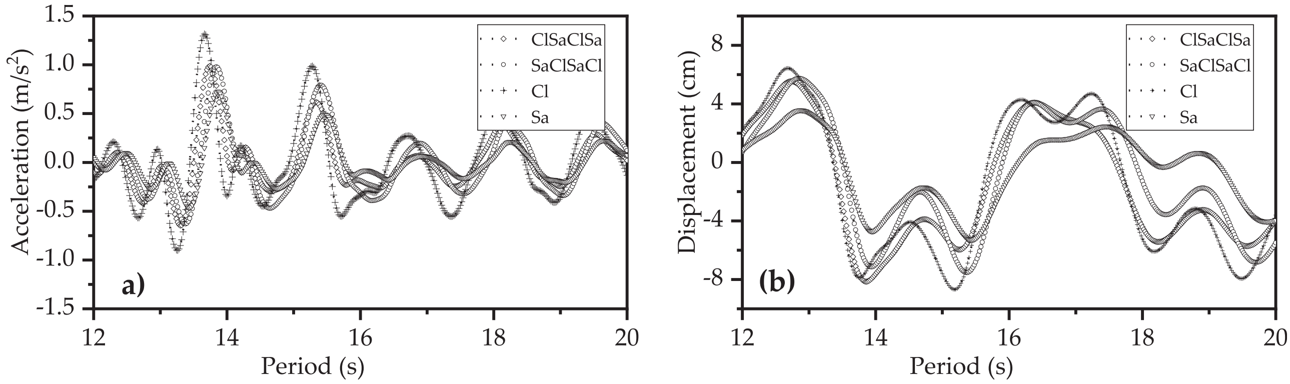

Fig. 5. a) Acceleration time histories, b) surface displacement time histories of response analyses (*Source*: Authors' results)

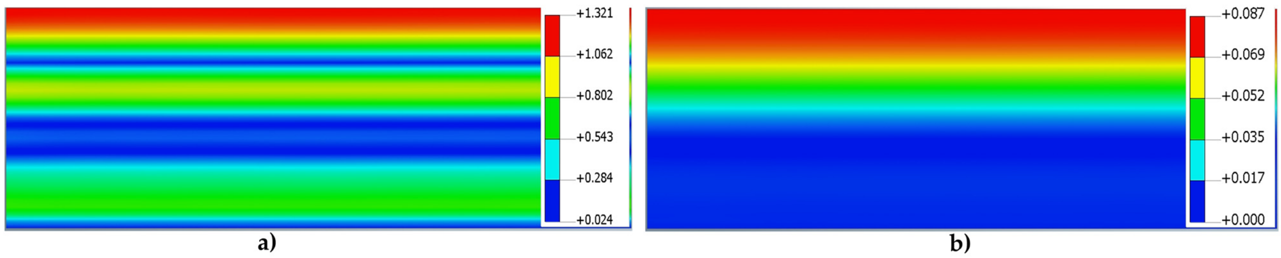

Fig. 6. Simulated peak ground a) acceleration (m s^{-2}) and b) displacement (m) for Cl profile (*Source*: Authors' result)

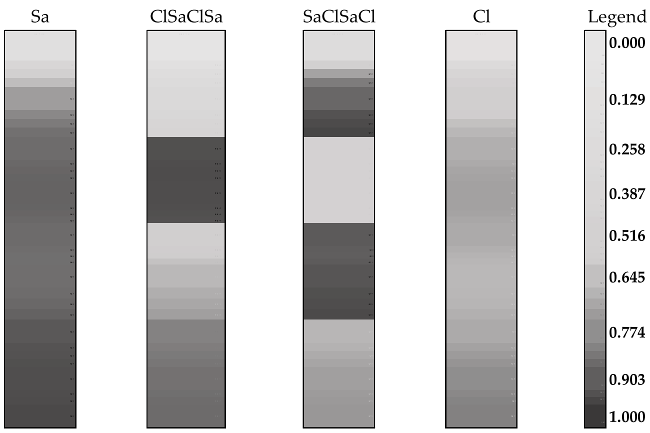

Fig. 7. Color gradient of shear modulus decreasing ratio (*Source*: Authors' result)

by black color gradient across the entire depth of profile. In contrast, the Cl profile experiences higher seismic action, noticeable through dark to light grey gradient throughout the profile depth. As expected, clay soils behave differently in response to seismic loading compared to sands. Clay soils recorded lower shear modulus decreasing ratio than sands, indicating that clay is less stiff and more prone to deformation under seismic forces (e.g., see SaClSaCl and ClSaClSa profiles). This suggests that softer materials may experience amplified ground motion, potentially resulting in higher levels of shaking.

