Bozok J Eng Arch, 2026; 5(1) 100-110
DOI: 10.70700/bjea.1934651

Bozok
Journal of Engineering and Architecture

e-ISSN: 3023-4298
Research Article /Araştırma Makalesi

Comparative nonlinear site response analysis in reclaimed sand deposits: a case study in Iskenderun, Türkiye from the 2023 Kahramanmaraş earthquakes

Tugce BASER[1*]

[1]*Associate Professor, Department of Civil Engineering, Saint Louis University, 3450 Lindell Blvd, Saint Louis, MO, USA.*

ARTICLE INFO

Article history:

Received
20.04.2026
Accepted
02.06.2026
Published
29.06.2026

Keywords:

2023 Kahramanmaras earthquakes
Seismic site response
DEEPSOIL
Nonlinear soil behavior
Ground motion amplification
Site effects
Soil-structure interaction

ABSTRACT

The 2023 Kahramanmaraş earthquake sequence (Mw7.7 and Mw7.6) inflicted widespread geotechnical failures across southern Türkiye, causing severe structural damage, particularly within the coastal fill zones of İskenderun. This study presents a detailed comparative site response analysis using DEEPSOIL to simulate and evaluate nonlinear soil behavior at free field and near field site conditions under strong ground motion conditions. Series of cone penetration tests were performed immediately after the earthquake sequence to determine the soil profiles and site characterization. Shear wave velocity profiles, inferred from CPT-11 data, were utilized in one-dimensional nonlinear history analyses. The seismic input motion was derived from Hatay's AFAD Station #4631 acceleration record. The dynamic response evaluation examined time-domain acceleration histories, peak ground acceleration (PGA), shear strain distributions, cyclic stress-strain behavior, and spectral acceleration characteristics. Results unequivocally indicate that the softer free-field site produced higher amplification (PGA ~0.40g, SA ~1.2g, peak shear strain ~0.40), while the stiffer near-field site showed a more elastic response (PGA ~0.34g, SA ~0.95g, peak shear strain ~0.25). Subtle differences in subsurface conditions and structural proximity can produce substantially different seismic responses, highlighting the need for site-specific nonlinear modeling in seismic hazard assessment and performance-based design in earthquake-prone regions.

Geri kazanılmış kum zeminlerde karşılaştırmalı doğrusal olmayan zemin tepki analizi: 2023 Kahramanmaraş depremleri kapsamında İskenderun (Türkiye) örneği

MAKALE BİLGİSİ

Makale Tarihleri:

Geliş tarihi
20.04.2026
Kabul tarihi
02.06.2026
Yayım tarihi
29.06.2026

Anahtar Kelimeler:

2023 Kahramanmaraş depremleri
Sismik zemin tepkisi
DEEPSOIL
Doğrusal olmayan zemin davranışı
Yer hareketi büyütmesi
Saha etkileri
Zemin-Yapı etkileşimi.

ÖZET

2023 Kahramanmaraş deprem dizisi (Mw 7.7 ve Mw 7.6), Türkiye'nin güneyinde yaygın geoteknik hasarlara yol açmış, özellikle İskenderun'daki kıyı dolgu alanlarında ciddi yapısal zararlar meydana getirmiştir. Bu çalışmada, güçlü yer hareketi koşulları altında serbest saha ve yakın saha zemin koşullarında doğrusal olmayan zemin davranışını incelemek ve karşılaştırmak amacıyla DEEPSOIL yazılımı kullanılarak ayrıntılı bir zemin tepki analizi gerçekleştirilmiştir. Deprem dizisinin hemen ardından gerçekleştirilen koni penetrasyon deneyleri (CPT) ile zemin profilleri belirlenmiş ve saha karakterizasyonu yapılmıştır. CPT-11 verilerinden türetilen kayma dalgası hızı profilleri, tek boyutlu doğrusal olmayan zaman tanım alanı analizlerinde kullanılmıştır. Sismik girdi hareketi, Hatay AFAD 4631 numaralı istasyonuna ait ivme kaydından elde edilmiştir. Dinamik tepki değerlendirmesi kapsamında ivme-zaman geçmişleri, maksimum yer ivmesi (PGA), kayma şekil değiştirmesi dağılımları, çevrimsel gerilme-şekil değiştirme davranışı ve spektral ivme özellikleri incelenmiştir. Elde edilen sonuçlar, daha yumuşak zemin özelliklerine sahip serbest saha koşullarında daha yüksek büyütme değerlerinin (PGA ≈ 0.40g, SA ≈ 1.2g, maksimum kayma şekil değiştirmesi ≈ 0.40) ortaya çıktığını; buna karşılık daha rijit zemin koşullarına sahip yakın saha ortamında ise daha elastik bir davranışın (PGA ≈ 0.34g, SA ≈ 0.95g, maksimum kayma şekil değiştirmesi ≈ 0.25) gözlendiğini açıkça göstermektedir. Yeraltı koşullarındaki küçük farklılıklar ve yapı-zemin etkileşimi, sismik tepkinin önemli ölçüde değişmesine neden olabilmektedir. Bu bulgular, deprem tehlikesinin doğru değerlendirilmesi ve performansa dayalı tasarım yaklaşımlarının geliştirilmesi açısından sahaya özgü doğrusal olmayan modelleme çalışmalarının gerekliliğini vurgulamaktadır.

ORCID ID: Tugce Baser: 0009-0004-4771-9490

***Corresponding author(s):** Saint Louis University, 3450 Lindell Blvd, Saint Louis, MO, USA

E-mail: tugce.baser@slu.edu

To cite this article/Bu makaleye atıfta bulunmak için: Baser, T.. "Comparative nonlinear site response analysis in reclaimed sand deposits: a case study in Iskenderun, Türkiye from the 2023 Kahramanmaraş earthquakes", Bozok Journal of Engineering and Architecture, vol. 5, no. 1, pp. 100-110, 2026.

1. INTRODUCTION

The catastrophic earthquake sequence that struck southeastern Türkiye on February 6, 2023, with moment magnitudes of Mw7.7 and Mw7.6, respectively, unleashed widespread destruction across eleven provinces. This unprecedented seismic event tragically resulted in more than 50,000 fatalities and caused extensive damage to critical infrastructure [1]. The most severe impacts were concentrated in southern Türkiye, as illustrated in Figure 1, where provinces such as Hatay, Adana, Gaziantep, and Kahramanmaraş experienced pervasive devastation attributable to intense ground shaking and widespread geotechnical failures. Among the most critically impacted urban centers was the coastal city of İskenderun in Hatay province. This region suffered extensive geotechnical failures, including widespread liquefaction, significant lateral spreading, pronounced settlement, and catastrophic building collapses, particularly prevalent in areas underlain by reclaimed coastal fill zones [2-3]. Post-earthquake field reconnaissance missions revealed striking spatial variability in damage levels, even among closely spaced sites [4-5]. This observation raised concerns regarding the influence of local site conditions and their differential contribution to varying degrees of ground motion amplification.

