EFFECTS OF NONLINEAR SOIL-STRUCTURE INTERACTION ON THE INELASTIC SEISMIC DEMAND OF PILE-SUPPORTED BRIDGE PIERS

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ABSTRACT:

The significance of the effects of soil-structure interaction (SSI) on the seismic performance of structures is not yet clearly understood. This is attributed to the complex nonlinear nature of SSI and the lack of sufficient statistical description of its effects on the seismic response of structures. In this regard, this paper presents a study on the effects of nonlinear SSI on the inelastic seismic demand of bridge piers by comparing the flexible-base and fixed-base seismic demands of prototype pile-supported bridge piers. The prototype system comprised a common highway bridge pier supported on a pile group. The height of the pier and the thickness of the site soil layer were varied to provide first mode fixed-base structural periods of 0.3 to 2.0 s and first mode site periods (at low amplitude of motion) of 0.6, 1.0 and 2.0 s. An ensemble of 26 ground motions recorded on rock or stiff soil was selected and applied at the bottom of the soil layers. The numerical models for nonlinear dynamic analyses included the site soil, the foundation and the pier, and were developed with the commercial finite difference program FLAC. This paper discusses the effects of SSI on ductility and total displacement demands of the piers. It also investigates the accuracy of the nonlinear static pushover analysis for demand estimation of pile-supported bridge piers. It was observed that where SSI is significant, pushover analysis may overestimate the base shear of the piers and the global ductility factor may overestimate their ductility demand.

KEYWORD: Soil-Structure Interaction, Inelastic Seismic Demand, Nonlinear Dynamic Analysis, Pushover Analysis, Bridge Piers, Pile Foundation

1. INTRODUCTION

The estimation of seismic demand involves many challenges, one of which is the evaluation of the effects of seismic soil-structure interaction (SSI) on the inelastic response of structures. Seismic SSI is potentially a highly nonlinear phenomenon, which causes the structural response to differ from that of the ideal structure with a rigid base. SSI may particularly play a significant role in the response of bridge structures due to their relatively simple structural form and the low degree of redundancy of these structures that make them sensitive to the effects of SSI and SSI-induced displacements. SSI may cause large differential displacements of the piers. This can be detrimental to displacement-sensitive components of bridges, such as bearing seats, restrainers, or expansion joints, and may compromise the bridge's structural integrity or damage non-structural elements such as pipe, electrical, and telephone lines. SSI may also affect the ductility demands of the bridge piers. The effect on the ductility demand is commonly assumed to benefit the structure due to additional damping introduced by SSI. However, it has been shown that this does not always hold true and depending on the SSI system properties (i.e., elongated period) and the spectral characteristics of the ground motions passed through soil layers, SSI may result in increased ductility demand (e.g., Mylonakis and Gazetas, 2000).

There is wealth of research on several aspects of seismic SSI, but they have largely been component-oriented and focused on the evaluation of the complex soil-foundation interaction in response to earthquake loading, with less attention on the effects of this interaction on the overall system response. On the other hand, researchers that have dealt with the effects of SSI on the overall system response provide limited statistics on the effects of SSI on the structural response and have dealt with complexities in different ways (e.g. Ciampoli and Pinto 1995, Martin and Lam, 2000; Hutchinson et al., 2004). Therefore, there is a need for further statistics of the effects of nonlinear SSI on the inelastic seismic response of structures which account for various complexities of SSI. In this regard, this paper presents a study on the effects of nonlinear SSI on the ductility and displacement demand of bridge piers through constructing response databases of prototype soil-foundation-structure systems subjected to strong ground motions, with and without accounting for SSI. It also explores the accuracy of nonlinear static pushover analysis in predicting the seismic demands on SSI systems through studying the prototype systems.

2. PROTOTYPE BRIDGE PIER-FOUNDATION-SOIL SYSTEMS

A typical pile-supported highway bridge pier was considered for this work. The height of the pier and the thickness of the site soil layer were varied to provide first mode fixed-base structural periods of 0.3, 0.6, 0.8, 1.0, 1.5 and 2.0 s and first mode site periods (at low amplitude of motion) of 0.6, 1.0 and 2.0 s. The soil consisted of saturated soft clay with average shear wave velocity in the upper 30 m of V_{s30} = 145 m/s and average strength (upper 30 m) of S_{u30} = 40 kPa. The foundation consisted of a 6×6 pile group with 0.3 m square piles spaced at 1.25 m and driven to a depth of 15 m below the 7.5×7.5×1.5 m pile cap. The pier had a typical cross section of 1.5 m in diameter with 1% of longitudinal reinforcement. A 3500 kN gravity load was applied at the top of the piers to represent the weight of the bridge's superstructure.

