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ROLE OF MESH TYPE IN 3D DYNAMIC SOIL–STRUCTURE INTERACTION SIMULATIONS

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Abstract: With the advancement of numerical modeling techniques, the problem of soil–structure interaction (SSI) has become the subject of extensive research in recent years. One of the most critical stages of this problem is the site response analysis (SRA). SRA provides designers with valuable insights into the soil's expected seismic response in the superstructure's absence. The present work investigates the influence of mesh type on dynamic SSI through three-dimensional (3D) finite element-based SRA. Models were developed using three different mesh types—hexahedral, tetrahedral, and hybrid—with absorbing boundary conditions applied along the lateral edges. The 3D model results were verified by comparison with one-dimensional (1D) analyses subjected to the same ground motion. In the study, the soil was assumed to exhibit linear elastic behavior, and all 1D and 3D analyses were performed based on this assumption. The 3D models could accurately represent the 1D site response through ground surface response spectrum. The findings reveal that the dynamic response of the soil system is mainly independent of the element type provided that a properly structured and sufficiently refined mesh is employed. Conversely, auto-generated irregular meshes tend to produce inaccurate results. Among the mesh types evaluated, hybrid meshes offer the most favorable balance regarding computational efficiency.

Keywords: Mesh type, Finite element method, Site response analysis, Soil-structure interaction, Dynamic analysis

3B Dinamik Yapı-Zemin Etkileşimi Modellemelerinde Ağ Tipinin Rolü

Öz: Yapı-zemin etkileşimi problemi sayısal modellemenin gelişmesiyle beraber son yıllarda birçok araştırmaya olanak sağlamaktadır. Bu problemin en önemli adımlarından biri zemin davranış analizleridir. ZDA yapının yokluğunda zeminin deprem yükleri altında göstereceği tepkileri anlamak ve yorumlamak için tasarımcıya önemli veriler sunmaktadır. Bu çalışmada ağ tipinin dinamik yapı zemin etkileşimi üzerindeki etkisi 3-boyutlu sonlu elemanlar yöntemi aracılığıyla ZDA üzerinden araştırılmaktadır. Çalışmada 3 farklı ağ tipi (hexahedral, tetrahedral ve hybrid) kullanılarak oluşturulan modellerin yanal sınırlarına geçirgen sınırlar yerleştirilmiştir. Geliştirilen 3-boyutlu modeller aynı deprem etkisi altında yapılan 1-boyutlu model sonuçlarıyla karşılaştırılarak doğrulanmıştır. Analizlerde, zeminin doğrusal elastik davranış sergilediği varsayılmış ve tüm 1B ve 3B analizler bu varsayım temelinde gerçekleştirilmiştir. 3B modeller, zemin yüzeyi tepki spektrumu aracılığıyla 1-boyutlu sonuçları başarılı bir biçimde temsil etmektedir. Çalışma, doğru bir şekilde yapılandırılmış bir ağ yapısı kullanıldığında, zemin sisteminin dinamik tepkisinin eleman tipinden büyük ölçüde bağımsız olduğunu ortaya koymaktadır. Buna karşılık, otomatik oluşturulmuş düzensiz ağ yapıları hatalı davranışa yol açabilmektedir. Değerlendirilen ağ tipleri arasında, hibrit ağlar hesaplama verimliliği açısından en uygun ağ tipi olduğu anlaşılmaktadır.

Anahtar Kelimeler: Ağ tipi, Sonlu elemanlar yöntemi, Zemin davranış analizleri, Yapı-zemin etkileşimi, Dinamik analiz

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1. INTRODUCTION

The numerical investigation of the soil–structure interaction (SSI) problem has become increasingly common with the advancement of computer processing capacities and the capabilities of computational software. SSI problem is addressed using two approaches called direct and substructure methods. In the direct method, both the soil and the structure, together with piles and foundations if available, are modeled together (Fatahi et al., 2018; Nguyen et al., 2017). In contrast, the substructure method considers the problem in two steps by separating the structure and soils (Liu et al., 2015; Timurağaoğlu, 2024). These steps are known as kinematic and inertial interaction. These methods have enabled more accurate and detailed modeling of complex interaction mechanisms between structural systems and underlying soils. As a result, seismic performance assessments have improved, leading to safer and more resilient designs. Soil–structure interaction encompasses a range of complex physical phenomena, including wave propagation, energy dissipation, and soil nonlinearity. This complexity has been thoroughly investigated in numerous studies through advanced numerical modeling (Bolisetti et al., 2018; Kampitsis et al., 2015; Kim & Jeong, 2011; Luo et al., 2016; Nateghi-A & Rezaei-Tabrizi, 2013; Nguyen et al., 2016; Sáez et al., 2013; Tabatabaiefar et al., 2013; Wu et al., 2020; X Zhang & Far, 2022). These studies have enabled more realistic simulations investigating the seismic response of various structural types.

