A review of seismic soil-pile-superstructure interaction methods

Ahmad Dehghanpoor, David Thambiratnam, Tommy Chan
Department of Civil Engineering and Built Environment – Queensland University of Technology, Brisbane City, Queensland, Australia

ABSTRACT
The role of the Seismic-Soil–Pile–Superstructure Interaction (SSPSI) is usually assumed negligible for structural design purposes. This is mainly to avoid the complex task of computing the inertial and kinematic interactions for superstructure-pile and soil-pile systems respectively. The results obtained from recent earthquakes demonstrate that considering a fixed-base structure could be misleading, and neglecting the effects of SSPSI could lead to risky designs mainly for mid-rise and high-rise buildings founded on soft soils.
The SSPSI behavior is predominantly nonlinear and this makes it complicated. The field observations of pile failures after seismic events have highlighted the importance of incorporating kinematic effects in the design process. Hence, some codes states those kinematic effects should be considered during the pile design process. In a soil-pile-superstructure system, the seismic load is resisted by the interaction effects between pile, soil and superstructures, which in turn depend on soil, pile and superstructure materials and geometry, slenderness ratio in pile, pile type (vertical or inclined), loading type and its specifications. The difficulty in the accountability of the influencing factors necessitates a detailed investigation on SSPSI. Reviewing the existing literature reveals that studies on SSPSI effects have been generally carried out in two different directions: investigation methods and types of pile foundation. As a result, a SSPSI detailed literature review is presented in this paper.

1. INTRODUCTION

Computing the SSPSI is an advanced multidisciplinary research field in civil engineering. In order to have an extensive investigation on SSPSI effects, a broad knowledge in geotechnical and structural engineering is essential. The main task of pile foundations is transferring heavy loads from superstructures to soil deposits in poor soil conditions. Basically, skin friction at the soil-pile contact acting on shaft and base of pile (tip) play the load transferring role. Mid-rise and high-rise buildings and bridges are good examples of superstructures that are supported by deep foundations exposed to significant dynamic loads such as earthquake, wind, impact loads and any other types of lateral loads. Studies on soil–structure interaction have demonstrated that the response of the structure supported on flexible soil is different from the response of the same structure based on a rigid support (Bielak 1976; Wolf 1985).

The SSPSI complexity involves the pile-cap interaction, pile-soil interaction, pile-superstructure interaction and specifications of piles-superstructures including the materials, dimensions, soil properties and the type of excitations that have critical effects on the response of the entire system. The interaction could be kinematic and/or inertial (Kramer 1996; Stewart et al. 1999). The kinematic interaction on SSPSI due to seismic excitation makes the soil motion, generally different for each point at any given instant. This type of interaction is highly dependent on the foundation type, geometry and ground motion wavelengths. Inertial effects result from the combined dynamic behavior of superstructure, pile, and supporting soil media. Soil media, owing to its properties, increases the degrees of freedom of superstructure and makes it possible to dissipate energy of incoming seismic waves by the radiation of waves away from the superstructure and hysteretic deformation of supporting soil media. Regardless of ordinary structures, inertial effect for massive superstructures, which founded on stiff soils or rock, can have significant effects.

This paper will present a review on SSPSI phenomenon in two different categories: methods of investigation and types of piles (vertical or inclined).

2. INVESTIGATION METHODS

2.1. Analytical Methods

Analytical investigations are the basis of numerical formulations. The theoretical formulations are to be considered for the advanced modifications in the numerical closed-form expressions. Elastic continuum (Gazetas 1991; Poulos and Davis 1980; Tajimi 1969) and Beam on Nonlinear Winkler Foundation (BNWF) (Matlock and Reese 1960; Reese and Cox 1969) are the most common analytical methods for soil-pile interaction.

