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Comparative Analysis of Embedded Beam Rows and Volume Elements in the Modeling of a Pile-Supported Bridge Pier

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ABSTRACT

This study investigates the differences between modeling piles as Embedded Beam Rows and Volume Elements in supporting a pier foundation under dynamic loading. Using PLAXIS2D, the system was analyzed under uni-directional and bi-directional excitations derived from the Northridge earthquake. The results show that both modeling approaches captured the vertical load transfer mechanism; however, the foundation settlement in the Volume Element model was found to be about five times larger due to its explicit representation of pile-soil contact, allowing for soil yielding and nonlinear deformation. The Embedded Beam Row model, using simplified linear springs, produced a stiffer response and smaller settlements. Additionally, the horizontal acceleration at the tower head was higher than at the foundation, mainly due to dynamic amplification and the tower's flexible cantilever behavior. The study highlights the strengths and limitations of each modeling technique, offering insights for future seismic analyses of pile-supported structures.

Keywords:

Soil-Pile-Structure Interaction, Embedded Beam Row, Volume Element, Finite Element Modeling, PLAXIS2D.

1. Introduction

Pile foundations are crucial in geotechnical engineering, particularly when the top soil layers are not strong enough to support the weight of a structure. When the shallow soil is unstable, too weak, or too compressible to bear the weight of big structures like buildings, bridges, or other infrastructure, these foundations are commonly used. They offer a reliable method of moving the weights of a structure to deeper [1], more solid soil layers or bedrock, where the soil has a higher and more stable carrying capacity. This ensures that even under extreme weather conditions or heavy loads, the structure will remain safe and strong over time. There are several methods for simulating pile foundations in computational geotechnics, but two popular ones are the application of embedded beam rows and volume elements. Both techniques are used in geotechnical software, such as PLAXIS, FLAC, and others, which simulates soil-structure interactions and generates accurate pile performance predictions under a range of loading conditions.

Over the past few decades, numerous researchers have conducted both numerical studies to assess the performance of pile foundations. In their numerical analyses, they employed various methodologies to simulate the behavior of piles under load.

In one study, Turello et al. [2] created a numerical formulation for a three-dimensional embedded beam element that is utilized to describe piles. A contact surface between the pile and the earth is specifically included in this formulation. It was created to illustrate soil-pile interaction phenomena more generally, therefore it can be used for a variety of loading scenarios or ground motions, even if it is especially used to describe lateral loading of piles. Smulders et al. [3] and Engine et al. [4] created a numerical model that includes an embedded pile model, which includes interfaces at the pile's skin and foot in addition to thin beams. The finite element program PLAXIS was used to successfully implement this model. By choosing the right interface parameters, the model's interfaces can simulate rigid or flexible connections and slippage at the pile-soil contact surfaces. These interfaces represent the interaction between the pile and the surrounding soil. One of the main benefits of this approach is that, even if the embedded pile goes into the interior of soil elements, it may be incorporated into an already-existing finite element mesh after initial setup. The development of effective finite element models for pile group applications is made possible by this feature. It was demonstrated that embedded beams offer a useful technique for simulating several piles in complicated real-world applications.

A research on the difficulties presented by large-scale designs with numerous inclusions, like piles, barrettes, or columns, was carried out by Truty [5]. In these situations, the conventional method of modeling both the rigid inclusions and the subsoil using continuum finite elements may result in unreasonably large computing models. In order to address this problem, Truty [5] suggested and validated a novel approach for simulating stiff inclusions as beam elements embedded in a 3D continuum. Simulations involving piles and barrettes subjected to axial and horizontal stresses, massive piled foundation rafts, and reinforced concrete slabs supported by columns show that this approach offers a good level of accuracy with minimum mesh dependence. An important benefit of this method is that, once the subsurface 3D mesh is created, changes to the rigid inclusions' lengths and locations can be made without affecting the subsurface or superstructure components-unless local mesh refinements are required, in which case they can be done almost automatically.