The incorporation of the soil medium into numerical models introduces additional complexities. This is especially true when simulating wave propagation and SSI effects under dynamic loads. Including shallow or piled foundations into the system introduces additional complexity to the overall structural behavior. Accurate representation of soil-pile interface (SPI) plays a critical role in ensuring the reliability and accuracy of the analysis results. Recently, there have been several studies on SPI problems using various contact methods (Alsaleh & Shahrour, 2009; Deb & Pal, 2021; Fatahi et al., 2018; L Zhang & Liu, 2017). The influence of SPI on the response of piles is already highlighted in a comparative study (Timurağaoğlu et al., 2021) emphasizing that neglecting slippage and the formation of a gap (using full/perfect contact) may increase the pile's horizontal and vertical load capacity and change the stress distribution in soil around pile.

In this context, the fidelity of seismic response predictions is highly sensitive to both the discretization scheme (Ashford & Sitar, 2001; Ghavidel et al., 2018; Roth et al., 2009) and the type of elements employed. A finer mesh enhances the precision of finite element models of SSI, especially in capturing critical soil and foundation behavior at the vicinity of foundations. Therefore, selecting an appropriate mesh density is essential to capture the spatial variability of stress waves and ensure convergence of the dynamic solution. According to Lysmer (1978), the shortest wavelength, corresponding to the highest excitation frequency, must be discretized using at least eight finite elements to accurately capture its motion. Equally important is the choice of element type, as different formulations (e.g., linear vs. higher-order, hexahedral vs. tetrahedral) exhibit varying capabilities in representing complex SSI behavior and wave propagation characteristics. Accurate soil modeling is especially critical in dynamic analyses, as the representation of wave propagation, damping behavior, and SSI effects can significantly influence structural performance predictions. Karabulut & Gülal (2023) evaluates the impact of different mesh types on the accuracy of seismic potential prediction in tectonic modeling, using the Main Marmara Fault as a case study. Despite significant advancements in dynamic SSI modeling, limited studies have directly addressed the influence of mesh typology on the accuracy of seismic response predictions in 3D SSI analyses.

This study aims to fill this gap by systematically evaluating how different mesh configurations affect the results of 3D site response analyses. In this research, particular attention was given to the impact of mesh typology on the 3D dynamic SSI to ensure that the soil medium was represented with sufficient accuracy under dynamic loadings. For checking consistency, a two-layer soil profile adopted from the literature was considered. Based on this profile 3D models were developed using different mesh types, and dynamic analyses were conducted under identical boundary conditions and subjected to the same ground motion. The model is also meshed using auto generation technique using tetrahedral and hybrid meshes. The effect of mesh type is comprehensively evaluated through displacement-depth and acceleration-depth relationships, along with a comparison of response spectra at the center of ground surface.

2. ADOPTED SOIL PROFILE AND GROUND MOTION

The adopted model, illustrated in Figure 1, represents a two-layer soil profile with a total height of 30 meters and is based on the study by de Sanctis et al. (2010). As outlined in the study, a damping ratio of 10% was uniformly assigned to both soil layers to account for energy dissipation during dynamic loading conditions. Both soil layers are characterized by identical physical properties, including a mass density (ρ) of 1940 kg/m³, a thickness (H) of 15 meters, and a Poisson's ratio (ν) of 0.4. However, the layers differ in their shear wave velocities, which are defined as Vs_1 = 100 m/s for the upper layer and Vs_2 = 400 m/s for the lower layer, respectively. The parameters of soil layers are given in Table 1.

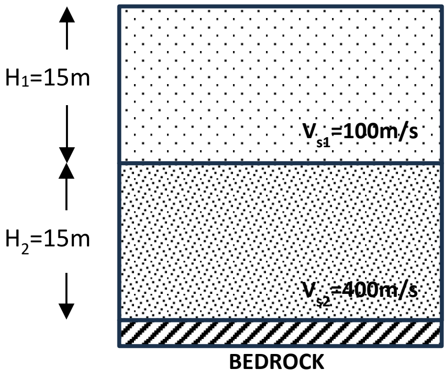

Figure 1:
Adopted two-layered soil model

Table 1. Soil parameters used in the analyses

Layer	Thickness (m)	Vs (m/s)	υ	Density,ρ (kg/m3)	G (kN/m2)	E (kN/m2)
1	15	100	0.4	1940	19400	54320
2	15	400	0.4	1940	310400	869120

The soil profile was discretized into 10 equal layers, each 3-meter thick, and linear dynamic analyses were conducted using the DEEPSOIL software. The study used the ground motion record from the Friuli earthquake, specifically the Tolmezzo station (A-TMZ000) (see Figure 2). This seismic record corresponds to an earthquake with a moment magnitude of Mw = 6.5, a peak ground acceleration (PGA) of 0.357g, and an epicentral distance of approximately 23 km.