Following major seismic events, geotechnical investigations frequently emphasize the importance of site-specific response analyses in elucidating observed discrepancies in structural performance. In the context of İskenderun, the prevalence of liquefaction-induced damage underscored an urgent need for high-resolution soil characterization and sophisticated nonlinear site response modeling. This is especially crucial in coastal and reclaimed fill zones, where conventional design assumptions, often based on simplified models, may prove inadequate or misleading [6].

Recent advancements and numerous studies have consistently demonstrated that nonlinear site response analyses, when effectively combined with high-quality in situ test data such as those obtained from the Cone Penetration Test (CPT), offer a significantly more accurate and realistic representation of seismic behavior in complex soil profiles [7]. Furthermore, CPT-based shear wave velocity (Vs) estimations have proven exceptionally effective for developing robust, site-specific subsurface models. This capability enables more realistic and predictive simulations of dynamic soil behavior under the severe demands of strong ground motion [8].

Figure 1. Map showing the 11 provinces in southern Türkiye most affected by the February 6, 2023 earthquakes (Mw 7.7 and 7.6)

Despite the increasing adoption and recognition of nonlinear analysis tools within earthquake geotechnical engineering, limited research has systematically explored the intricate phenomenon of how two geographically adjacent sites, subjected to ostensibly similar seismic input, can exhibit drastically different ground responses. Such divergence often stems from subtle yet critical differences in intrinsic soil properties, stratigraphy, and the influence of structural proximity or configuration. This study directly addresses this significant knowledge gap by undertaking a comprehensive comparative evaluation of the seismic site response at two precisely located CPT sites within İskenderun: CPT-13, designated as a "Free Field" site, and CPT-14, characterized as a "Near Field" site due to its proximity to existing structures. This work aims to provide profound insights into the underlying mechanisms driving differential site behavior through detailed numerical modeling utilizing the advanced DEEPSOIL software and leveraging actual input motion recorded at a nearby seismic station. Ultimately, this research seeks to contribute substantively to refining local seismic hazard assessments and bolstering urban infrastructure's resilience in Türkiye's highly seismically active regions.

2. BACKGROUND

The seismic response of reclaimed fill zones is governed by two interrelated phenomena: ground motion amplification and liquefaction-induced ground failure. Both mechanisms are strongly influenced by the low shear wave velocity (Vs) that characterizes loose, young fill deposits. Shear wave velocities in hydraulically placed reclaimed fills typically range from 80 to 200 m/s in the upper 10–15 m, substantially lower than those measured in naturally consolidated alluvial deposits or engineered compacted fills. This low Vs leads to pronounced impedance contrasts at the fill-foundation soil interface, creating conditions favorable for significant amplification of incoming seismic waves. Site amplification factors exceeding 2–4 have been documented in instrumented reclaimed fill sites during moderate to strong earthquake shaking, with peak spectral accelerations shifting toward the fundamental period of the fill layer, which typically falls between 0.2 and 0.8 seconds—a range resonant with low- to mid-rise structures.

Liquefaction is the most catastrophic seismic hazard associated with saturated, loose, granular reclaimed fills. Under cyclic shear stresses induced by earthquake shaking, excess pore water pressure builds rapidly in undrained or partially drained conditions, reducing effective stress and causing the soil skeleton to lose shear strength. When pore pressure ratios approach unity ($r_u \approx 1.0$), the soil transitions to a near-liquid state, manifesting at the surface as sand boils, ground cracks, lateral spreading, and differential settlement. The cyclic stress ratio (CSR) required to trigger liquefaction in reclaimed fills is substantially lower than that for naturally deposited sands of equivalent density, primarily because hydraulic placement produces a metastable, loose fabric with a high susceptibility to strain-induced pore pressure generation. The cyclic resistance ratio (CRR) of such fills, as estimated from SPT blow counts or CPT tip resistance (q_c), is correspondingly low, yielding factors of safety against liquefaction (FS = CRR/CSR) that frequently fall below 1.0 under design-level earthquake loading.

Lateral spreading is a particularly destructive manifestation of liquefaction in coastal reclaimed areas. When a liquefied layer underlies a gently sloping ground surface or a free face such as a waterfront, the overlying crust can translate horizontally by several meters, causing severe damage to pile foundations, buried utilities, bridge abutments, and port structures. Lateral displacements of 0.5–5 m have been documented in reclaimed fill zones following major earthquakes, including the 1964 Niigata earthquake (Japan), the 1989 Loma Prieta earthquake (USA), the 1995 Kobe earthquake (Japan). These events collectively illustrate that coastal reclamation, when conducted without adequate ground improvement and quality control, creates extensive zones of latent seismic vulnerability that may persist for decades until a sufficient seismic event triggers failure.

The interplay between nonlinear stiffness degradation and hysteretic energy dissipation produces a complex, amplitude-dependent site response that cannot be adequately captured by equivalent-linear methods at the large strain levels characteristic of strong ground motion in loose fills. Nonlinear time-domain analysis, as implemented in programs such as DEEPSOIL, is therefore necessary to realistically simulate the progressive stiffness loss, pore pressure-induced softening, and the resulting period elongation that shifts spectral demand toward longer structural periods. Critically, this period shift can place increased demand on mid-rise structures that may not have been designed for such loading, a phenomenon directly relevant to the observed pattern of building collapses in İskenderun following the 2023 earthquakes. Field evidence from multiple seismically impacted reclaimed fill zones worldwide has confirmed that structures founded on such soils and designed without accounting for nonlinear site effects frequently experience damage levels far exceeding those predicted by code-level linear or equivalent-linear analyses.

The spatial variability inherent to reclaimed fills further complicates site response prediction. Unlike natural geologic formations deposited under relatively uniform fluvial or marine conditions, reclaimed fills were often placed in phases by different contractors, using different borrow materials, and with variable compaction effort. As a result, adjacent investigation points separated by only a few tens of meters can reveal markedly different Vs profiles, fines contents, and liquefaction resistance values. This spatial heterogeneity directly produces the striking variability in damage patterns observed following earthquakes in reclaimed coastal zones—a phenomenon particularly pronounced in İskenderun following the 2023 Kahramanmaraş sequence, where structures located within meters of each other exhibited vastly different levels of distress. Characterizing and modeling this variability requires dense in situ investigation programs, preferably employing CPT soundings at close intervals, combined with sophisticated nonlinear site response analyses that respect the site-specific Vs profile at each investigation point.