In a study by Ukritchon et al. [6], numerical analyses of 3D finite element modeling were carried out for a square pile group foundation intended for a wind turbine, subjected to significant moments and coupled vertical loads. Using an embedded pile element, the study applied 3D finite element analysis to a single pile as well as a pile group. The embedded pile element makes it possible to analyze a large number of piles in a pile group foundation efficiently, in contrast to previous methods that model piles as volume elements. The study concluded that using the embedded pile element to model the behavior of a single pile at the limit state provides accurate results, comparable to those obtained through manual methods.

In a study by Al-Ne'aimi and Hussein [7], a 34-story multi-story building foundation supported by a piling group was analyzed using PLAXIS3D finite element software under the influence of enormous moments and vertical loads. According to their findings, differential settlements increased while overall settlement at the raft's center decreased as the number of piles grew. Additionally, they found that for a given pile spacing, the raft's bending moment reduced as the pile length grew. On the other hand, the raft's bending moment increased when pile distance decreased for a specific pile length. Furthermore, as the number or length of piles increased, so did the skin friction and end-bearing ratios, with the skin friction growing more quickly as a result of load redistribution. Volume piles exhibited lower raft settlement values, pile shear forces, and moments, according to the study's comparison of volume piles and embedded piles. The embedded pile element, which is indirectly attached to the mesh by springs and permits soil to "flow-through" the embedded pile row, is responsible for the difference.

In their thorough assessment of the literature on piled raft foundations, Deb and Pal [8] critically examined the development of piled raft technology from its conception to the present. They collected important study results on different approaches to modeling piles, how they interact with the soil around them, and elements like lateral resistance and friction. This review provides a thorough overview of the field's progress and identifies major developments in our knowledge of piled raft foundations.

Sumarsono [9] evaluated the response of bored piles in the Auditorium building at Brawijaya University to seismic loads using analytical and numerical techniques based on finite elements with 2D (embedded beam row) and 3D (volume pile) modeling. How pile deformation and lateral resistance are analyzed numerically depends on how idealized the model is. Additionally, the lateral resistance was investigated utilizing combination lateral loads, pile stiffness, and soil stiffness when the values varied.

Granitzer and Tschuchnigg [10] compared the conventional Embedded Beam (EB) and the advanced Embedded Beam with Interaction Surface (EB-I) elements for modeling deep foundations. They found that the EB-I offers improved accuracy in predicting soil displacements, skin resistance, and mesh sensitivity by modeling interaction along a surface rather than a centerline. However, they cautioned that special attention is needed when applying these methods to composite structures.

This study aims to provide a numerical evaluation of the differences between modeling piles as embedded beam rows and as volume elements in supporting the foundation of a tower structure. The study investigates the performance of these two modeling approaches under uni-directional and bi-directional earthquake excitations.

2. Numerical Modeling

2.1. Constitutive soil model

For modeling the soil layer in PLAXIS2D, HS small model [11] was used. It is a constitutive model commonly used to describe the behavior of soil in geotechnical engineering, particularly for clay and sand. It is widely employed in numerical simulations like PLAXIS2D to model the behavior of soils under a variety of loading conditions. The model accounts for the effects of both elasticity and plasticity, which is important for capturing soil deformations accurately. It consists of some stiffness, strength, and small strain parameters. The definition of these parameters and the selected values for each of them are presented in Table 1.

2.2. Structural Model

The structure modeled in this thesis consists of a tower supported by a gravity base foundation system. The gravity base has a total width of 3.75 m and a thickness of 2 m, providing the primary support and stability for the tower. The tower itself has a height of 13 m and a wall thickness of 0.5 m, extending upward from the center of the base. At the top of the tower, a head section is included, measuring 1.25 m in height and 1.76 m in width, representing the upper portion where loads are typically transferred or instrumentation may be installed. The entire foundation is embedded 1.5 m into the supporting soil layer to ensure sufficient confinement and resistance against lateral and overturning forces. Additionally, the structure is reinforced by two piles, each with a length of 10 m, placed beneath the base to enhance the bearing capacity and reduce settlement. The connection between the piles and the foundation is assumed to be rigid, ensuring full moment transfer and eliminating relative rotation between these structural components during loading. The properties of the structural materials used in the numerical analysis are given in Table 2.