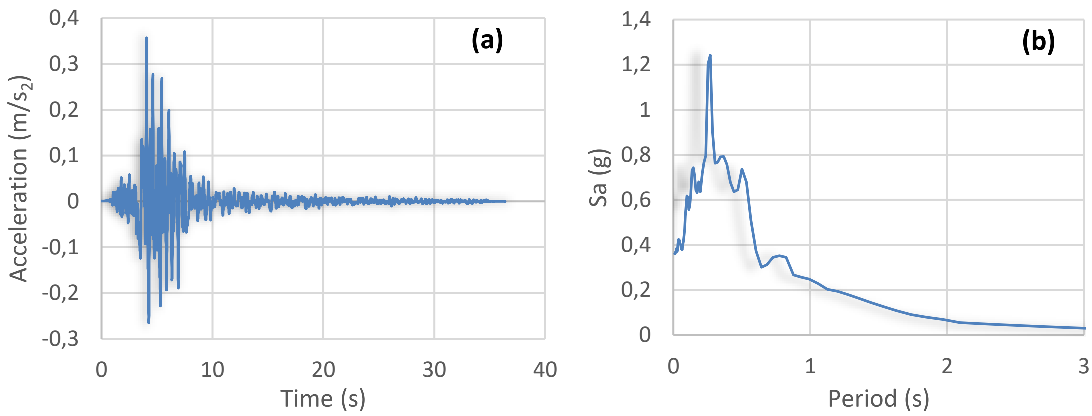

Figure 2:
(a) Acceleration-time and (b) response spectrum of Tolmezzo record

3. NUMERICAL MODELING STRATEGY

Due to differences in boundary conditions and wave propagation assumptions, the 1D analysis results are used here as a partial consistency check for the 3D model rather than as a full validation. This is a methodological limitation of the validation procedure of 1D and 3D models. To check the consistency the adopted three-dimensional (3D) finite element modeling (FEM) approach, results from two-layered soil profile available in the literature (de Sanctis et al., 2010) is employed. Following the initial check, the model was systematically modified to incorporate three different finite element types—namely tetrahedral, hexahedral, and hybrid elements—to evaluate the sensitivity of the SRA to mesh typology.

The above soil profile is modeled with 1D wave propagation using Deepsoil program (Hashash et al., 2024) and 3D finite element software using Midas GTS NX (Midas GTS NX, 2023). The developed models are presented in Figures 3a and 3b, respectively. In both DEEPSOIL and MIDAS software, the model's base was assumed to be fixed. In the 1D analysis, a rigid half-space assumption was applied, whereas in the 3D model, translational degrees of freedom were restrained. Therefore, options such as using an elastic or rigid half-space base condition in the 1D model or constraining the base or implementing springs to prevent reflection in the 3D model, could significantly affect the results. Furthermore, an elastic half-space should be selected if an outcrop motion is used and a rigid half-space should be selected if a within motion is used. However, the selected boundary condition was chosen exactly as applied in the referenced study used for calibration. In this study, the rigid half-space in the 1D model and the displacement restraint in the 3D model represent boundary conditions that exhibit mutually consistent behavior. To satisfy the non-reflective boundary condition as specified in the Turkish Building Earthquake Code (TBSC, 2018), free-field elements available in MIDAS were implemented along the lateral boundaries of the 3D model. These elements are based on the infinite element formulation proposed by Lysmer & Kuhlemayer (1969). Additionally, to minimize wave reflections from the lateral soil boundaries, the horizontal dimensions of the soil domain were extended to 200×200m.

As previously stated, 3D models were developed using three distinct mesh types: tetrahedral, hexahedral, and hybrid. The hybrid mesh configuration incorporates a combination of tetrahedral, hexahedral, and pyramid elements to form a composite meshing scheme. Furthermore, two different meshing strategies were adopted: structured and automatic. The primary objective of the structured meshing or grid approach was to generate more uniform and refined mesh patterns and better convergence and higher resolution, which are often desirable for enhancing numerical accuracy. On the other hand, the auto generated meshing option—commonly available in commercial software and frequently preferred by practitioners—was utilized due to its practicality and efficiency. While controlled meshing tends to be time-consuming, it allows for a more precise discretization. In contrast, auto meshing facilitates quicker model development, often using fewer elements. The 3D models generated with both controlled and automatic meshing techniques are illustrated in Figure 3. The analysis adopted a time step of 0.02s for all models. The mesh size in all models is selected as 10m.