Numerous well-documented case histories confirm these mechanisms in reclaimed fill settings. The 1964 Niigata earthquake triggered iconic liquefaction failures in hydraulically placed fills along the Shinano River, the 1995 Kobe earthquake produced extensive lateral spreading and stiffness degradation on Port Island, the 1999 İzmit earthquake caused submergence of the Gölcük naval base, and the 1989 Loma Prieta earthquake concentrated damage in the hydraulic-fill Marina District. Together, these events establish that reclaimed fills consistently exhibit amplified seismic response, accelerated pore pressure generation, and elevated ground failure potential, underscoring the need for rigorous, site-specific geotechnical investigation and nonlinear analysis.

3. METHODOLOGY

3.1 Site Conditions and Observed Ground Failures

The coastal fill zone of İskenderun experienced severe and widespread geotechnical damage during the February 2023 Kahramanmaraş earthquakes. This damage manifested in various forms, including extensive liquefaction evidenced by numerous sand boils, pronounced differential settlement leading to structure tilting, and total structural collapses. Field observations confirmed a critical finding: even closely spaced boreholes or investigation points revealed drastically different structural outcomes in their immediate vicinity, strongly emphasizing the decisive role of localized subsurface variability in determining seismic performance. Figure 2 provides compelling visual evidence of field observations from three representative locations within the study area in İskenderun. Figure 2(a) shows sand ejecta and cracking near container storage areas, indicating liquefaction where soil loses its strength and stiffness due to seismic shaking, allowing water and sand to be expelled to the surface accompanied by surface cracking. Figure 2(b) shows settlement-induced displacement around a mosque foundation, highlighting significant localized settlement likely due to densification of loose granular soils or bearing capacity failure of foundation soils, leading to structural distress and displacement. Figure 2(c) shows total collapse and severe damage in a multi-story residential zone accompanied by visual evidence of ejecta, depicting the most severe level of damage and underscoring the compounding effects of site response and ground failure mechanisms. These observations underscore the critical need for a detailed understanding of the subsurface conditions and their influence on the seismic response.

(a) (b) (c)

Figure 2. Ground failure observations in İskenderun's coastal fill zone: (a) sand ejecta near the port area, (b) settlement around mosque foundations, and (c) structural collapse and ejecta evidence around Building 3

3.2 Site Characterization and CPT Data

A comprehensive site investigation was conducted along the coastal fill zone of İskenderun, Türkiye, a region profoundly impacted by the 2023 earthquakes. For this study, data from three Cone Penetration Test (CPT) locations were utilized: CPT-13 (designated as a Free Field site), CPT-14 (designated as a Near Field site), and CPT-11. CPT-13 and CPT-14 were strategically selected for the comparative site response analysis due to their spatial proximity, yet markedly different observed structural outcomes and damage patterns in their immediate surroundings. CPT-11, located geographically between CPT-13 and CPT-14, served a crucial role: its data was employed to derive the representative shear wave velocity (Vs) profile for both CPT-13 and CPT-14. This approach was adopted under the reasonable engineering assumption of laterally consistent geologic conditions across the relatively short distance separating the three CPT soundings. The precise locations of the CPT soundings along the coastline are depicted in Figure 3. This

Figure 3. Location of CPT soundings across the study area. CPT-13 (Free Field) and CPT-14 (Near Field) were selected for site response analysis, and CPT-11 was used to derive Vs profiles

figure illustrates the spatial relationship between the boreholes and the adjacent built environment, providing context for the "Free Field" and "Near Field" designations.Shear wave velocity and the regional estimations from the CPT data were performed using established empirical correlations. These correlations link measured CPT parameters, specifically tip resistance (q_c), sleeve friction (f_s), and pore pressure measurements (u), to the small-strain stiffness of the soil, a commonly adopted correlation for V_s. For instance, relationships by Jefferies and Davies [9] and Lunne [10] are widely used and relate V_s to q_t (corrected tip resistance) and soil type. The general form of such empirical relationships involves power-law functions as follows:

$$V_s = A \cdot (q_t - \sigma'_{v0})^B \cdot (\mathrm{OCR})^C$$

where A, B, and C are empirical coefficients, σ_{v0}' is the effective overburden stress, and OCR is the overconsolidation ratio. Specific coefficients would be chosen based on regional calibration or soil type. The methodology applied herein follows procedures commonly utilized in liquefaction-prone deposits and reclaimed fill zones, as detailed by Andrus and Stokoe [11] and Kayen and Mitchell [12]. Furthermore, CPT-based shear wave velocity (Vs) estimations have proven effective for developing robust, site-specific subsurface models. This capability enables more realistic and predictive simulations of dynamic soil behavior under the severe demands of strong ground motion [13-14]. Based on the CPT data and inferred soil behavior, the general soil profiles are characterized as follows:

- CPT-13 (Free Field): This site generally consists of looser, softer fill materials in the upper layers, transitioning into clayey (CL) and then silty sand/sandy silt (SM/SP−SM) at greater depths. Soft fill at the surface contributes to its observed nonlinear behavior.
- CPT-14 (Near Field): In this location, subsurface has relatively to have stiffer soil deposits closer to the surface, characterized by clayey (CL) materials overlying silty sand/sandy silt (SM/SP−SM) layers, potentially leading to a more elastic response. The overall profile at CPT-14 indicates denser, more competent soils than CPT-13.

3.3 Ground Motion Selection

The seismic input motion critical for this study was meticulously obtained from the Turkish Disaster and Emergency Management Authority (AFAD), the official body responsible for seismic monitoring in Türkiye. The acceleration record from AFAD Station #4631, situated in Hatay province, was selected as the representative bedrock input motion. This particular station was chosen due to several key factors as (1) the relative proximity to the study area in İskenderun ensures that the recorded motion is geographically relevant to the investigated sites; (2) the station recorded significantly high peak ground acceleration (PGA) values during the February 6, 2023, Mw7.7 event, indicative of strong ground shaking representative of the actual seismic hazard experienced; and (3) as illustrated in Figure 4, which depicts the regional PGA distribution across southern Türkiye, Hatay province experienced some of the highest levels of seismic excitation during the earthquake sequence, further validating the representativeness of the selected ground motion.