3. INPUT GROUND MOTIONS

An ensemble of 26 ground motion time-histories was selected from historic ground motions recorded on rock or very stiff soil to represent moderate to severe ground shaking with different time and frequency characteristics. The selected records have a mean acceleration response spectrum that is comparable with the design response spectra proposed by the Canadian Highway Bridge Design Code (CAN/CSA-S6-00, 2000) for Zonal Acceleration Ratio (A) of 0.2 and 0.3, representing, respectively, the seismic hazard of the cities of Vancouver and Victoria in the Province of British Columbia, Canada. The selected ground motions are from earthquakes with magnitudes of 5.8 to 7.6 recorded at distances from 8.0 to 48.8 km with peak ground acceleration (PGA) ranging from 0.080g to 0.587g (g is the acceleration of gravity). Peak ground velocities are from 2.9 cm/s to 62.0 cm/s and peak ground displacements are from 0.2 cm to 51.8 cm. To avoid uncertainties introduced by the scaling of ground motions, the records were not scaled or further processed. All records were taken from the Pacific Earthquake Engineering Research (PEER) Center's strong motion database (http://peer.berkeley.edu/smcat/). Details of the selection of ground motions can be found in Ghalibafian (2006).

4. NONLINEAR DYNAMIC ANALYSIS AND VERIFICATION PROCEDURE

State-of-the-art nonlinear dynamic analyses were carried out using the commercial finite difference program FLAC (Itasca, 2005). The numerical model included the soil, the foundation, and the bridge pier as shown in Figure 1. The soil material was defined by an elasto-plastic Mohr-Coulomb constitutive model. The nonlinear hysteretic behaviour of the soil prior to yield was based on well-known modulus reduction curves and was modeled using the hysteretic damping of FLAC. Additional Rayleigh stiffness damping was added to compensate for the low damping demonstrated by the program at small strains. Non-reflecting boundaries were used for the soil, and the input motion was applied at the bottom of the soil layer.

Piles were modeled with pile elements that interact with the surrounding soil through a series of normal and shear coupling springs. These springs are elasto-plastic with stress-dependent yield strength. In clayey soils, the yield strength of the shear coupling springs depends on the cohesive strength. The limiting force of the normal spring simulates the three-dimensional effect of the pile pushing through the soil (gapping accounted for) and is a function of the cohesive strength and the stress-dependent frictional resistance between the pile and the soil. In the absence of test results, the behaviour of the pushing pile can be evaluated by modeling sections of the pile at various elevations in the soil, the results of which can be used to calibrate the normal springs. This calibration can be further verified against available data in the literature. The pile cap was modeled using plane strain elements with concrete properties. These elements interact with the surrounding soil elements through interface elements made of a series of normal and shear springs that connect the opposing surfaces at the interacting nodes. The bridge piers were modeled using beam elements. Both material and geometric nonlinearities were considered. The material nonlinearity included the flexural yielding and the hysteretic behaviour of the plastic hinges of the piers, and the geometric nonlinearity included the P-Δ effect. Consideration of shear failure was outside the scope of this work. Approximation was required for modeling of structural elements along with two-dimensional plane strain soil elements to account for the appropriate width of soil that interacts with each structural element in the out-of-plane direction of the model. The approximation was done by property scaling as explained in Itasca (2005) and Ghalibafian (2006).

The verification of the numerical analysis was performed at both component and system levels. At the component level, the behaviour of each component, modeled individually, was compared against the expected behaviour from the available literature, or against the behaviour predicted by other validated analysis methods. To verify the overall system behaviour, an instrumented bridge pier in California that was subjected to an actual earthquake (Shakal et al., 1989) was modeled and the computed response was compared with the recorded response. The results obtained were plausible and verified the analysis procedure. Details of the verification study can be found in Ghalibafian (2006) and Ghalibafian et al. (2006b).