In all models, damping was defined using the Rayleigh model, which represents linear combination of frequency-dependent damping through mass- and stiffness-proportional coefficients. The first and second modes correspond to frequency range in defining Rayleigh damping is selected as 1.4Hz and 10Hz, respectively. In cases where equal damping ratios are assigned to two selected frequencies within the Rayleigh damping formulation, it is essential to recognize that the resulting damping ratio is not uniform across the entire frequency range bounded by these sample points. Specifically, intermediate frequencies—those lying between the two target frequencies—tend to exhibit reduced damping ratios, meaning that these frequencies are attenuated to a lesser degree. It is essential to select these values carefully to ensure that the resulting damping ratios are appropriate for all modes that contribute significantly to the structural response. Considering the aforementioned aspects, the Rayleigh damping coefficients were computed in this study as $\alpha = 1.54324$ and $\beta = 0.00279$ to adequately represent the intended damping behavior within the selected frequency range for 1D and 3D analyses.

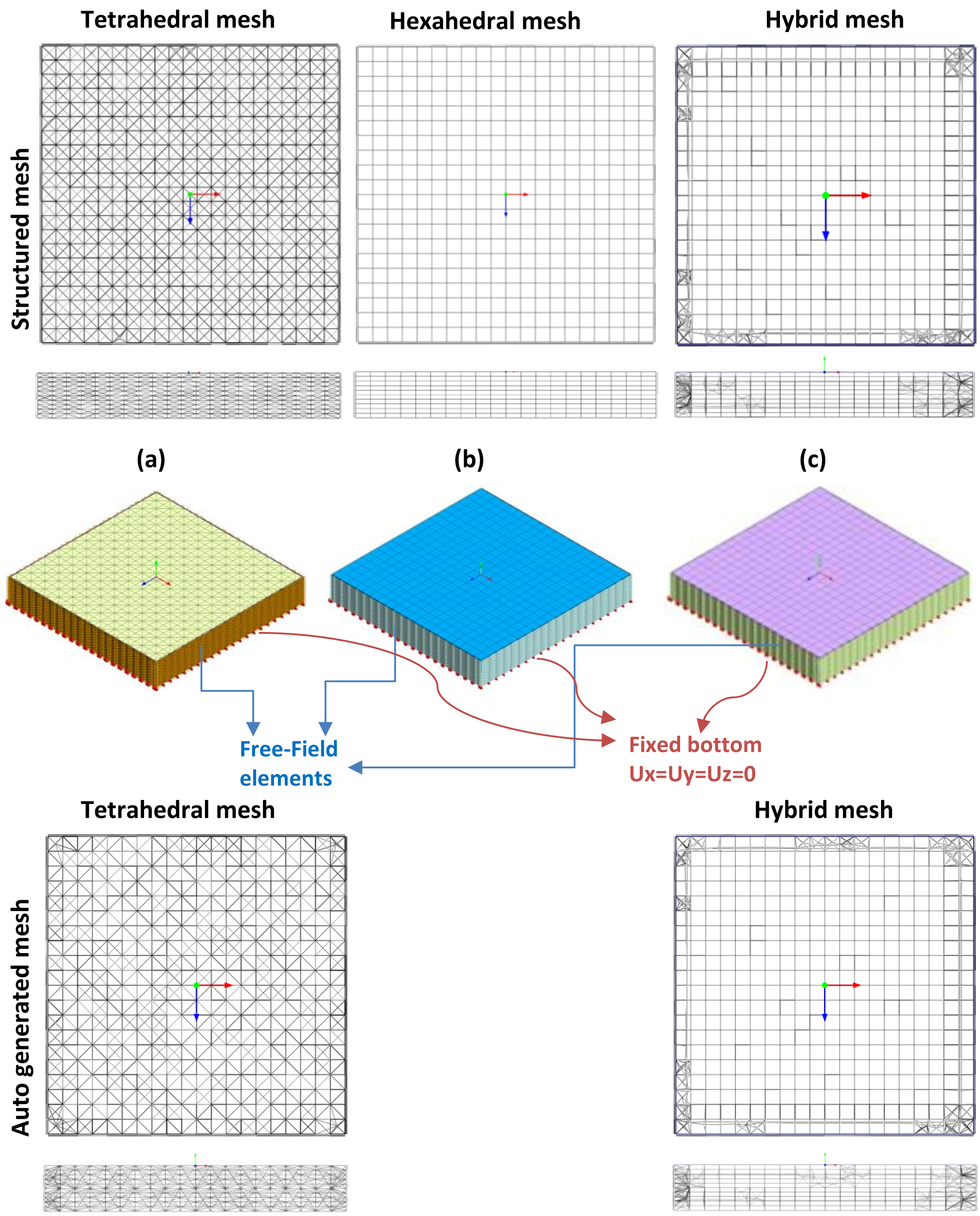

Figure 3:
Generated 3D models (a) Tetrahedral (b) Hexahedral and (c) Hybrid element