Figure 8 shows acceleration time histories (Fig. 8a) and displacement (Fig. 8b) of Sa profile obtained from both 2D and 1D equivalent linear analyses. This comparison serves as a validation of the accuracy and reliability of MIDAS GTS NX software. The 1D equivalent analysis was conducted

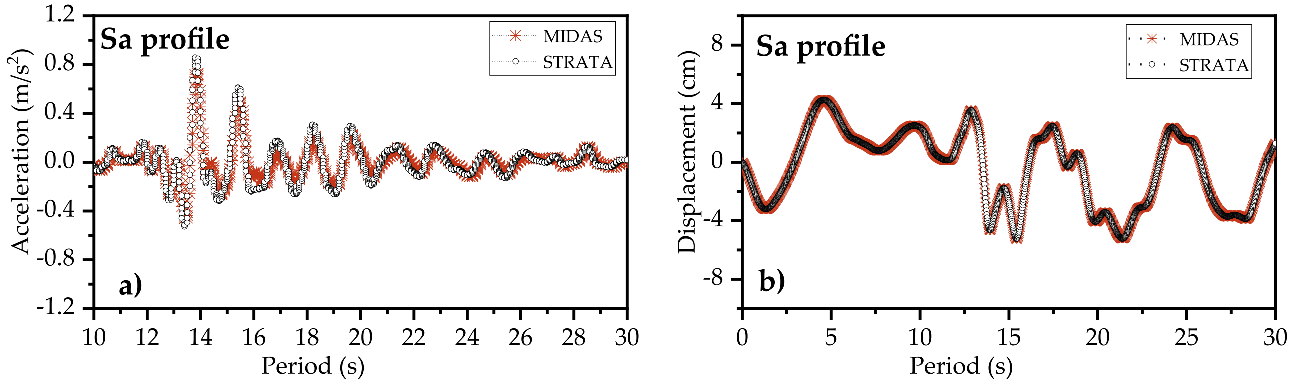

Fig. 8. Comparison between MIDAS GTS NX and STRATA response results, a) acceleration time histories, and b) displacement (*Source*: Authors' result)

using the STRATA computer program, a widely adopted software for site response analysis. Notably, the results exhibit excellent agreement, underscoring the robust capabilities of the MIDAS GTS NX software.

6. GROUND RESPONSE WAVELET COHERENCE ANALYSIS

Figure 9 illustrates the results of wavelet coherence analysis between surface acceleration of different profiles. The cone of influence is shown as shade under broken line. Regions of varying coherency are depicted with a heat map, ranging from low coherency (light regions) to high coherency (dark regions). The *y*-axis represents scale or frequencies, and *x*-axis represents the period of vibration. The arrows represent variations between two time-series. Right-pointing arrows indicate movement in the same direction (co-movement). Downward-pointing arrows indicate lagging of the first index. Left-pointing arrows denote variables that are out-of-phase. The results show a clear strong coherence between accelerations computed from SaClSaCl and ClSaClSa profiles. While some signs of low coherence exist between accelerations computed from Cl and Sa, Cl and ClSaClSa, Cl and SaClSaCl, there is strong overall coherence. Arrows mostly point to the right demonstrating co-movement with high coherence effects present throughout the period of vibration.