2.1.1. Elastic Continuum

The elastic continuum methods are based on closed-form expressions for implementation of point loads to a semi-infinite elastic medium. The accuracy of elastic continuum methods highly depends on the evaluation of soil elastic parameters. One of the main drawbacks of this approach is the difficulty of directly incorporating the soil nonlinearity. However, it is more appropriate to be adopted for small strain and steady state problems. Elastic continuum theory was applied to describe a dynamic soil-pile interaction (Tajimi 1969). It involved studying pile response for a given ground motion. Interaction between piles and soil was solved theoretically by using linear visco-elastic model of soil. By applying the elastic continuum method, an analytical approach was presented to predict pile deformation and load capacity (Poulos and Davis 1980). Furthermore, parametric solutions for different cases were reviewed to prove how such solutions can be used for design purposes, and to assess the applicability of these approaches to practical problems. In the solutions, the pile was assumed to be loaded by a horizontal force acting at an eccentricity above the ground line. Unless otherwise stated, the slope is assumed to be vertical and to extend the full length of the pile. For a free head pile, ground line displacement and rotation of free headed pile are given by Eq.1,2 respectively (Poulos and Davis 1980):

$$\rho = \frac{H}{N_h L^2}\left(I'_{\rho H} + \frac{e}{L} I'_{\rho M}\right)/F'_{\rho} \qquad [1]$$

$$\theta = \frac{H}{N_h L^3}\left(I'_{\theta H} + \frac{e}{L} I'_{\theta M}\right)/F'_{\theta} \qquad [2]$$

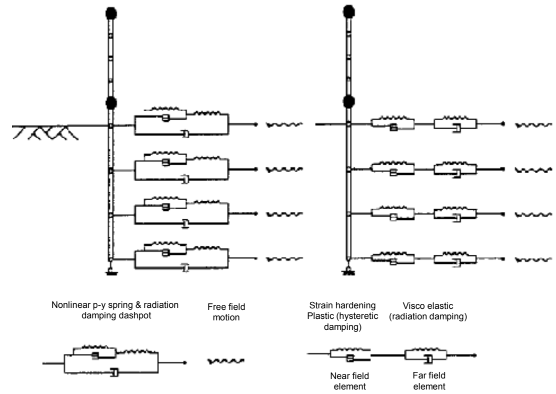
Where N_h is rate of increase of soil modulus with depth; I' is elastic influence and F' is yield factor.

(Gazetas 1991) investigated the response of foundations under dynamic loads based on elastic continuum theory and prepared detailed design graphs. In addition, he provided impedance functions to estimate stiffness and damping parameters for pile head and soil deposits.

2.1.2. Beam on Nonlinear Winkler Foundation (BNWF)

The BNWF theory assumes that each layer of soil reacts individually with the adjacent layers and hence a series of linear or nonlinear springs and dashpots are employed to be representative of the soil behaviour. The principle idea of BNWF concept is to present the stress-strain variations for soil because of soil-pile interaction effects and to provide a set of curves along the pile depth direction. When lateral dynamic loads act on piles, the associated curves for soil resistance per unit pile length at depth can systematically reflect the pile stiffness and soil nonlinearity, as well as the nature of the pile under the load.

(Reese and Cox 1969) presented a better understanding on the behavior of soil-pile interaction from the soil reaction–pile deflection (p–y) curves of the soil. Moreover, he developed dimensionless curves from the developed p–y method for single pile foundations under lateral loads. This research has been developed by (Chore et al. 2012a, b), finite element equations obtained for the nonlinear analysis of pile groups under lateral loads using p–y curves. Several implementation of the BNWF method were used by (Wang et al. 1998) for prediction of a single pile in a soft clay soil profile. (Nogami et al. 1992), (Kagawa 1980) demonstrated the linear viscous dashpots as a representative radiation damping in far field in series with hysteretic damping of p-y elements as nonlinear response in the near field, was shown to be strictly preferable to a parallel arrangement (Figure1).



(a) (b)

Figure 1. Soil-pile-structure model with (a): parallel damping (b): series damping (Kagawa 1980; Nogami et al. 1992)

(Boulanger et al. 1999) developed a dynamic material model p-y to implement on a finite element program that the element has the ability to simulate plastic deformations of the soil, opening and closing of the gap between the pile and soil.

SSPSI effects on pile groups are more complicated than that on single-pile-supported structures because it involved rocking motions (axial pile behavior), lateral resistances on the pile cap, and group effects. A pile-group-supported structure was studied (Curras et al. 2001) using the similar dynamic p-y model (Boulanger et al. 1999) to examine efficiency of the dynamic p-y method compared with continuum theories. The results were compared to dynamic centrifuge model tests and had a good agreement with experimental centrifuge results, though this research was limited by elastic assumption for structural behavior (Figure 2).