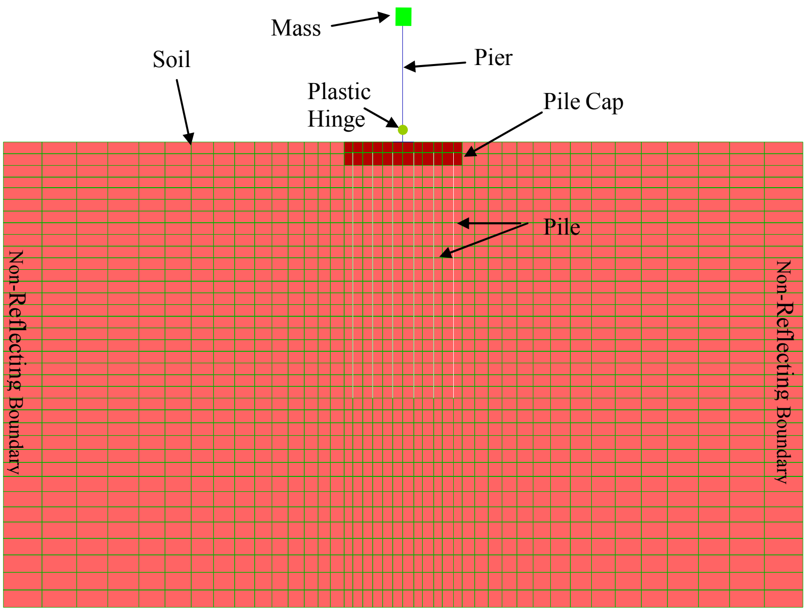


Figure 1: Geometry of the FLAC model (top 30 m of soil)

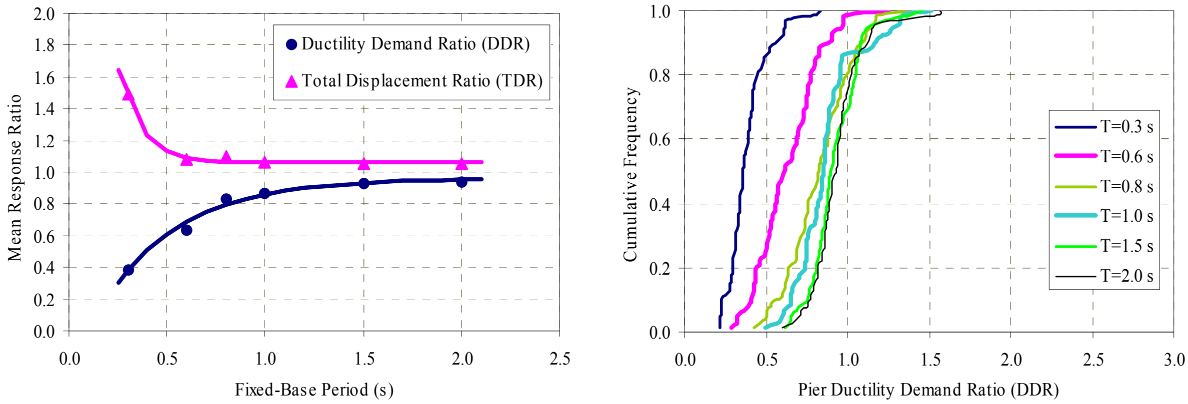
To analyze the prototype systems, first, site response analyses were performed by analyzing columns of the soil to obtain the free field motions. The free field motions were then used as the input motions for the analysis of the fixed-base piers. Finally, the analysis of the soil-foundation-structure systems was performed for the 3 soil layers, 6 bridge piers and 26 input ground motions. Various seismic demands were extracted, including the ductility and displacement demands of the piers from both flexible-base and fixed-base analyses. The ductility demand is the ratio of the maximum inelastic deformation of the pier to its yield deformation, both measured with respect to the pier's base. The total displacement is the sum of the displacement of the top of the pier with respect to its base plus the pier's displacements due to translation and rotation of foundation (zero when fixed-base).