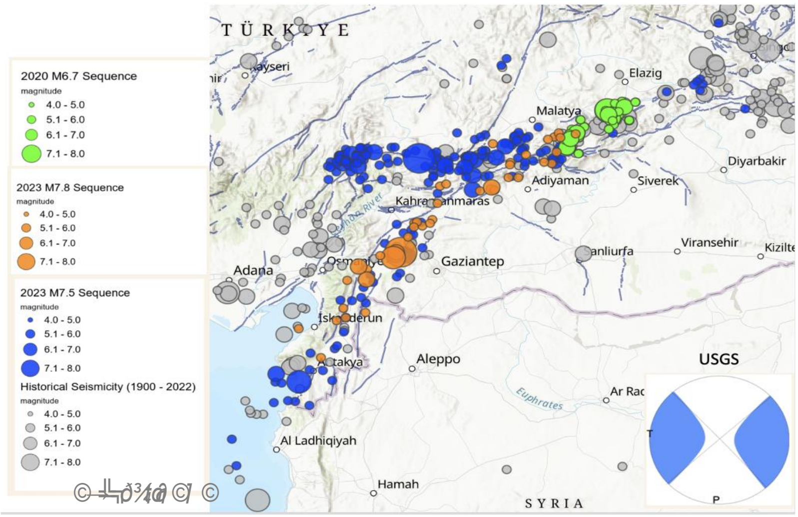

Figure 4. The measured peak ground acceleration (PGA) was distributed across southern Türkiye during the February 6, 2023, Kahramanmaraş earthquakes. Hatay station (#4631) was selected as the input ground motion source for DEEPSOIL analysis (Source: USGS)

The selected ground motion was assumed to represent the bedrock motion at the base of the soil columns for both CPT-13 and CPT-14. Before its use in the DEEPSOIL analysis, the raw acceleration record typically undergoes standard processing, including baseline correction and filtering, to remove noise and ensure numerical stability during the time history analysis. While not detailed in the original document, the specific processing steps would involve high-pass and low-pass filtering to define a seismologically meaningful frequency band.

3.4 Nonlinear Site Response Modeling with DEEPSOIL

One-dimensional (1D) nonlinear seismic site response analyses were rigorously conducted utilizing the DEEPSOIL v7.0 platform [15]. This widely recognized software provides advanced computational capabilities, incorporating advanced constitutive models to accurately capture strain-dependent modulus reduction and hysteretic damping effects within layered soil systems. The Vs profiles, previously derived from the CPT-11 data and interpreted for CPT-13 and CPT-14, were systematically input into the DEEPSOIL model. Similarly, the processed acceleration record from AFAD Station #4631 served as the base input ground motion.

The nonlinear material behavior of the soil layers was modeled using a stress-strain compatible backbone curve formulation, a critical component in accurately representing the degrading stiffness and increasing damping with increasing shear strain. This formulation follows established methodologies, such as those proposed by Park and Hashash [16] and Phillips and Hashash [17]. The specific model utilized in DEEPSOIL, such as the Modified-Kramer or MKZ model, would be chosen to represent the soil's hysteretic behavior. Rayleigh damping, typically used to dampen small strains, and modified Darendeli-type curves were employed to represent the strain-dependent stiffness degradation and energy dissipation characteristics. The Darendeli [18] curves are empirically derived relationships that define how shear modulus and damping ratio changes with shear strain, tailored to various soil types and confining pressures. The parameters for these curves (e.g., maximum shear modulus, damping ratio, reference shear strain) would be determined based on the CPT-derived soil properties and typical values for the identified soil types.

The model domain was explicitly assumed to be horizontally layered, simplifying the complex 3D reality to a 1D idealization. A significant modeling assumption was that excess pore water pressure generation was *not* included in this analysis. This decision was primarily driven by the limitations of available in situ pore pressure measurements from the CPT soundings. While this simplifies the analysis, it is important to acknowledge that in highly liquefiable soils, pore pressure buildup can significantly alter soil stiffness and damping, potentially leading to greater ground motion amplification or attenuation depending on the specific conditions. This limitation should be considered when interpreting results for liquefaction-prone areas.

Model calibration and sensitivity checks followed benchmarking procedures recommended in past validation efforts [19-20]. These procedures typically involve comparing model outputs against known analytical solutions or observed behaviors from instrumented sites to ensure the robustness and accuracy of the simulation. Turkish studies have adopted similar approaches for assessing historical ground motions and their amplification through shallow fills and variable soil layers [21], providing a contextual basis for the chosen methodology. The role of strong-motion-induced nonlinear effects in near-surface soil behavior was also carefully considered, drawing insights from prior studies that utilized similar modeling frameworks [22].

4. RESULTS AND DISCUSSION

4.1 Acceleration Time Histories and Peak Ground Acceleration

The comparative analysis of acceleration time histories recorded at the ground surface for CPT-13 (Free Field) and CPT-14 (Near Field) provides crucial insights into their differential seismic response. As shown in Figure 5, both sites were subjected to the identical seismic input motion at their base from AFAD Station #4631. However, the surface response profiles revealed distinct differences in energy transmission and amplification characteristics.

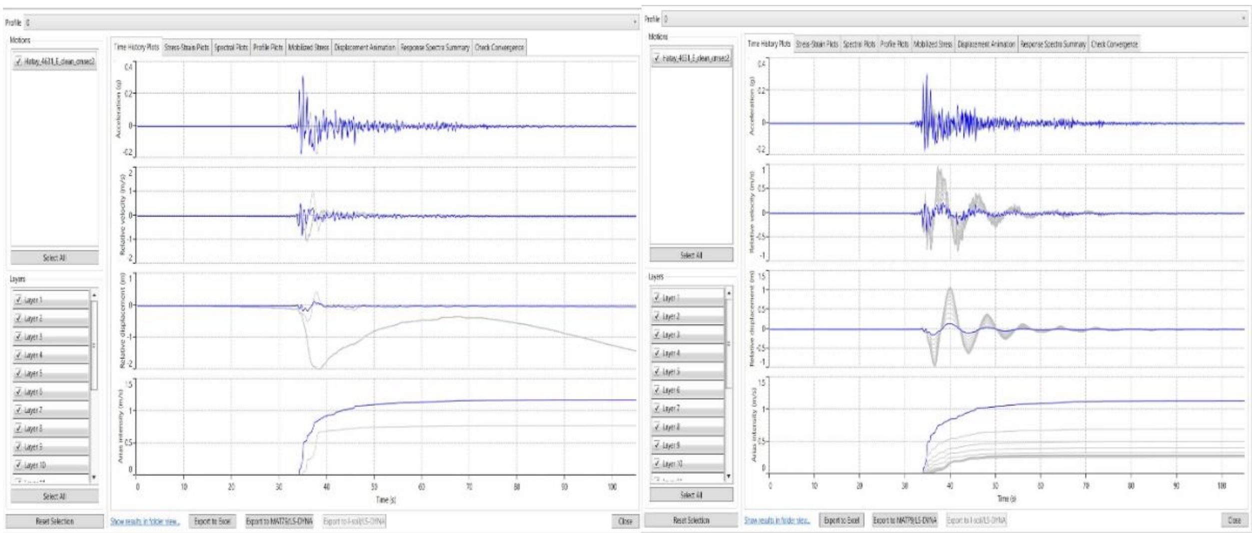

Figure 5. Acceleration response at (a) CPT-13 (Free Field) and (b) CPT-14 (Near Field), showing differences in PGA and Arias intensity development under the same input motion