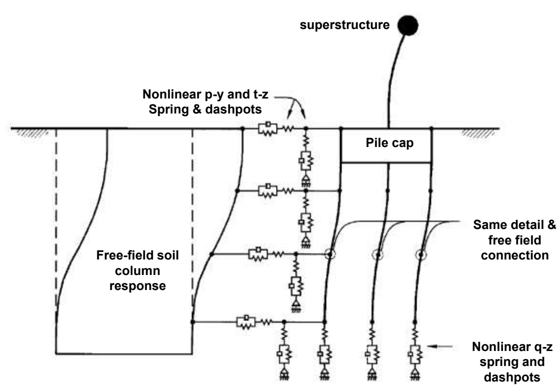


Figure 2. Schematic of dynamic BNWF analysis method (Boulanger et al. 1999)

Some studies were focused for a generalized BNWF model capable of accounting for various important soil–structure interaction (SSI) response features (Allotey and El Naggar 2008; Mostafa and Naggar 2002). In addition, a backbone curve was represented in different models with either a nonlinear or a multilinear curve fitted to a specified nonlinear monotonic force–displacement curve. However, a noticeable drawback of Winkler based models was observed by (Allotey and El Naggar 2008; Liam Finn 2005) that was the missed shear force transferring between springs due to idealization of the soil continuum with discrete soil reactions. A simplified Winkler model for a single pile was considered by (Thavaraj et al. 2010) as shows in Figure 3.

By applying the free field motions as input for Winkler spring, an assumed near-field domain system including soil and pile was excited. The equation governing the motion is presented as Eq.3:

$$EI\frac{\partial^4 v}{\partial x^4}+\rho A\left(\frac{\partial^2 v}{\partial t^2}+\frac{\partial^2 v_g}{\partial t^2}\right)+c\left(\frac{\partial v}{\partial t}-\frac{\partial v_{ff}}{\partial t}\right)+k_h\left(v-v_{ff}\right)=0 \quad [3]$$

Where A: pile area; ρ: pile density; I: second moment of pile area; E: Young's modulus; k_h: soil reaction coefficient for soil; c: equivalent dashpot coefficient; v: the relative displacement of pile with respect to the base excitation; v_g: base excitation; v_{ff}: the relative free field displacement.

The spring behaviour was assumed to be nonlinear but simulated as an incrementally linear elastic tangent stiffness theory.

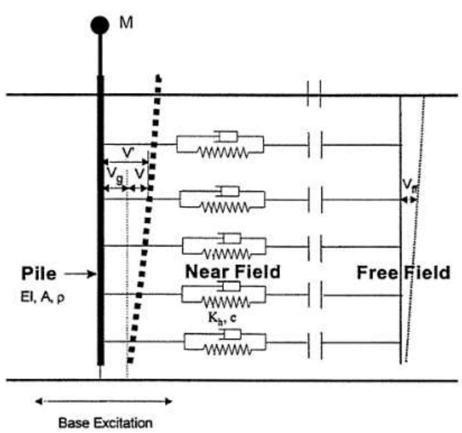


Figure 3. Winkler model for pile-soil interaction (Thavaraj et al. 2010)

The development of a generalized dynamic normal force–displacement beam on nonlinear Winkler foundation (BNWF) model was focused by (Allotey and El Naggar 2008) for observing and accounting various important soil–structure interaction (SSI) response features. These important features include different types of backbone curves, different types of unloading and reloading curves, accounting for cyclic degradation under generalized loading, accounting for soil cave-in, and modelling radiation damping. (Choi et al. 2015) presented a new functional form of p-y by using bounding surface plasticity theory and it applied into the finite element code to investigate the role of soil nonlinearity for a soil-pile system. The p-y relationship was developed for static loading conditions, with cyclic correction factors intended to represent degradation due to many slow loading cycles. Furthermore, the dynamic p-y capacities perceived in several previous research work is larger for some special types of soil and more studies are required to predict soil-pile interaction effects.

The validation of dynamic p-y modelling for taking to account SSPSI effects in embankment and pile foundation system was investigated by (Xie et al. 2016) and closed-form expressions have been extended for p-y models of embankment as functions of abutment geometry and soil properties (Figure 4). The modelling approach implemented to simulate the seismic responses of a typical bridge as a representative of a superstructure and verified through comparisons with the recorded responses. The results in both time and frequency domains were comparable to the actual recorded responses of the typical case study.