5. EFFECTS OF SSI ON DUCTILITY AND DISPLACEMENT DEMANDS

The effects of SSI are presented by Ductility Demand Ratio (DDR) and Total Displacement Ratio (TDR), which are ratios that demonstrate when SSI is significant and show how the pier's response without SSI is different than the response when the effects of SSI are accounted for. DDR is the ratio of the bridge pier's ductility demand when SSI is included (flexible-base) to that when SSI is not included (fixed-base). It indicates whether SSI reduces or amplifies the ductility demand of the structure. If DDR<1.0, then SSI is reducing the ductility demand, but if DDR>1.0, then SSI is amplifying the response. The importance of this consideration is that SSI in general is assumed to reduce the ductility demand of the structure and therefore ignoring SSI is usually assumed to be a conservative assumption. However, this may not hold true and SSI may have an adverse effect on the ductility demand of bridge piers as discussed by other researchers such as Mylonakis and Gazetas (2000). TDR is the ratio of the total displacement with SSI to that without SSI (flexible-base to fixed-base total displacement ratio). TDR is of importance for bridge structures as it indicates the effects of SSI on the relative displacement of the bridge piers. This has design implications for deck-to-pier connections such as deck support length or restrainers. The ductility and displacement demands needed to estimate DDR and TDR are obtained from the nonlinear dynamic analyses of prototype systems. DDR and TDR are presented here as functions of the fixed-base natural period of the piers, a format commonly used in structural engineering. Results may also be presented as functions of the ratio of the flexible-base natural period to the fixed-base natural period (T_{sys}/T), which is a system parameter correlated with the pier-to-foundation stiffness ratio (Finn, 2004). Such presentation of results and its merits are not discussed in this paper, but can be found in Ghalibafian (2006) and in the companion paper Ghalibafian et al. (2008).

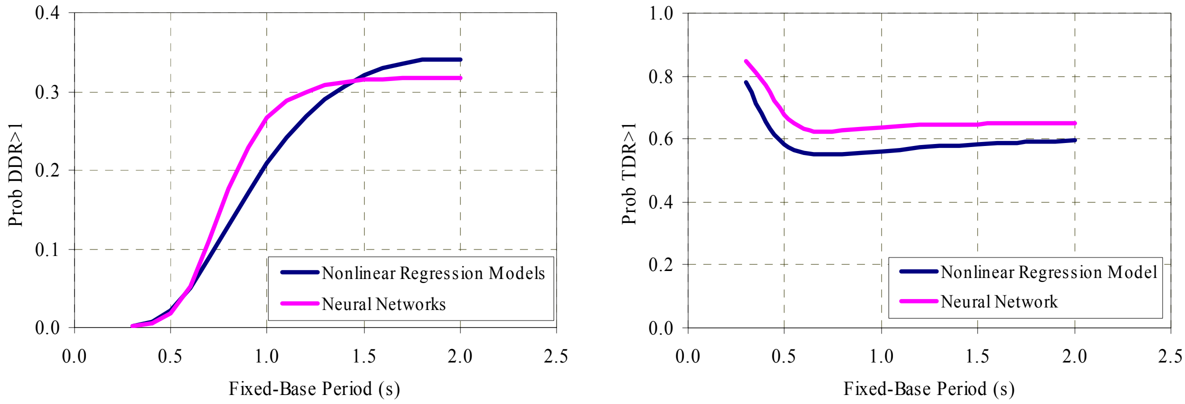
The mean values of DDR and TDR are plotted in Figure 2a as functions of the piers' fixed-base natural period. Figure 2a shows that SSI becomes more effective with decreasing period. It also shows that SSI decreases the ductility demands at the expense of increasing total displacement demands. However, a look at the cumulative frequency distribution of DDR at each period, depicted in Figure 2b, reveals that SSI does not always reduce the ductility demand and, on the contrary, may increase it (where DDR>1.0). This confirms the previous findings with regard to the adverse effects of SSI on ductility demand. To better explore this observation, results were processed probabilistically by performing reliability analyses to estimate the probability of DDR>1.0 and TDR>1.0. The reliability analyses were performed using the general reliability analysis program RELAN (Foschi et al., 2000). The analyses account for the scatter of DDR and TDR by using the databases developed for their means and standard deviations. The input random variables include the natural period of the fixed-base structure with a coefficient of variation (COV) of 0.1. The reliability analyses were performed using a Montecarlo simulation that uses response surfaces for the mean and standard deviation, both represented by either nonlinear regression models or neural networks. Results are presented here for both nonlinear regression fit and neural network representation of the response surfaces (Figure 3). Details of the reliability analysis can be found in Ghalibafian (2006) and Ghalibafian et al. (2006a). It is noted that the probabilities here are not total probabilities as they are conditional on the occurrence of the ground motions used in this study. Calculation of total probabilities requires estimation of the probability of occurrence of the input ground motions which is outside the scope of this work. It is also pointed out that the probabilities obtained for DDR from Figure 2b only account for the scatter of the response statistics, whereas the probabilities obtained from Figure 3a represent the joint consideration of the scatter of the response statistics and the uncertainty in the natural periods (COV of 0.1).