CPT-13 consistently exhibited a higher peak ground acceleration (PGA) of approximately 0.40g. Furthermore, the Arias intensity profile for CPT-13 displayed a sharper and more rapid rise, indicating swift transfer of seismic energy from the base to the surface. This heightened amplification at CPT-13 can be attributed to the relatively softer and looser soil profile, which amplifies higher frequencies and accumulates larger strains under seismic loading.

In contrast, CPT-14 displayed a comparatively lower PGA of approximately 0.34g. The arias intensity for CPT-14 showed a more gradual energy buildup, suggesting significant attenuation effects. This attenuation is likely due to the stiffer subsurface materials identified at CPT-14, which are more capable of dissipating seismic energy through beneficial damping mechanisms, thus reducing surface accelerations. Despite the proximity of the sites, these stark differences unequivocally underscore the profound significance of site-specific soil properties, including stiffness, density, and local layering, in modulating ground motion amplification. Even minor spatial variations can lead to substantial differences in observed surface PGA and energy content.

4.2 Shear Strain Distribution and Nonlinear Behavior

The analysis of stress-strain hysteresis loops directly measures the soil's nonlinear response and energy dissipation capabilities during seismic loading. As depicted in Figure 6, the hysteresis loops derived for CPT-13 are notably wider and more distorted than CPT-14. This pronounced width and distortion at CPT-13 directly indicate significant nonlinear behavior and greater energy dissipation through hysteretic damping. The peak shear strain at this free-field location reached approximately 0.4, signifying considerable deformation within the soil layers. This strain level is consistent with highly nonlinear responses in loose, soft soils.

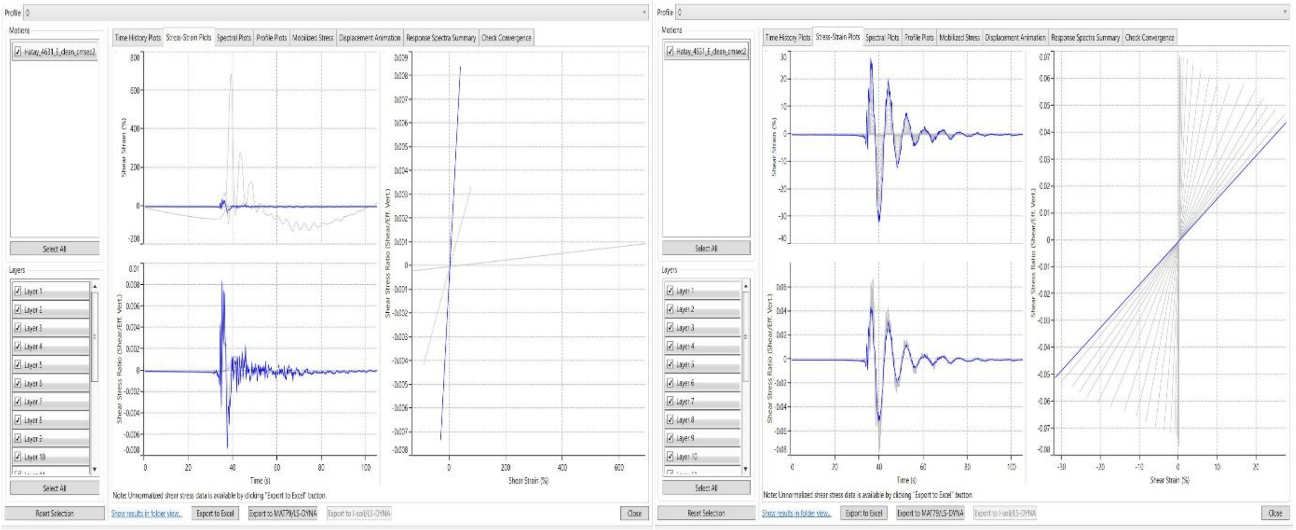

Figure 6. Stress–strain hysteresis loops at (a) CPT-13 and (b) CPT-14, highlighting greater energy dissipation and nonlinear strain behavior at the free-field location

Conversely, CPT-14 exhibited a significantly lower peak shear strain of 0.25. Its hysteresis loops were narrower and more elliptical, characteristic of a predominantly elastic or near-elastic soil response with minimal hysteretic energy loss. These results are entirely consistent with previous research on the impact of soil plasticity and cyclic mobility on seismic response [23-24]. The increased shear strain and pronounced hysteresis observed at CPT-13 strongly point towards a softer, looser soil profile, particularly in its upper layers, as detailed in Section 2.2. Such profiles are inherently more susceptible to strain accumulation and strength degradation under strong seismic loading [25-26]. In contrast, the behavior at CPT-14 reflects an elastic-dominated response, suggesting a denser, stiffer soil column with minimal strength degradation and lower energy loss throughout the shaking duration. This differential response highlights how soil fabric and density play a critical role in controlling the degree of nonlinearity and, consequently, the ground motion characteristics at the surface.

4.3 Spectral Acceleration and Amplification

Spectral acceleration (SA) curves are fundamental in seismic engineering as they represent the maximum acceleration experienced by a single-degree-of-freedom system with varying natural periods, effectively showing the amplification of different frequency components of ground motion. Figure 7 provides a crucial comparison of the SA responses for CPT-13 and CPT-14.

CPT-13 demonstrates a sharp and distinct SA peak of approximately 1.2g at a spectral period of nearly 0.3 seconds. This significant amplification of short-period motions is critical, as it directly impacts low- to mid-rise structures, which typically have natural periods in this range. The amplification at CPT-13 can be directly attributed to resonant conditions developing within its soft surface layers and the pronounced nonlinear strain effects observed in Section 3.2. These findings align well with observations from past nonlinear site response simulations, where soft, shallow deposits often exhibit significant amplification at their fundamental periods

[27-28]. The nonlinear behavior can cause period elongation, shifting the peak amplification to longer periods than the linear elastic response.