Table 1. Soil properties used in the numerical model

Soil Type	Type	γ (kN/m^3)	E_{50}^{ref} (kN/m^2)	E_{oed}^{ref} (kN/m^2)	E_{ur}^{ref} (kN/m^2)	m	c'_{ref} (kN/m^2)	φ' (°)	$\gamma_{0.7}$	G_0^{ref} (kN/m^2)	υ'_{ur}
Sand	Drained	17	24.1×10^3	24.1×10^3	72.4×10^3	0.5	1	30	1.4×10^{-4}	83.5×10^3	0.3

γ: Unit weight	E_{50}^{ref}: Secant stiffness in the standard drained triaxial test
E_{oed}^{ref}: Tangent stiffness for primary oedometer loading	E_{ur}^{ref}: Unloading/reloading stiffness
m: Power for stress-level dependency of stiffness	c'_{ref}: Cohesion
φ': Friction angle	$\gamma_{0.7}$: Shear strain at which G_s=0.722G_0
G_0^{ref}: Shear modulus at very small strains	υ'_{ur}: Poisson ratio

Table 2. Material properties used in the numerical model of the structure

Element	Material Type	γ (kN/m^3)	E (kN/m^2)	ν
Gravity Base		27		
Tower	Linear Elastic	19	30×10^6	0.2
Head		27		

2.2.1. Embedded beam pile model

In the first modeling approach, piles are simulated using embedded beam elements, which efficiently capture pile-soil interaction without explicitly meshing the pile or defining interface elements. This method reduces computational effort while accurately representing load transfer along the pile shaft and tip. It realistically simulates axial, lateral, and bending behavior, as interaction forces are automatically computed based on relative displacements between the pile and surrounding soil. Thus, embedded beam elements provide a reliable and efficient way to model pile behavior in complex foundation systems. The properties of the piles modeled as embedded beam elements are listed in Table 3.

Table 3. Material properties used in the numerical model of the embedded beam elements

Element Type	Material	γ (kN/m^3)	E (kN/m^2)	Diameter (m)	Beam Type
Pile	Linear Elastic	8	30×10^6	1	Massive Circular Beam

It should be noted that although the embedded beam element is used to model the concrete pile, it does not occupy any actual volume. Therefore, the unit weight of the concrete should be assigned a reduced value to ensure that the initial vertical stress distribution in the soil remains unchanged after the piles are introduced. Therefore, instead of using the concrete unit weight (γ = 25 kN/m^3), a reduced equivalent unit weight is calculated using the following expression and assigned to the embedded beam element in PLAXIS2D.

Concrete unit weight (γ_c): 25 kN/m^3
Pile diameter (D): 1 m, So: cross-sectional area = 0.785 m^2
Soil unit weight (γs_{oil}): 17 kN/m^3
Embedded beam unit weight (γ_{EB})=γ_c-γ_{soil}=8 kN/m^3

2.2.2. Volume pile model

In the second modeling approach, piles are represented as volume elements, providing a detailed and realistic simulation of their geometry and stress distribution. Unlike embedded beam elements, this method allows explicit modeling of the pile-soil interface, including contact parameters such as friction, adhesion, and slip. It accurately captures stress and strain variations along the pile and around the tip, enabling direct observation of load transfer mechanisms. Although it requires finer meshing and higher computational cost, the volume element approach offers greater accuracy and realism-especially for studying nonlinear soil behavior, group effects, and local phenomena. The properties of the piles modeled as volume elements are presented in Table 4.

Table 4. Material properties used in the numerical model of the volume elements

Element Type	Material	γ (kN/m^3)	E (kN/m^2)	Diameter (m)
Pile	Linear Elastic	25	30×10^6	1

2.3. Boundary Conditions, Uni-Directional and Bi-Directional Excitations

In the static analysis phase, the lateral boundaries of the model were assigned equal degrees of freedom (DOF), ensuring uniform movement along the sides. During the dynamic analysis phase, free-field boundary conditions-representing drained soil behavior-were implemented to simulate far-field conditions, following the recommendations provided in the literature [12, 13]. The model base was fixed in both horizontal and vertical directions to prevent displacement, whereas the lateral boundaries were constrained only horizontally, allowing free vertical movement. The horizontal and vertical components of the 1994 Northridge earthquake (station: Castaic – Old Ridge Route) were applied at the model base as input motions. For the case of uni-directional excitation, only the horizontal acceleration record was applied, while for the bi-directional excitation, both the horizontal and vertical components were applied at the rigid base.The

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corresponding time-history records were obtained from the NGA-West2 database [14]. Fig. 1 presents the acceleration time histories of the selected ground motion.