In addition to the previously described models, two supplementary models were developed by assuming a foundation footprint of 50×50m. In these models, element sizes were varied spatially to improve computational efficiency while maintaining accuracy in critical regions: smaller elements were assigned near the foundation to capture localized dynamic behavior, whereas larger elements were employed closer to the lateral boundaries. This meshing strategy was applied to both hybrid and tetrahedral mesh types, resulting in two additional distinct three-dimensional models. The mesh size is selected as 4m in the vicinity of foundation while 10m mesh size is utilized at the boundaries. In both models, the mesh was generated using a structured meshing approach in horizontal and vertical directions as shown in Figure 4. Thus, the results will be compared with the regular meshing options defined above, separately.

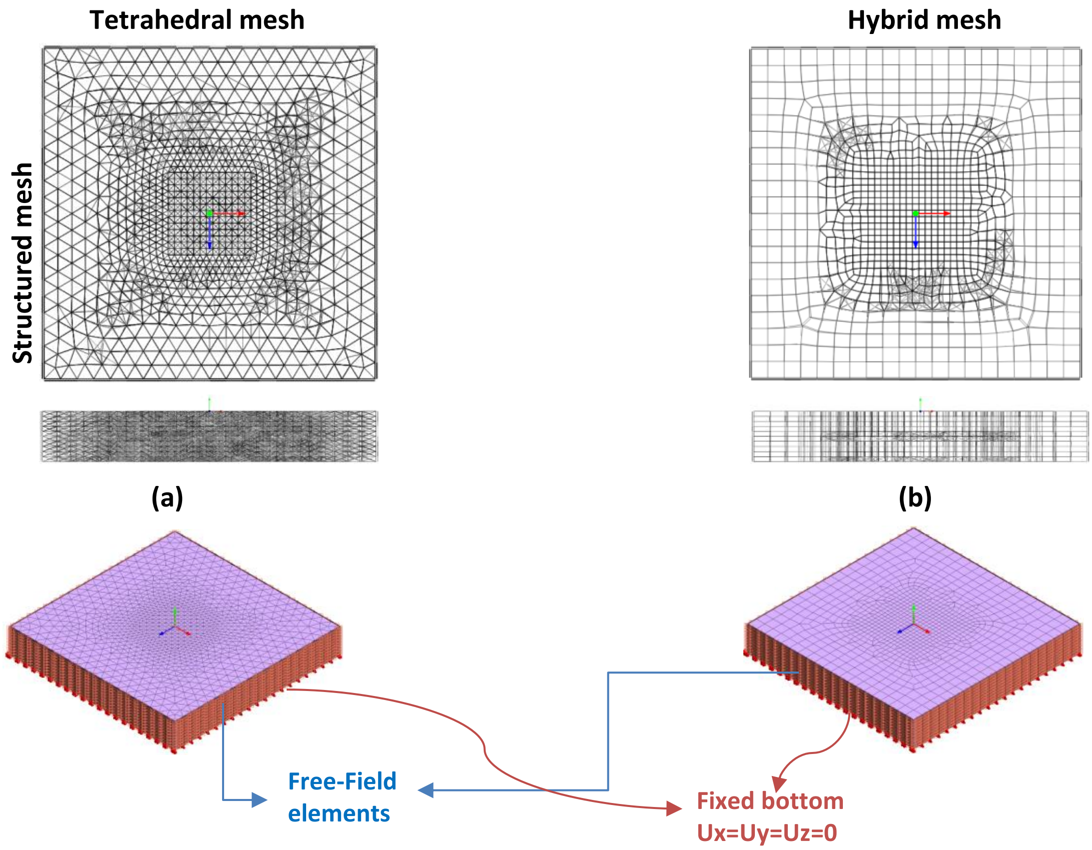

Figure 4:
Generated densely meshed 3D models (a) Tetrahedral (b) Hybrid element

4. ASSESSMENT OF ANALYSES RESULTS

The numerical analysis results are comprehensively evaluated by examining both the variation of displacement and acceleration with depth and the response spectra obtained at the center of ground surface. This approach allows for a detailed assessment of how dynamic parameters evolve throughout the soil profile and how different mesh types and modeling strategies influence the seismic response characteristics at the center of surface.