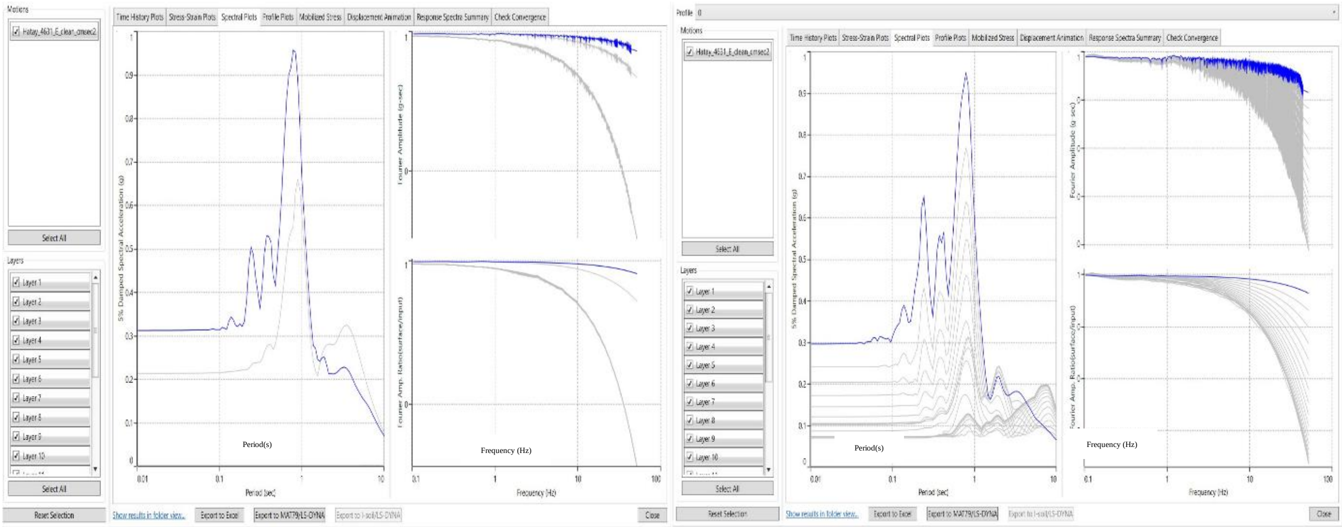

Figure 7. Spectral acceleration curves at (a) CPT-13 and (b) CPT-14. CPT-13 exhibits stronger amplification at ~0.3 s, while CPT-14 shows a flatter and more stable response

In contrast, CPT-14 shows a lower peak SA of approximately 0.95g. More importantly, its response is significantly flatter and broadly distributed across different spectral periods. This indicates a more stable and less resonant response. The more elastic behavior of CPT-14, corresponding to a well-graded soil profile with higher stiffness and lower susceptibility to resonant amplification, supports observations from prior studies in Eurocode-based site effect investigations [29-30]. The absence of a sharp, high-amplitude peak suggests that while ground motions are still significant, they are not disproportionately amplified at a single critical period, leading to a potentially less hazardous response for a wider range of structures.

A summary comparison of the key geotechnical and seismic response characteristics for CPT-13 and CPT-14 is provided in Table 1 to emphasize their engineering implications. Future research should aim to incorporate 2D/3D effects and pore pressure generation where sufficient data are available to refine these analyses further.

Table 1. Summary Comparison of Seismic and Geotechnical Parameters for Free Field and Near Field

Parameter	**CPT-13 (Free Field)**	**CPT-14 (Near Field)**
V_s (upper layers)	< 200–250 m/s (soft fill)	> 300 m/s (denser layers)
Peak Ground Accel. (PGA)	~0.40g	~0.34g
Peak Spectral Accel. (SA)	~1.2g at T ≈ 0.3 s	~0.95g; broader distribution
Peak Shear Strain	~0.40 (at 6–8 m depth)	~0.25
Response Character	Strongly nonlinear; wide hysteresis loops	Near-elastic; narrow hysteresis loops
Dominant Soil Units	Loose fill / CL / SM–SP-SM	Stiffer CL / SM–SP-SM
Structural Implication	Elevated risk for low- to mid-rise structures	More stable foundation conditions

4.4 Interpretation and Engineering Implications

The results of this comparative study unequivocally demonstrate that despite the extremely short horizontal distance separating CPT-13 and CPT-14, the two sites exhibited distinctly different and significant seismic responses during the simulated ground motion event. CPT-13, characterized as a free-field location situated in an open area with a significant thickness of soft fill material (as inferred from CPT-11 and general site characteristics), responded in a highly nonlinear manner. This response was marked by high shear strain accumulation, significant energy loss through hysteretic damping, and amplified surface accelerations, particularly at short periods. This behavior is typical of loose, uncompacted fill materials that undergo substantial stiffness degradation under strong shaking.

Conversely, CPT-14, identified as a near-field location and positioned closer to existing structural foundations, exhibited a more elastic and stable response. This behavior is consistent with its inferred stiffer soil deposits, less prone to large strains, and significant stiffness degradation. The presence of nearby structures at CPT-14 might also suggest a degree of dynamic soil-structure interaction, which, while not explicitly modeled in this 1D analysis, could contribute to the observed differences in ground response [7][31].

These findings profoundly emphasize the critical importance of comprehensively accounting for highly localized geotechnical variability and the potential influence of structure-soil interaction in urban seismic design, especially in complex environments like coastal fill zones. Relying solely on broad regional classifications or generalized code-based zoning without detailed, site-specific data can lead to severe underestimation of seismic demand and, consequently, unsafe designs. In-fill zones and reclaimed coastal areas, which often consist of heterogeneous and potentially liquefiable materials, require meticulous and detailed geotechnical investigations, ideally incorporating CPT soundings and advanced site response analyses.

Similar findings highlighting the dramatic influence of localized side effects have been reported in other case studies from seismically active regions globally, including other parts of Türkiye and Japan. These studies, like the current one, reinforce the notion that even subtle changes in soil layering, density, or the presence of structures can significantly alter ground motion characteristics. While this study provides valuable insights, it is important to acknowledge certain limitations:

- 1D nonlinear site response analysis assumes horizontally layered soil deposits and vertical propagation of shear waves. Complex 3D basin effects, irregular topography, and lateral variability of soil properties can influence seismic response. Future studies could explore 2D or 3D modeling if detailed lateral geotechnical data becomes available.
- No Pore Water Pressure Generation: The analysis did not include the generation and dissipation of excess pore water pressure due to a lack of detailed in situ measurements. This phenomenon significantly influences soil stiffness and damping in liquefied soils, potentially leading to different acceleration and strain responses. Future work should ideally incorporate pore pressure models if relevant CPTu or other data is available.
- CPT-11 for Vs. Profile: The assumption of using CPT-11 for Vs. Profiles at CPT-13 and CPT-14, while reasonable, given their proximity and general geological consistency, are an approximation. Site-specific Vs. Measurements at each CPT location would provide more precise input for the models.
- Influence of Nearby Structures: While CPT-14 was designated "Near Field," the 1D analysis does not explicitly model soil-structure interaction (SSI) effects. SSI could further modify the ground response near structures. Future research could integrate SSI models to gain a more complete understanding.