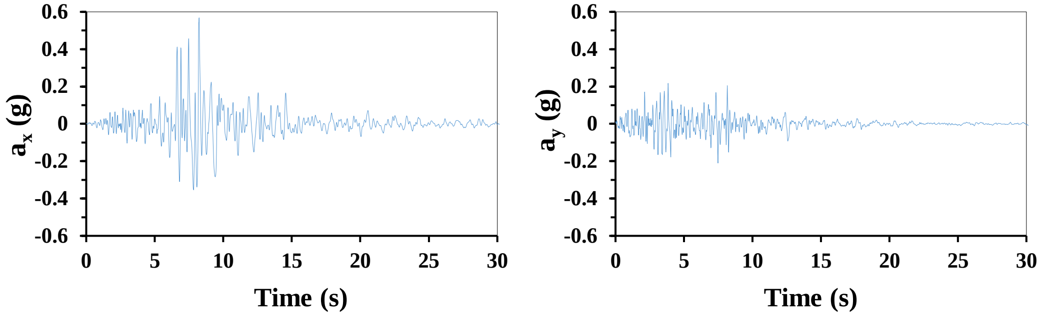

Figure 1. Horizontal and vertical acceleration records applied at the base of the model.

2.4. Model Geometry

After defining the material properties and geometric parameters, a series of 2D numerical models were developed to simulate soil–structure interaction. These models considered both dry and wet soil conditions, with piles represented using either embedded beam elements or volume elements. Figs. 2 and 3 illustrate schematic views of two representative 2D models, including all relevant details.

3. Results and Discussion

This section presents the numerical results obtained from the two-dimensional simulations carried out to investigate the behavior of the soil-pile-structure system for different methods of pile modeling and under different loading conditions.

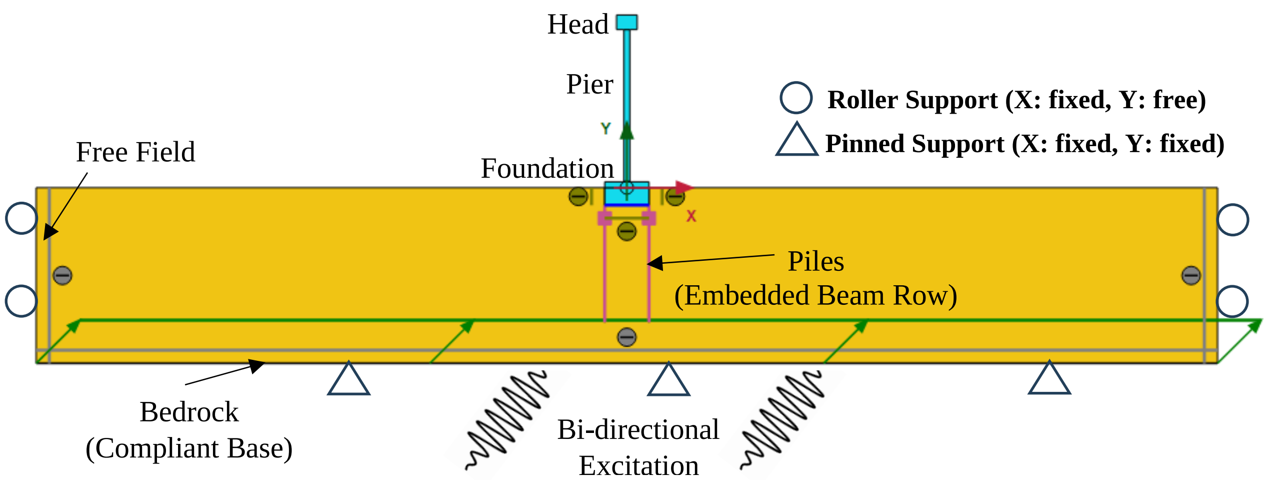

Figure 2. Soil-pile (embedded beam row)-structure model.