Figure 3a shows the probability of DDR>1.0 as a function of the fixed-base natural period. This figure shows that the probability of SSI amplifying the ductility demand of the structure is increased with increasing period of the structure. This is because SSI plays a lesser role in dissipating energy as the pier-to-foundation stiffness ratio is decreased. Therefore, since the spectral values of the ground motions might be higher at the elongated system period, and since the SSI energy dissipation is less, there is a greater probability for the SSI system to experience seismic demands greater than that of the fixed-base structure at longer periods. Figure 3b presents the probability of SSI increasing the total displacement demand of the pier. It can be seen that this probability is greater for stiffer structures with shorter periods for which the effects of SSI are more pronounced. It can also be observed that there is at least about 60% chance of greater total displacement demands of the pile-supported bridge pier (compared to the fixed-base pier) which warrants necessary attention to the design of the deck-to-pier connections when SSI is involved.



(a) (b)

Figure 2: (a) Mean response ratios DDR and TDR; (b) Distributions of pier Ductility Demand Ratios (DDR)



(a) (b)

Figure 3: (a) Probability of DDR>1.0; (b) Probability of TDR>1.0 as functions of the fixed-base period

6. EVALUATION OF NONLINEAR STATIC PUSHOVER ANALYSIS

Nonlinear static pushover analysis is employed for both demand and capacity estimation of structural systems. For demand estimation, pushover analysis is performed to determine the distribution of the inelastic deformations and forces between various components of the system by gradually pushing the structure to an estimated target displacement. For capacity estimation, pushover analysis is performed to push the structure to large nonlinear deformations so that the global capacity parameters of the system, such as the global yield displacement, can be determined. Predictions of demand and capacity by pushover analysis are accurate when the system can be reliably replaced by a single degree of freedom (SDOF) system, otherwise, results obtained from pushover analysis might not be reliable. Since pile-supported bridge piers are not well-represented by an SDOF system when SSI is significant, the accuracy of pushover analysis for demand estimation is investigated by comparing demands obtained from nonlinear dynamic analysis and pushover analysis. Since capacities estimated by pushover are used in global ductility demand estimation, the accuracy of capacity estimation by pushover analysis is also studied. The pushover analysis was performed in the FLAC model by applying a very low amplitude constant velocity (1e-6 m/s) horizontally at the centre of mass at the top of the pier.

6.1. Base shear demand

Figure 4 shows a comparison of the force-displacement curve obtained from the pushover analysis with the data points extracted from the nonlinear dynamic analyses of the piers with fixed-base periods of 0.3 s and 0.6 s. The displacements in these figures are the total displacements (i.e. global displacements) of the piers and are normalized with respect to the height of the piers. It is reminded that the total displacement is the sum of the pier's displacement with respect to its base (i.e., pier's deformation) plus the displacements induced by foundation translation and rotation. For the pier with T = 0.3 s, Figure 4a shows that for target displacements greater than about 0.4% of the piers' height, the shear forces predicted by the dynamic analysis are less than those of the pushover curve. This is due to greater predicted foundation displacements when the system is analysed dynamically as opposed to when it is analysed statically by pushover analysis. Hence, the pushover analysis predicts greater contribution of the pier's deformation to the total displacement which results in a greater predicted shear force for a given target displacement. The same difference can be observed for the pier with T = 0.6 s (Figure 4b), but with less deviation between the results obtained from pushover and dynamic analyses. For piers with periods greater than 0.6 s, plausible predictions were made by the pushover analyses (Ghalibafian, 2006). Thus, it is concluded that as SSI becomes more effective with decreasing natural period of the pier, the predictions of pushover analysis becomes less accurate as it cannot properly account for the dynamic SSI when the interaction is significant.