The number of nodes, the total number of elements, and the computational time required for the analyses conducted with the Friuli–Tolmezzo ground motion record for each of the developed 3D models are presented in Table 2. The hexahedral element type, owing to its well-structured mesh configuration, achieves a reasonable computational time with a relatively low number of elements. In contrast, tetrahedral mesh configurations, particularly at high resolutions (e.g., Tetrahedral-dense), impose a significant computational burden due to the substantially increased element count. Hybrid mesh systems, which incorporate a combination of hexahedral, tetrahedral, and pyramid elements, emerge as the most balanced and efficient modeling approach regarding both computational cost and accuracy. Auto-generated mesh applications reduce the total analysis time. However, they often lead to coarser mesh distributions, which can compromise simulation accuracy and cause deviations from refined solutions.

Table 2. Comparison of analysis results for Friuli-Tolmezzo record

Element type	Grid Class	Element formulation	Nodes in element	No. of nodes	No. of element	CPU time (min)
Hexahedron	Structured	Linear	8	5819	4840	6.47
Tetrahedron	Structured	Linear	4	6369	28263	17.37
Hybrid	Structured	Linear	4-8	5819	4840	3.72
Tetrahedron-auto	Auto	Linear	4	2943	8458	4.32
Hybrid-auto	Auto	Linear	4-8	3128	2769	1.72
Tetrahedron-dense	Structured	Linear	4	12543	62528	51.02
Hybrid-dense	Structured	Linear	4-8	11483	10926	9.90

The response spectra obtained at the center of ground surface for each 3D model is compared with 1D model results in Figure 5 together with referenced study available in literature (de Sanctis et al., 2010). The black line in the Figure corresponds to the first fundamental period of soil domain which is around 0.74s (1.35Hz). The generated 3D models using structured mesh techniques with tetrahedral, hexahedral, and hybrid elements demonstrated a high level of consistency with the results obtained from the 1D Deepsoil analyses. Although the models generated using the auto-mesh technique contained fewer elements and nodes, enabling faster computational performance, they resulted in response spectra that deviated from 1D analysis results within the periods lower than fundamental period of the soil system. For this reason, the use of auto-mesh techniques in dynamic SSI analyses is not recommended. Although this approach significantly reduces computational time by generating coarser and fewer elements, it compromises the accuracy of the results. Therefore, for reliable seismic response predictions, especially in critical engineering applications, structured and well-refined meshing strategies should be preferred over automated meshing independent of element typology. Figure 5 reveals that the discrepancy between the auto-mesh models and the other mesh configurations becomes most pronounced around a period of approximately 0.75s. This observation is particularly significant, as it corresponds closely to the fundamental period of the soil system, suggesting that mesh quality may critically influence the accuracy of dynamic response predictions.

The results of the model employing finer mesh elements in the regions where the foundation is to be placed are presented in Figure 6. The graph generally indicates that the 1D analysis results strongly agree with the 3D finite element analyses. The results indicate that the 3D analyses performed with dense meshes of Tetrahedral and Hybrid configurations in the vicinity of the foundation, where horizontally and vertically structured meshes are used, exhibit dynamic responses similar to those of the 1D analysis. This finding is significant in terms of numerical model consistency and supports the reliability of the 3D models employed. This approach constitutes a critical point for the designer in the subsequent stages of SSI analysis, such as kinematic or direct analyses. Indeed, when the foundation is included in the model, the designer will likely prefer to use smaller elements to more realistically represent the behavior and structural responses.