Advance Researches in Civil Engineering
ISSN: 2645-7229, Vol.6, No.4, pages:49-59

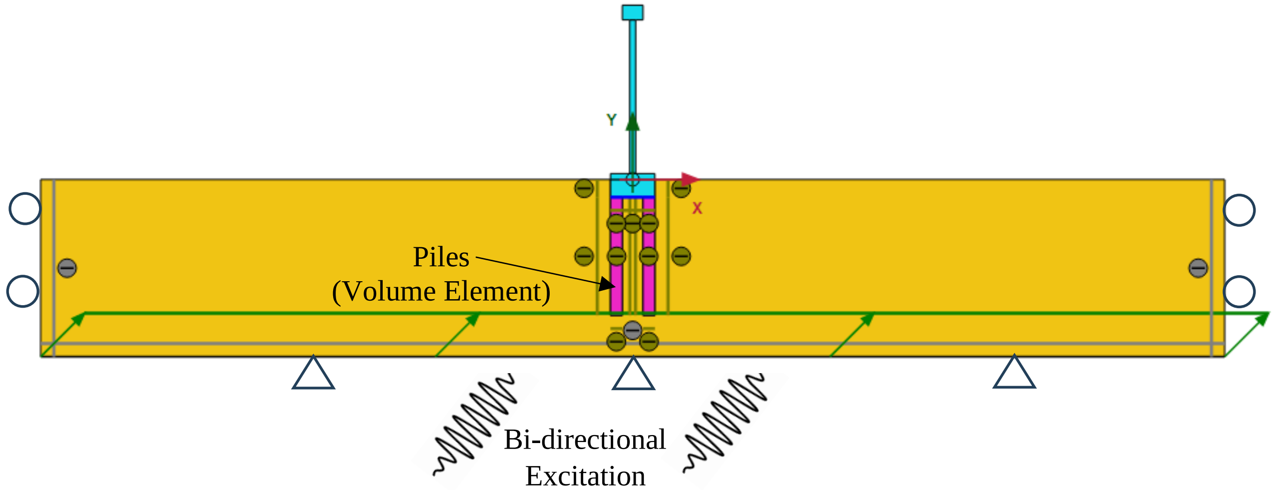

Figure 3. Soil-Pile (volume element)-structure model.

Fig. 4 illustrates a comparison of the lateral displacement of the pier head, Ux, supported by piles modeled by two different approaches under uni-directional and bi-directional excitations. Quantitatively, when the model was subjected to uni-directional excitation, the maximum lateral displacement at the tower head was approximately 0.28 m for the model in which the piles were represented as embedded beam elements, and about 0.32 m for the model using volume elements. Under bi-directional excitation, the maximum lateral displacement at the tower head was approximately 0.24 m for the embedded beam element model and about 0.28 m for the volume element model. The slightly larger displacement observed in the volume element model indicates a relatively higher degree of flexibility in the structural response. Overall, it can be concluded from the figure that the maximum lateral displacement at the pier head is nearly similar for both modeling approaches-whether the piles are represented as embedded beam rows or as volume elements.

