Title	Dynamic Frequency-Dependent Soil-Pile-Structure Interactions in Damage-Controlled Bridge Piers with Different Foundation Systems and Their Incorporation into a Response Displacement-Based Seismic Design Framework
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Dynamic Frequency-Dependent Soil-Pile-Structure Interactions in Damage-Controlled Bridge Piers with Different Foundation Systems and Their Incorporation into a Response Displacement-Based Seismic Design Framework

(異なる基礎形式を有する損傷制御型橋脚における周波数依存的な地盤-杭-構造物動的相互作用の解明と応答変位法に基づく耐震設計フレームワークへの拡張)

With bridge piers serving as key structural members responsible for safely transferring superstructure loads to the foundation, minimizing seismic damage is of paramount importance. This study proposes a smart bridge pier composed of four steel pipes interconnected by shear links arranged at multiple levels along the pier height. The steel pipes primarily carry vertical loads, while the shear links dissipate seismic energy through hysteretic behavior based on a damage-control design concept. Two foundation systems are considered: (i) a conventional pile group with a footing (F-type), and (ii) a directly connected steel pipe–pile system (S-type) incorporating underground beams at the pile head. Shaking table tests at a 1:20 scale were previously conducted for both systems embedded in dry (D-ground) and liquefiable (L-ground) soils, referred to as D-F, D-S, L-F, and L-S cases.

In this study, a three-dimensional elastoplastic finite element analysis is performed to reproduce the experimental results. The steel pipe columns and underground beams are modeled using bilinear beam elements, while the shear panels are represented by bilinear beam elements combined with central spring elements. Piles and their interaction with the surrounding ground are modeled using hybrid elements consisting of beam and solid components. The Cyclic Mobility model, incorporating subloading and superloading concepts, is adopted as the constitutive law for both dry and liquefiable soils, with parameters derived from triaxial and isotropic consolidation tests. A half-model is employed considering symmetry in geometry and loading, and boundary conditions are set to replicate experimental conditions before being extended for parametric analyses.

The numerical results show good agreement with experimental observations in terms of the relationship between inertial force and pier-top displacement, as well as shear panel behavior prior to yielding. Although some discrepancies appear in the post-yield range, such as wider hysteresis loops and deviations in initial stiffness, particularly for the S-type system. However, overall trends, including peak responses and deformation patterns along the piles, are well captured. Notably, at an excitation frequency of 2 Hz, the S-type system exhibits smaller responses than the F-type system, confirming its structural advantage. However, parametric analyses over a wide frequency range reveal that this advantage depends on frequency, with the S-type showing larger responses at lower frequencies due to resonance effects.

To further clarify the underlying mechanisms, the study examines soil–structure interaction by separating inertial and kinematic components through additional analytical configurations. Specifically, the superstructure is removed to isolate pure kinematic interaction, while the soil is removed to isolate pure inertial interaction from the original D-F configuration. A phase-difference-based approach is then introduced. In this approach, the phase of the pile response in the D-F system is compared with a reference phase derived from the inertial-only configuration, defined by the relationship between pile response and superstructure inertia. Likewise, the phase relationship between pile response and soil motion is compared with that from the pure kinematic configuration. The dominant interaction mechanism is identified based on the degree of agreement between the pile response phase and each reference state. The results indicate a transition from inertial-dominated behavior at lower frequencies (around 2 Hz) to kinematic-dominated behavior at higher frequencies. Furthermore, comparison of pile-head earth pressure with inertial force reveals an increasing contribution of earth pressure with increasing input frequency, accompanied by a shift in its directional relationship—from being aligned with inertial force to opposing it—particularly in F-type configurations. Pile moment distributions also show that, although each interaction mechanism can independently generate significant demand, their combined effect may reduce the overall response due to phase differences.

Based on these findings, a simplified static analysis framework is proposed by extending the Japanese railway design method. The framework incorporates both inertial and kinematic effects through interaction factors, while accounting for phase differences and soil nonlinearity. At lower frequencies, an inertia-dominated load combination, acting in a direction consistent with kinematic effects, successfully reproduces the dynamic analysis results in terms of pile–pier deformation and bending moments. In contrast, at higher frequencies, the kinematic-dominated load combination specified in the conventional design method tends to yield overly conservative estimates. To address this issue, refined kinematic interaction factors are proposed for such cases. The framework is further extended to liquefiable soils by incorporating stiffness degradation associated with excess pore water pressure. Moreover, the method can be applied to S-type configurations through appropriate calibration of the kinematic interaction factors.

Overall, this study establishes a validated numerical simulation framework and provides new insight into soil-pile-structure interaction under dynamic loading. It also offers a rational basis for improving simplified seismic design methods for pile-supported bridge piers, particularly in capturing the coupled effects of inertial and kinematic interactions.