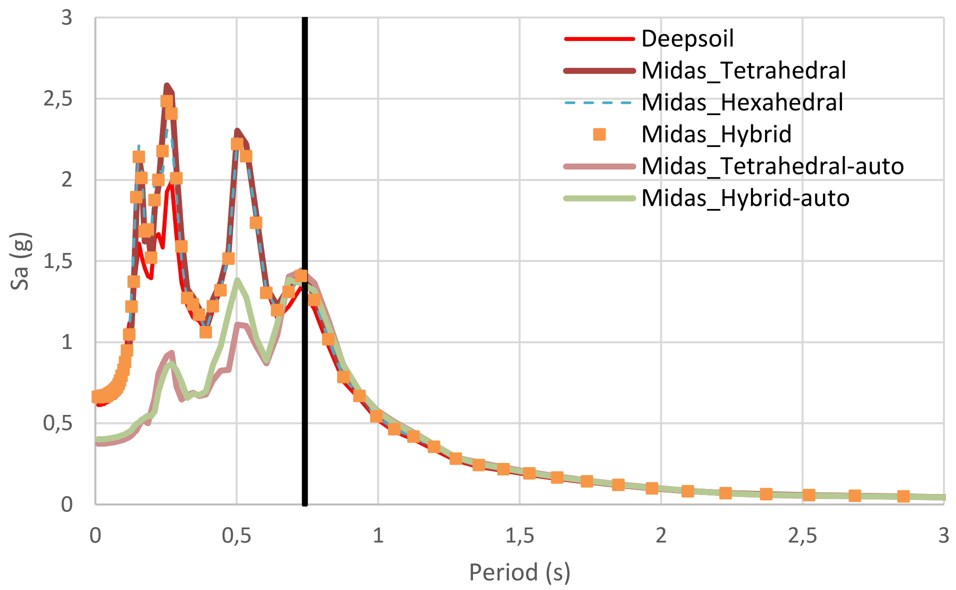

Figure 5:
Comparison of response spectrums for each model

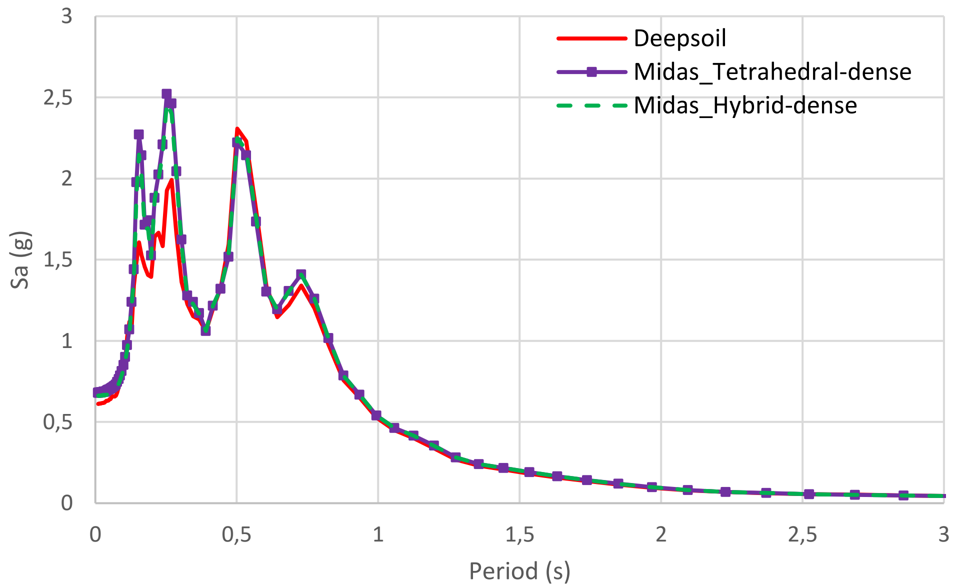

Figure 6:
Comparison of response spectrums for densely meshed models

Figure 7 illustrates the maximum responses obtained along the soil depth from 3D site response analyses together with 1D results. The displacement–depth relationship is presented in Figure 7a, while the acceleration–depth profile is shown in Figure 6b. Since the auto-mesh approach utilizes fewer elements and provides results at a limited number of nodal points, its outcomes are not included in this comparison. The performed 3D analyses demonstrate a high level of agreement with the displacement distribution obtained from the 1D analysis. This result indicates that different 3D mesh types (tetrahedral, hexahedral, and hybrid) can reliably predict displacement behavior and accurately capture surface response characteristics when using structured and refined meshing strategies both in horizontal vertical directions.

The displacement–depth profile in Figure 6a exhibits a noticeable change in slope at approximately 15 m depth, corresponding to the interface between two soil layers with contrasting shear wave velocities. This transition from a softer upper layer to a stiffer lower stratum result in a marked reduction in displacement magnitude, indicating an increase in stiffness and impedance. The abrupt change in mechanical properties at this depth significantly alters the propagation characteristics of seismic waves, leading to reflections and refractions that influence the overall dynamic response of the soil system.

Figure 7b shows that 3D Midas models, especially Hybrid and Tetrahedral mesh structures, can represent acceleration distribution with sufficient accuracy compared to 1D DEEPSOIL analysis. However, some local deviations are evident in the model. While this highlights the impact of modeling techniques and mesh structure on SSI analysis results, it is important to note that the global behavior is still adequately represented as can be seen in Figure 5.