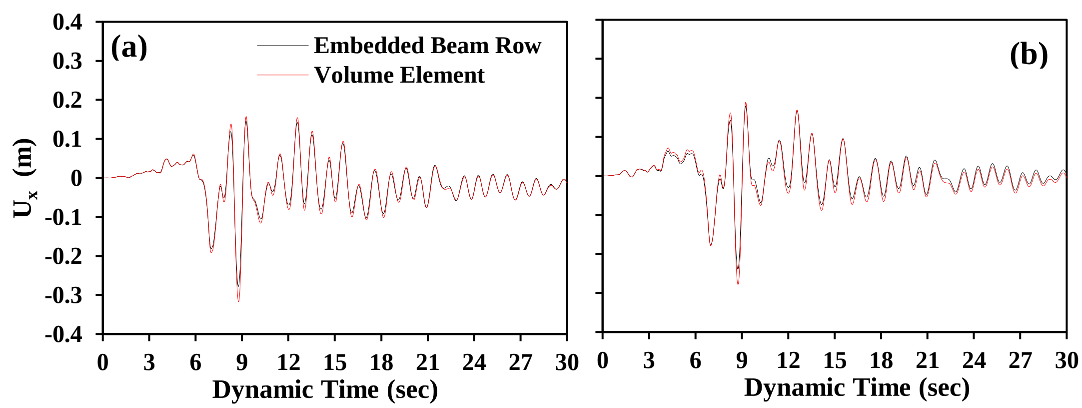

Figure 4. Comparison of the head's lateral displacement for the model subjected to: (a) uni-directional excitation, (b) bi-directional.

Fig. 5 illustrates a comparison of the settlement of the pier foundation supported by piles modeled by two different approaches under uni-directional and bi-directional excitations. Again, it can be observed that the settlement time history of the pier foundation is very similar for both modeling approaches. It is noticeable that the foundation settlement obtained from the model subjected to bi-directional excitation is almost six times greater than that under uni-directional loading (0.12 m and 0.02 m, respectively).

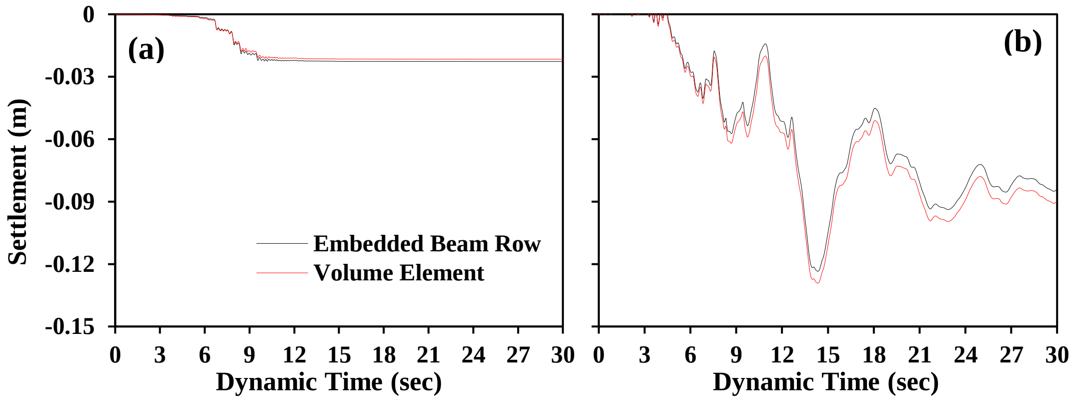

Figure 5. Comparison of the foundation's settlement for the model subjected to: (a) uni-directional excitation, (b) bi-directional

Figs. 6 and 7 illustrate a comparison of the horizontal acceleration at the pier head and foundation supported by piles modeled using two different approaches under uni-directional and bi-directional excitations. It can be concluded that the piles modeled by both approaches exhibit similar behavior under both excitation conditions. It is also noticeable that the acceleration recorded at the foundation is lower than that at the pier head (0.44 g and 0.86 g, respectively).