5. CONCLUSIONS

This study focused on comparative nonlinear site response analysis of two closely located sites in İskenderun, Türkiye: CPT-13 (Free Field) and CPT-14 (Near Field). Utilizing DEEPSOIL simulations with shear wave velocity (Vs) profiles derived from CPT data, the research revealed distinct ground response behaviors at the two sites despite their proximity and identical seismic input. These differences are primarily attributed to variations in soil stratigraphy, stiffness, and the resulting stress distribution patterns under dynamic loading. The key findings and their significant engineering implications are summarized as follows:

- CPT-13 exhibited demonstrably lower Vs values (typically less than 200−250 m/s), consistent with soft, loose fill material in its upper layers. This indicates a highly compliant soil profile. In stark contrast, CPT-14 showed significantly stiffer soils with Vs values generally exceeding 300 m/s, suggesting denser and more competent layers. This fundamental difference in initial stiffness was pivotal in controlling the degree of ground motion amplification and the observed shear strain behavior.
- CPT-13 experienced substantially higher peak shear strain (approximately 0.4 at depths of 6−8 m), coupled with wider hysteretic loops and localized stress gradients. This clearly indicates a significant nonlinear response, where the soil stiffness degrades considerably, leading to greater energy dissipation through hysteretic damping. Conversely, CPT-14 consistently showed lower peak shear strain (approximately 0.25), accompanied by more uniform stress profiles and a predominantly elastic response, indicating minimal stiffness degradation and energy loss.
- The spectral acceleration (SA) response for CPT-13 reached a sharp peak of approximately 1.2g at a spectral period of around 0.3 seconds. This pronounced amplification of short-period motions poses a considerable hazard to low- to mid-rise structures with similar natural periods. In contrast, CPT -14's SA peak was more moderate (approximately 0.95g) and exhibited a broader, flatter distribution across spectral periods, indicating less selective amplification. This aligns with observations from previous nonlinear modeling studies where stiffer sites tend to have broader spectral responses [5].
- The observed stratigraphic differences between the two sites directly explain the variations in their seismic behavior. CPT-13's soil profile, characterized by soft fill overlying clay (CL) and then silty sand/sandy silt (SM/SP−SM), is conducive to strain-sensitive amplification and resonance. This layering promotes larger deformations. Conversely, CPT -

14's profile, featuring stiffer clayey (CL) and silty sand/sandy silt (SM/SP−SM) layers, attenuates seismic waves more effectively due to their higher stiffness and damping capacity.

- The highly nonlinear response, significant ground motion amplification, and high surface displacement potential observed at CPT-13 imply a considerable seismic risk for structures, particularly low- to mid-rise buildings, constructed on such sites. The results from CPT-14 represents a more stable site with favorable conditions for seismic performance, offering better support for structures and a lower risk of excessive deformation.

These findings critically emphasize the importance of detailed, site-specific geotechnical modeling in earthquake-prone coastal zones, particularly those characterized by complex reclaimed fill materials.

AUTHOR CONTRIBUTIONS

Tugçe Baser: Writing – Original Draft, Formal Analysis.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ETHICS

There is no ethical issue regarding the publication of this article.

REFERENCES

[1] P. M. Mai, T. Aspiotis, T. A. Aquib et al., "The Destructive Earthquake Doublet of 6 February 2023 in South-Central Türkiye and Northwestern Syria: Initial Observations and Analyses," The Seismic Record, vol. 3, no. 2, pp. 105–115, May 2023, doi: 10.1785/0320230007.

[2] P. Bassal, D. M. Moug, J. D. Bray, S. B. Kendir, K. Ö. Çetin, and A. Şahin, "Lateral spreading and flooding along the İskenderun coast in the 2023 Kahramanmaraş earthquake sequence," Jpn. Geotech. Soc. Spec. Publ., vol. 10, no. 44, pp. 1653–1658, Jun. 2024, doi: 10.3208/jgssp.v10.OS-33-04.

[3] D. M. Moug, J. D. Bray, P. Bassal, K. Ö. Çetin, A. Şahin, and S. B. Kendir, "Liquefaction-induced ground and building interactions in İskenderun from the 2023 Kahramanmaraş earthquake sequence," Earthquake Spectra, vol. 40, no. 2, pp. 913–938, 2024.

[4] Baser, T., Nawaz, K., Chung, A. et al. Ground movement patterns and shallow foundation performance in Iskenderun coastline during the 2023 Kahramanmaras earthquake sequence. Earthq. Eng. Eng. Vib. 22, 867–881 (2023). https://doi.org/10.1007/s11803-023-2205-9.

[5] Ozkula, G., Dowell, R.K., Baser, T. et al. Field reconnaissance and observations from the February 6, 2023, Turkey earthquake sequence. Nat Hazards 119, 663–700 (2023). https://doi.org/10.1007/s11069-023-06143-2.

[6] M. F. Qodri, V. D. A. Anggorowati, and L. Z. Mase, "Site-Specific Analysis to Investigate Response and Liquefaction Potential during the Megathrust Earthquake at Banten Province, Indonesia," Eng. J., vol. 26, no. 9, pp. 1–10, Sept. 2022, doi: 10.4186/ej.2022.26.9.1.

[7] E. Yee, J. P. Stewart, and K. Tokimatsu, "Nonlinear site response and seismic compression at vertical array strongly shaken by the 2007 Niigata-ken Chuetsu-oki earthquake," PEER Report 2011/107, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA, Feb. 2011.

[8] B. Stuyts, W. Weijtjens, C. Sastre Jurado, C. Devriendt, and A. Kheffache, "A critical review of cone penetration test-based correlations for estimating small-strain shear modulus in North Sea soils," Geotechnics, vol. 4, no. 2, pp. 604–635, Jun. 2024, doi: 10.3390/geotechnics4020033.

[9] M. G. Jefferies and M. P. Davies, "Use of CPTu to estimate equivalent SPT N60," "Geotechnical Testing Journal", vol. 16, no. 4, pp. 458–468, 1993, doi: 10.1520/GTJ10312J.