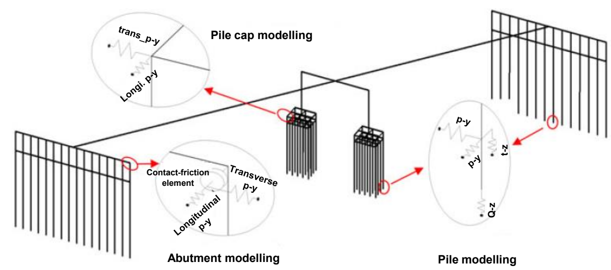


Figure 4. Full-scale model (Xie et al. 2016)

Analytical methods have assisted researchers for better understanding soil-structure interaction during many years while, numerical methods have facilitated more investigations on SSPSI for accurate results.

Data on the single pile impedance functions for different soil profiles and different pile materials presented by (Novak 1974). These complex functions employed by (Dehghanpoor 2013; Dehghanpoor and Ghazavi 2012; Ghazavi and Dehghanpour 2010) to present a simplified mathematical method for analysis of tapered and vertical piles under a combination of static and cyclic loads.

2.2. Numerical Analysis

A few numerical methods have the capability of computing the dynamic response of a soil-foundation-structure system considering SSPSI effects. Although numerical methods are the most common ways to consider nonlinear behavior of materials and geometries, each of them has some limitations in applications. Finite element and macro-element methods are good examples of applicable methods for dynamic analysis of a complex soil-foundation-structure system (Cai et al. 2000; Maheshwari et al. 2004; Nogami et al. 1992; Varun 2010; Wu and Finn 1997).

A full three-dimensional finite element model of a soil-pile-superstructure system, which incorporates the nonlinear behavior of the soil, the structure and its interface and with appropriate radiation boundary condition, will be capable of accurately predicting the behavior of the system under seismic loading. Any other method will be a simplification that brings with it a loss of generality and accuracy. However, 3D finite element for considering the effects of SSPSI is a computationally expensive and time-consuming procedure. Time variation of dynamic impedances of pile foundations that provides a realistic selection of the representative discrete stiffness and damping ratios required for most finite element models was presented by (Wu and Finn 1997).

Material nonlinearity significantly affects seismic response of pile foundations, structures and consequently SSPSI. However, type of excitation has the significant role to that response. For a harmonic excitation, the soil nonlinearity increases the pile head and structural responses at low frequencies. At high frequencies, both the pile head and the structural responses are slightly affected by the soil nonlinearity. For the transient excitation, soil nonlinearity increases both the pile head and the structural responses. Smoothed Fourier spectra show that in general, nonlinearity increases the responses at low and moderate frequencies but its effect is negligible at high frequencies (Maheshwari et al. 2004). In addition, effective amounts of inertial and kinematic interactions on structural and geotechnical damage parameters within a finite element code were investigated by (Maheshwari and Sarkar 2011) and the results have shown effect of inertial interaction causes to amplify the pile head response and to decrease the superstructure's response. Moreover, the influence of pile group leads to a drop in the peak values of response.

Finite element models are robust tools for SSPSI effects on designing sensitive structures such as tall buildings and nuclear structures under intense dynamic actions. By introducing nonlinear models for different types of soils, implementation of advanced soil models in a coupled soil-pile-superstructure system for these special structures is essential (Luo et al. 2016). They proposed a nonlinear 3D finite element model and compared results with those from an equivalent linear model to see if it was necessary to use the fully nonlinear method for achieving rigorous and consistent results. Furthermore, defining a versatile plastic model for soil enhanced the accuracy of results for a soil-pile-superstructure system (in this case an adopted Drucker-Prager model) and the effects of SPSI on a system is not sensitive to the variation of soil's dilation angle under dynamic loads. With the development of the finite element method and the rising of commercial FEM codes, researchers can explicitly reproduce 3D SSPSI problems. However, this type of numerical analysis is computationally expensive and needs high performance computers.

Macro-element method originated form integrating the material behavior over the locally affected volume and concentrating the global stress-strain response at representative locations of the soil-structure interface based on the externally applied loading. Macro-elements can provide the ability to couple the nonlinear behavior of soil and soil-pile interfaces such as plasticity of soil, sliding of pile cap and rocking of pile foundation system (Pender et al. 2012; Taciroglu et al. 2006). However, the ability of this method for modelling the superstructure is not adequate and there is no capability of simulating structural elements to monitor soil-structure-interaction effects. This method divides the system area in two different domains: near-field and far-field. The decomposition of the far-field and near-field domains allow efficient frequency-domain methods to be employed in the far field and superstructure analyses with nonlinear effects in the near-field domain. To explore behavior of near-field and far-field domains, implementation of additional series of parametric finite element simulations would be necessary (Li et al. 2016c).