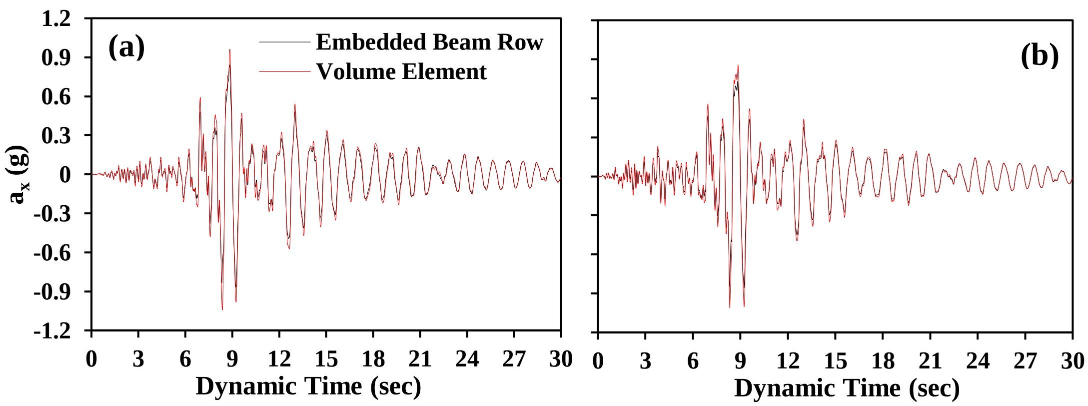

Figure 6. Comparison of the head's horizontal acceleration for the model subjected to: (a) uni-directional excitation, (b) bi-directional.

Advance Researches in Civil Engineering
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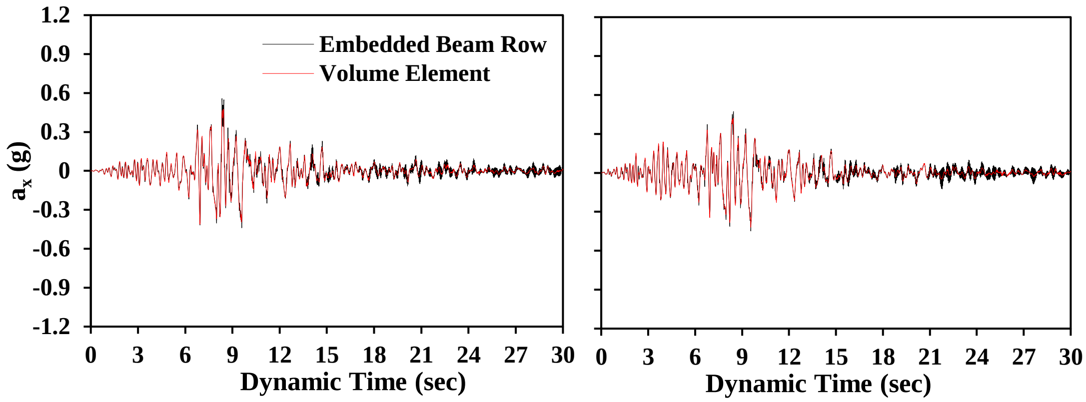

Figure 7. Comparison of the foundation's horizontal acceleration for the model subjected to: (a) uni-directional excitation, (b) bi-directional.

4. Conclusion

This study aims to provide a numerical evaluation of the differences between modeling piles as embedded beam row elements and as volume elements in supporting the foundation of a bridge pier. The study investigates the performance of these two modeling approaches under uni-directional and bi-directional earthquake excitations. For this purpose, the horizontal and vertical acceleration components of the Northridge earthquake were adopted as input motions to simulate realistic seismic loading. The numerical analyses were conducted using PLAXIS2D, where simulations were performed to assess the behavior of the system under the specified scenarios. The outcomes of the simulations are analyzed in terms of the lateral displacement of the pier head, the settlement of the foundation, and the horizontal acceleration responses recorded at both the pier head and the foundation level. A detailed comparison between the results obtained from the two modeling techniques provides valuable insights into the effectiveness and limitations of each approach in capturing soil-pile-structure interaction under dynamic loading. The key outcomes are listed below:

1-It is noticeable that the foundation settlement obtained from the model subjected to bi-directional excitation is considerably greater than that under uni-directional loading. This significant increase can be attributed to the combined effect of simultaneous horizontal and vertical ground motions, which intensify the stress and strain within the soil, leading to greater deformation and settlement of the foundation.

2-According to the findings, the tower head experiences a greater horizontal acceleration than the foundation level. This happens because the tower amplifies motion as seismic waves move higher, acting as a flexible cantilever. since of dynamic amplification, the upper portion of the structure undergoes more deformation and acceleration since it has less restriction and a lower effective mass. In the meantime, base acceleration is decreased by soil–structure interaction, which dampens some of the seismic energy at the foundation. Therefore, during seismic loading, the combined effects of soil damping, modal behavior, and structural flexibility result in larger acceleration reactions at the tower head.

Declaration of competing interest
The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Data availability
Not Applicable.

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