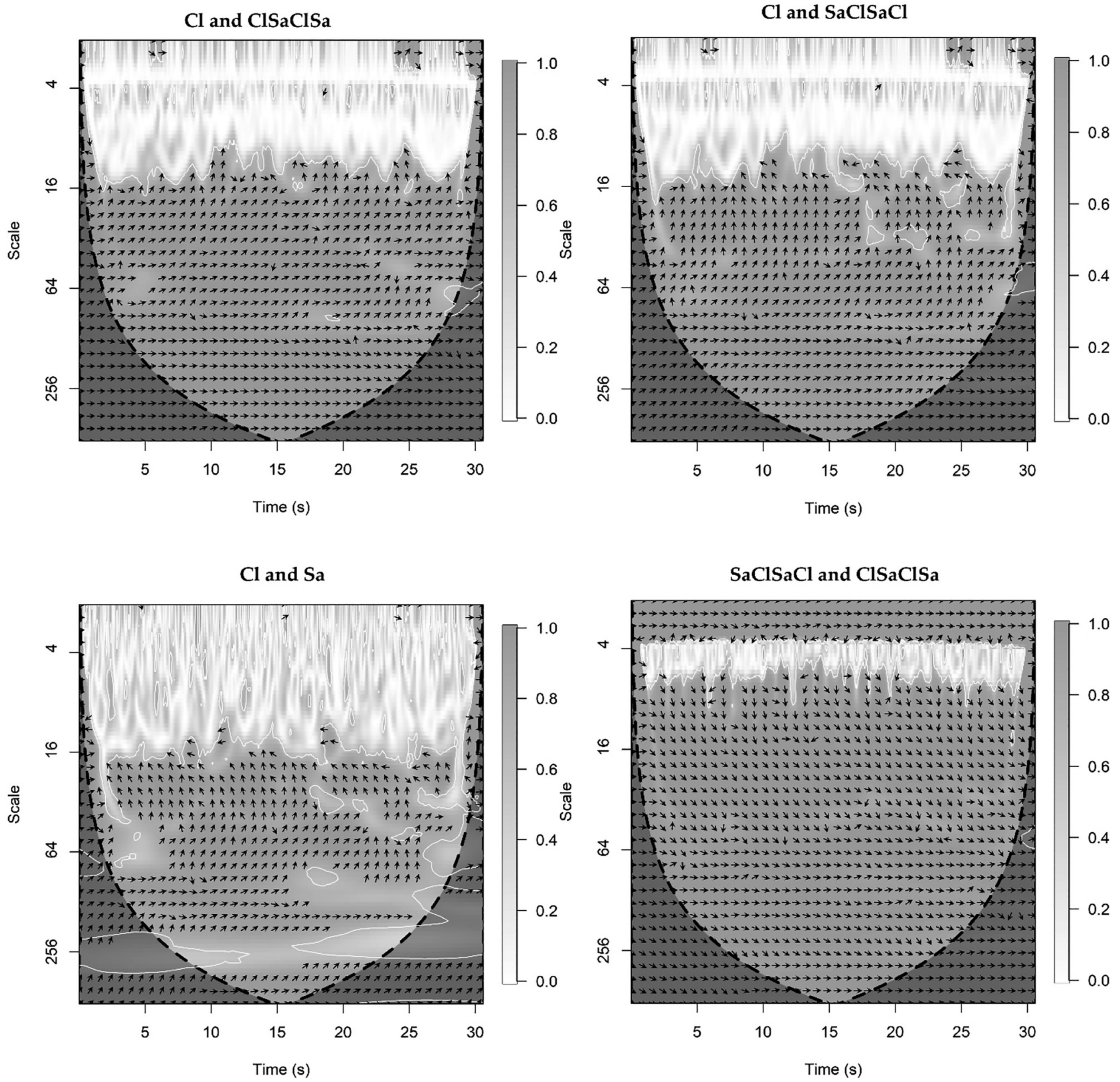

Fig. 9. Wavelet coherence analysis between acceleration time series computed from different site profiles (*Source*: Authors' result)

7. CONCLUSION

In this study, the impact of soil variability on seismic site response analyses were analyzed using four distinct site profiles (Cl, Sa, ClSaClSa, and SaClSaCl) through a 2D equivalent linear analysis approach. The seismic response of each profile was simulated using the MIDAS GTS NX commercial software. For each site profile, a strong rock motion record was selected and applied at the base of site profiles to calculate ground responses. Dynamic properties of the soils were chosen from the MIDAS library. The results of the analyses were presented in terms of shear modulus decreasing ratio, surface acceleration, and displacement time histories. Furthermore, the complex interaction between seismic waves and local soil deposits was evaluated through seismic signal coherence analysis. Based on the analyses results, the following conclusion can be drawn:

- The analysis peak ground acceleration, peak ground displacement, and modulus decreasing ratio computed from Cl profile clearly demonstrated that the Cl profile significantly influenced computed ground motion. This influence can be attributed to the inherent deformability of clays under cyclic seismic loading;
- Compared to other profiles, the Sa profile exhibited lower seismic activity. The peak ground acceleration, peak ground displacement, and modulus decreasing ratio computed from the Sa profile indicate minimal impact on seismic amplifications;
- The coherence analysis reveals a robust and clear correlation between accelerations computed from SaClSaCl and ClSaClSa profiles. While there are indications of limited coherence between accelerations computed from Cl and Sa, as well as between Cl and ClSaClSa, and Cl and SaClSaCl profiles, the overall coherence remains strong;
- Overall, the significance of this study lies in its ability to shed light on the complex interactions between seismic waves and variability of local soil deposits. This contribution was part of the ongoing research on modeling soil variability and quantification of uncertainty in soils.

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