This macro-element method was extended for SSPSI effects in liquefiable soil (Varun 2010) and was used for a parametric investigation on SSPSI effects. The lateral reaction p_d, was resulting from the viscoplastic dashpot as Eq.4:

$$p_d = c\frac{\partial u}{\partial t}\left[a + (1-a)\frac{\partial \zeta}{\partial u}\right]^{c_d} \quad [4]$$

'c' is the dashpot coefficient at small amplitude motions, 'c_d' is a viscoplastic parameter which controls the coupling of soil and soil-pile interface nonlinearity with radiation damping, ζ is a hysteretic dimensionless quantity. Generally, macro-element method simplifies SSPSI assessment by acceptable accuracy and substantially reduces computational effort compared with FEM, though the abilities for structural assessment of superstructures under SSPSI effects is too limited.

2.3. EXPERIMENTAL PROGRAMS

Physical models for computation of SSPSI effects are limited to shaking table and centrifuge tests. Each of these experiments has some benefits and drawbacks, while each system is required to calibrate for different test conditions. Force and displacement controlled conditions have provided a unique opportunity for researchers to have an accurate view of complex SSPSI phenomenon.

Implementation of dynamic centrifuge modelling for understanding SSPSI effects includes several benefits. One of them is about seismic response monitoring of the soil, pile foundation, and structure, simultaneously. Moreover, different centrifugal accelerations ranging from 20g to 100g helps researchers to preserve confining pressure for the soil. In other words, the accuracy of stress-strain relationship in centrifuge test compares with that of the prototype. Dynamic centrifuge model tests of structures with pile foundations were carried out for soft soils by (Boulanger et al. 1999; Wang et al. 1998) that had a good agreement with analytical method. (Hussien et al. 2016) implemented dynamic centrifuge test for seven models with acceleration equal to 40g and their results show pile-head is under two main frequencies.

Shaking table tests were used for dynamic analysis of structures and geotechnical earthquake engineering during the past several years. Shaking table tests can create arbitrary ground motions for different geotechnical and structural systems. These tests have been used as 1g modelling, in which the gravity acceleration for test and prototype are the same. Although this test lacks accuracy for modelling confining pressure on different types of soil, it is comparatively easy and low cost for a complex system. A multi direction shaking table test was performed on a large shake table (6.1 m x 6.1 m) for a single pile with a wide variety of inertial forces to examine both types of interactions (Meymand 1998) and scale modelling was applied by parametric analysis techniques. Shaking table tests were developed for a single-storey steel structure of weight 2.5 ton that was located on a pile cap, which is connected to a pile group (Chau et al. 2009). In this study, pounding action between soil and pile interface was addressed to better understanding of the main reason of large responses in the pile cap. A series of shaking table tests conducted for different type of the foundations under mid-rise building to investigate flexible base effects (Hokmabadi et al. 2014).

3. TYPES OF PILES: INCLINED VERSUS VERTICAL

Batter or inclined piles have been applied for piers of bridges, tall buildings and other superstructures for a long time without observing the benefits and drawbacks. The main advantage of a batter pile is that it has the ability to transfer lateral dynamic loads in axial direction as well as in other directions. In other words, it is possible for such piles to transfer axial compression loads, shear forces and bending moments. Consequently, batter piles provide larger stiffness rather than vertical piles with the same properties.

Using batter piles is always a controversial problem for civil engineers and researchers during the recent years. Some numerical studies highlighted their beneficial roles (Gerolymos et al. 2008; Giannakou et al. 2010); while other research outcomes indicated that vertical piles should be preferred to batter piles for sensitive cases due to soil movements and massive loads on pile caps (Poulos 2006).