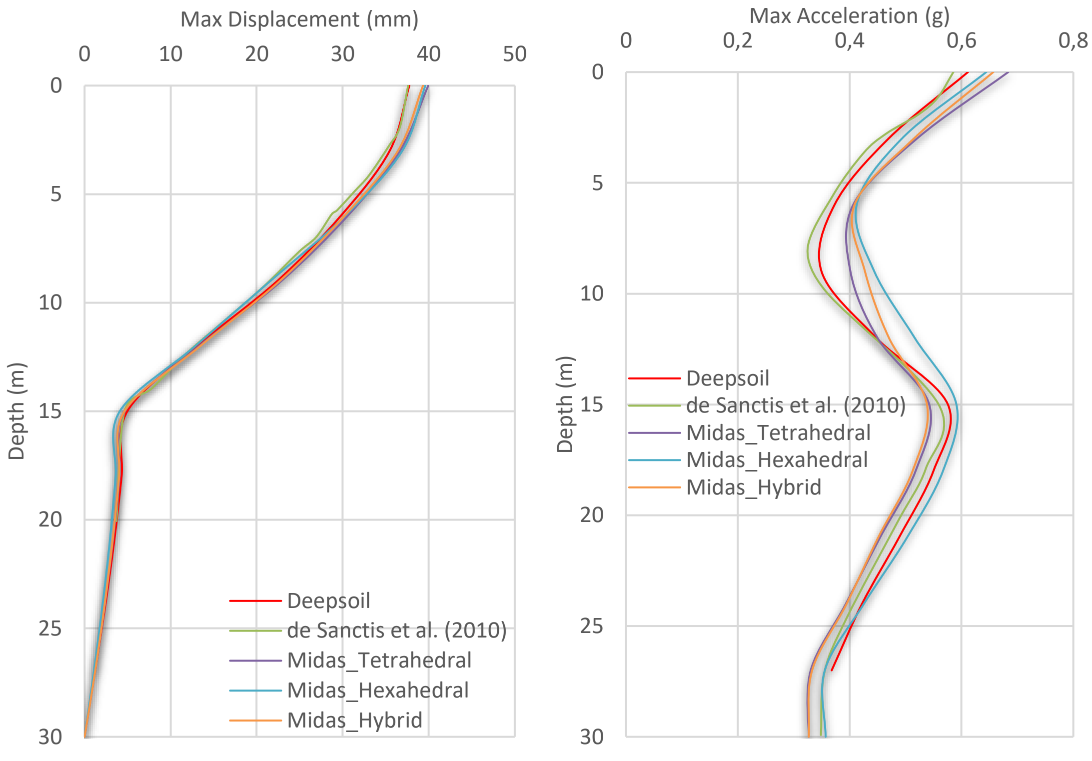

Figure 7:
Comparison of (a) displacement-depth and (b) acceleration-depth relationships

The results of this study have practical importance for engineering applications, especially in choosing mesh types in design software. Accurate seismic response predictions help ensure structural safety and efficient use of resources. Our findings show that mesh typology affects both the accuracy of results and the computational time. This information can guide engineers to select mesh types that provide a good balance between precision and efficiency, particularly in large-scale 3D SSI models. Therefore, the study offers valuable insights for practitioners aiming to optimize model reliability without excessive computational cost.

5. CONCLUSION

The impact of mesh typology on dynamic SSI analyses is scrutinized in the study. The comparative investigation detailed how element shape and formulation affect the transmission and attenuation of seismic waves within the soil domain. Generated 3D model is verified against 1D SRA results utilizing a soil profile adopted from literature. Each mesh configuration (hexahedral, tetrahedral, and hybrid elements) was assessed under identical boundary conditions and ground motion inputs, ensuring that any observed discrepancies in dynamic response could be directly attributed to mesh characteristics rather than external variables. The main findings derived from the study are as follows:

- The dynamic response of a soil system is not significantly influenced by the type of element—whether tetrahedral, hexahedral, or hybrid—so long as the mesh is sufficiently structured and refined in horizontal and vertical directions. Poorly constructed automatic meshes tend to produce unrealistic results, especially near the fundamental period of the soil system and lower. Hence, element type becomes a secondary factor in achieving accurate dynamic SSI predictions when mesh regularity and resolution are maintained in horizontal and vertical directions.

- The comparison of computational performance across mesh types indicates that hybrid models offer an optimal balance between accuracy and efficiency. They achieve significantly lower CPU times than high-resolution tetrahedral meshes while maintaining similar numerical resolution.

- The response spectra and depth-dependent displacement profiles show strong agreement between structured 3D mesh models and 1D analysis results. This consistency is especially evident in capturing peak surface responses. Additionally, all structured mesh types successfully reflect the impedance contrast at the 15-meter layer interface.

- Using smaller elements near the foundation significantly enhances the accuracy of soil–structure interaction (SSI) analyses. This modeling choice becomes particularly important in advanced stages such as kinematic or direct analyses, where realistic representation of structural response is essential.

The findings are particularly relevant for developing robust modeling practices in geotechnical and SSI analyses, where numerical precision is essential for performance-based earthquake engineering applications. The numerical study is conducted for a two-layer soil profile and a single ground motion record. While the results provide valuable insights into the behavior under these conditions, they should not be generalized to other soil profiles or seismic inputs without further analyses.

CONFLICT OF INTEREST

The author confirms that there are no known conflicts of interest and no shared interests with any institution, organization, or individual.

AUTHOR CONTRIBUTION

Mehmet Ömer Timurağaoğlu: Writing original draft; Determination and management of conceptual and design processes of the study; Critical examination of conceptual content; Data collection, analysis and interpretation; Final approval and full responsibility.

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