[10] T. Lunne, P. K. Robertson, and J. J. M. Powell, "Cone Penetration Testing in Geotechnical Practice", London, U.K.: Blackie Academic and Professional, 1997.

[11] R. D. Andrus and K. H. Stokoe II, "Liquefaction resistance of soils from shear-wave velocity," "Journal of Geotechnical and Geoenvironmental Engineering", vol. 126, no. 11, pp. 1015–1025, Nov. 2000, doi: 10.1061/(ASCE)1090-0241(2000)126:11(1015).

[12] R. Kayen and J. K. Mitchell, "Assessment of liquefaction potential using shear wave velocity," NCEER Report 97-0022, National Center for Earthquake Engineering Research, State University of New York at Buffalo, 1997.

[13] R. E. S. Moss, R. B. Seed, R. E. Kayen, J. P. Stewart, and A. Der Kiureghian, "CPT-Based Probabilistic and Deterministic Assessment of In Situ Seismic Soil Liquefaction Potential," J. Geotech. Geoenviron. Eng., vol. 132, no. 8, pp. 1032–1051, Aug. 2006, doi: 10.1061/(ASCE)1090-0241(2006)132:8(1032).

[14] R. Kayen, R. Moss, E. Thompson, R. Seed, K. Çetin, A. Der Kiureghian, Y. Tanaka, and K. Tokimatsu, "Shear-Wave Velocity–Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Potential," J. Geotech. Geoenviron. Eng., vol. 139, no. 3, pp. 407–419, Mar. 2013, doi: 10.1061/(ASCE)GT.1943-5606.0000743.

[15] Y. M. A. Hashash, M. I. Musgrove, J. A. Harmon, D. R. Groholski, C. A. Phillips, and D. Park, "DEEPSOIL V7.0: 1D Site Response Analysis Program for Earthquake Engineering Applications," içinde Proc. 5th Int. Conf. Earthq. Geotech. Eng., Santiago, Chile, 2017.

[16] D. Park and Y. M. A. Hashash, "Soil damping formulation in nonlinear time domain site response analysis," J. Earthquake Eng., vol. 8, no. 2, pp. 249–274, Mar. 2004, doi: 10.1142/S1363246904001420.

[17] C. Phillips and Y. M. A. Hashash, "Damping formulation for nonlinear 1D site response analyses," Soil Dyn. Earthquake Eng., vol. 29, no. 7, pp. 1143–1158, Jul. 2009, doi: 10.1016/j.soildyn.2009.01.004.

[18] M. B. Darendeli, "Development of a new family of normalized modulus reduction and material damping curves," Ph.D. dissertation, Dept. Civil Eng., Univ. of Texas at Austin, Austin, TX, 2001.

[19] J. P. Stewart, R. B. Seed, and G. L. Fenves, "Seismic soil-structure interaction in buildings. II: Empirical findings," J. Geotech. Geoenviron. Eng., vol. 125, no. 1, pp. 38–48, Jan. 1999. doi: 10.1061/(ASCE)1090-0241(1999)125:1(38).

[20] J. P. Stewart, S.-J. Chiou, J. D. Bray, R. W. Graves, P. G. Somerville, and N. A. Abrahamson, "Ground motion evaluation procedures for performance-based design – PEER Report 2001/09," Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA, Sep. 2001.

[21] M. K. Akın, S. L. Kramer, and T. Topal, "Dynamic soil characterization and site response estimation for Erbaa, Tokat (Turkey)," Nat. Hazards, vol. 83, no. 3, pp. 1833–1868, Nov. 2016, doi: 10.1007/s11069-016-2274-4.

[22] S. M. Olson, X. Mei, and Y. M. A. Hashash, "Nonlinear site response analysis with pore-water pressure generation for liquefaction triggering evaluation," J. Geotech. Geoenviron. Eng., vol. 146, no. 2, Art. no. 04019128, Feb. 2020, doi: 10.1061/(ASCE)GT.1943-5606.0002191.

[23] F. Avşar, R. de Borst, and M. F. Wheeler, "Constitutive model for 1-D cyclic soil behaviour applied to seismic response," Soil Dyn. Earthquake Eng., vol. 137, pp. 106260, 2020. DOI: 10.1016/j.soildyn.2020.106260.

[24] X. Wang, Y. Zhang, and L. Sun, "Cyclic cumulative strain of coarse-grained soil under large cyclic loading," Arch. Civil Mech. Eng., vol. 23, no. 2, pp. 56, 2023. DOI: 10.1016/j.acme.2022.12.005.

[25] X.-B. Peng, W.-J. Ren, T.-Q. Li, Y.-Y. Xue, X.-S. Tao, and L.-Y. Xu, "Seismic response of deep soft soil sites with varying shear wave velocities," "Front. Earth Sci. ", vol. 12, art. 1488519, 2024. DOI: 10.3389/feart.2024.1488519.

[26] A. Satyanto, G. Aubry, and F. Gallage, "Challenges associated with site response analyses for soft soils: modelling issues and strong motion implications," Soil Dyn. Earthquake Eng., vol. 86, pp. 120–134, 2016. DOI: 10.1016/j.soildyn.2016.06.022.

[27] P. Bazzurro and C. Allin Cornell, "Ground-motion amplification in nonlinear soil sites with uncertain properties," Bull. Seismol. Soc. Am., vol. 94, no. 6, pp. 2090–2109, Dec. 2004. DOI: 10.1785/0120030169.

[28] R. P. Dhakal, S. L. Lin, A. K. Loye, and S. J. Evans, "Seismic design spectra for different soil classes: a nonlinear parametric study," Bull. N. Z. Soc. Earthquake Eng., vol. 46, no. 2, pp. 79–96, Jun. 2013. DOI: 10.5459/bnzsee.46.2.79-96.

[29] K. Pitilakis, E. Riga, and A. Anastasiadis, "Design spectra and amplification factors for Eurocode 8," "Bull. Earthquake Eng. ", vol. 10, no. 5, pp. 1377–1400, Oct. 2012. DOI: 10.1007/s10518-012-9367-6.

[30] J. Rey, E. Faccioli, and J. J. Bommer, "Derivation of design soil coefficients (S) and response spectral shapes for Eurocode 8 using the European Strong-Motion Database," J. Seismol., vol. 6, no. 4, pp. 547–555, Dec. 2002. DOI: 10.1023/A:1021421613593.

[31] J. P. Stewart and G. L. Fenves, "System identification for evaluating soil-structure interaction effects in buildings," "Earthquake Eng. Struct. Dyn. ", vol. 27, no. 9, pp. 869–885, 1998. DOI: 10.1002/(SICI)1096-9845(199809)27:9<869::AID-EQE767>3.0.CO;2-P.