The seismic response of a structure assuming linear behavior can be improved in many aspects in the batter pile-supported structure. For tall slender structures on a symmetric batter pile group, not only there is a large lateral stiffness for foundation, but also the most satisfactory performance was observed for structures. It should be noted that the purely kinematic response of batter piles caused larger bending moments for batter piles rather than vertical piles while, the total kinematic and inertial response of structural systems founded on groups of batter piles would consider many reasons for optimism (Gerolymos et al. 2008; Giannakou et al. 2010). (Ghasemzadeh and Alibeikloo 2011) presented an analytical Winkler-based model to investigate SSPSI effects for batter floating piles with linear behavior assumption for soil and piles. The implementation of coupling numerical methods are alternative solutions to derive on damping and stiffness functions for batter piles. (Padrón et al. 2012; Padrón et al. 2010) presented a FEM-BEM numerical method to investigate on impedance functions for single and group batter pile (Figure 5). The results have shown that the axial stiffness of a pile is much higher than its transversal stiffness (relative to the pile axis) leads to the horizontal impedance of an batter pile increases with the inclination angle due to the combination of axial and flexural stiffness to withstand horizontal loads. In addition, the rocking impedance of a single pile is independent of the inclination angle.

(Li et al. 2016a, b) presented databases for understanding of batter piles behavior under seismic and harmonic loads. The effects of height of superstructure and input ground motion were investigated by dynamic centrifuge tests. The variation of residual moments, displacements and other damage parameters in the batter piles were analyzed and compared with similar vertical piles. A height increase in the superstructure's center of gravity (C.G.), makes SSPSI effects more critical for both batter and vertical configurations but it is more noticeable for the first one.

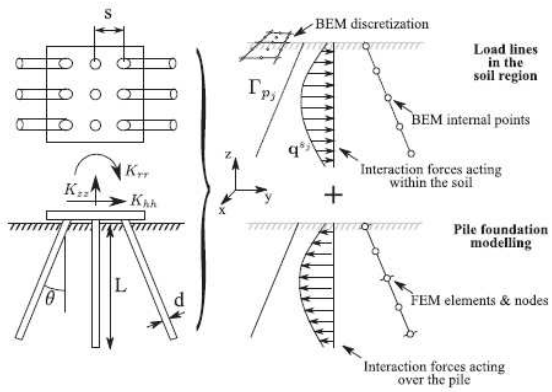


Figure 5. Batter pile modelling through BEM–FEM coupling formulation (Padrón et al. 2010)

4. CONCLUSION

A brief review of the Seismic Soil-Pile-Superstructure Interaction (SSPSI) effects and investigation methods for batter and vertical piles is presented in this paper that is summarized in the following:

- Regarding to pre-defined nonlinear specifications for assumed spring and damping in the soil and their variation versus shear modulus, the accuracy of the output obtained from nonlinear Winkler methods is varied. In p-y methods, the overall kinematic response in soil-pile systems is significantly influenced by the defined nonlinear dashpots and springs for soil and soil-pile gap interface that are system-dependent in details. Although nonlinear p-y application for pile group without any need to time-consuming numerical efforts and computations would be a unique feature, its implementation in a complex system including soil, superstructure and pile foundation has some limitations and difficulties. In other words, modifying the constitute law according to the nonlinear p-y model for applying to numerical purposes such as FEM leads to more realistic outcomes. A versatile numerical or analytical method for SSPSI not only must be detailed enough to consider soil nonlinearity but also should be capable of computing inertial interaction between superstructure and pile–foundation.

- Experimental studies to explore SSPSI effects are the most reliable techniques in this field, particularly in the case of centrifuge tests, in which results are more accurate than shaking table test generally. However, previous studies show that there is a good agreement between numerical methods' results considering elastic behavior assumptions for soil-pile system and shaking table test's results.

- There is no doubt that characteristics of superstructure and structural elements have inevitable role to either amplify or decrease inertial interaction effects and consequently overall dynamic responses of system. Due to shortcomings of macro-element or other simplified methods to explain the influence of structural elements and superstructures behavior in SSPSI in details, FEM are still the more practical method to explore the influence of structural elements in nonlinear SSPSI. In addition, the macro-element method has not been introduced in commercial codes yet and its use is limited.

- The behavior of pile foundations is problematical when subjected to faulting-induced deformation. The severe damages in piles caused by bedrock fault movement have been reported after catastrophic earthquakes, thus a comprehensive investigation on fault movement and fault rupture effects on kinematic interaction for pile-soil system is essential.

- After some failures for batter piles, several seismic codes recommend avoiding the use of batter piles, specifically for high-risk earthquake areas. Due to complicities in behavior of batter piles under seismic loads, all researches in batter using different inclination angles have been performed in elastic domain for both soil and piles. However, recent researches show that pile inclination has some benefits to overall dynamic responses of soil-foundation-superstructure system and advanced inelastic models are required to be considered in future investigations.

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