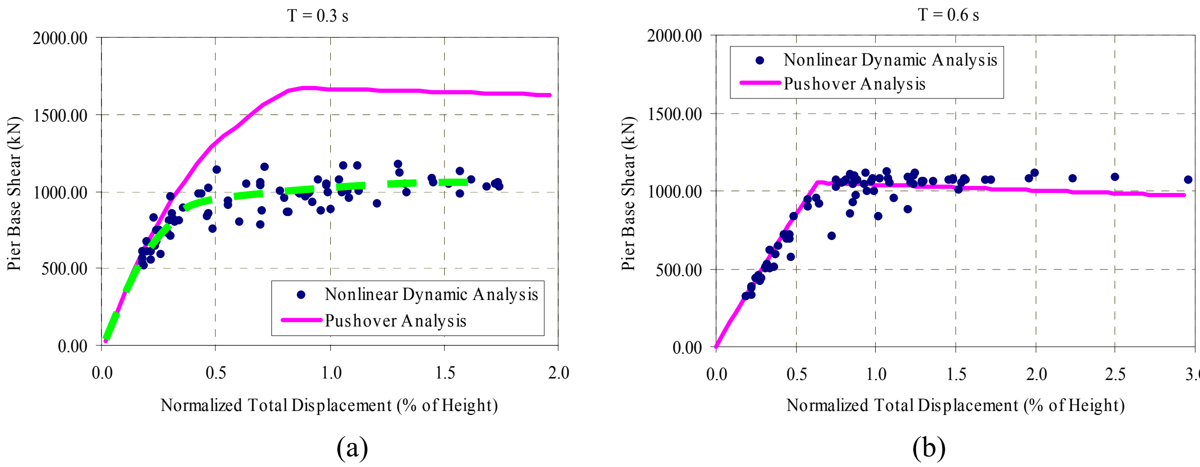


Figure 4: Comparison of the force-displacement relationships (including SSI) obtained from pushover and nonlinear dynamic analyses of the piers with (a) T = 0.3 s and (b) T = 0.6 s

6.2. Global ductility demand

Global ductility factor is a convenient demand parameter that is commonly used to measure the inelastic response of bridge piers. Estimation of the global ductility factor requires estimation of the total displacement demands (i.e., global displacement) of the system as well as the system yield displacement (i.e., global yield displacement) which could be estimated by performing pushover analysis. The objective here is to examine the accuracy of the global ductility factor in predicting the inelastic response of piers by using global yield displacements obtained from pushover analyses. For this purpose, the total displacements obtained from nonlinear dynamic analyses were used with the system yield displacements obtained from pushover analysis to estimated global ductility factors. Then, the ratio of the global ductility factor to local ductility factor obtained from dynamic analyses was calculated. The mean values of these global-to-local ductility ratios are plotted in Figure 5a. This figure shows that the predicted global ductility demands were greater than their corresponding local ductility demands, especially for the piers with periods of less than 1.0 s. This is an important observation because global ductility factors are expected to be less than their corresponding local ductility factors (for local ductility factors greater than 1.0) since they are computed by adding foundation-induced displacements to both numerator and denominator of the equation for the local ductility factor.

The reason for the overestimation of ductility by global ductility factor is because it employs the total displacement of the system, which includes the rigid body motion of the pier due to translation and rotation of foundation. Thus, since the total displacement of the system is not necessarily representative of the pier deformation, significant discrepancies between global and local ductility demands might be observed when SSI is significant. To further explain this reasoning, the pier deformations are plotted against total displacements of the system, both obtained from the dynamic analyses. This plot is shown in Figure 5b for the piers with T = 0.3 s. The onset of the yielding of the piers and the onset of the yielding of the soil-foundation-pier systems, as predicted by the pushover analysis, are also shown in Figure 5b. The onset of the yielding of the pier is identified by $\mu_{local} > 1.0$ and the onset of the yielding of the soil-foundation-pier system is identified by $\mu_{global} > 1.0$. Figure 5b clearly shows that pushover analysis may predict yielding of the pier while dynamic analysis predicts no yielding of the pier, even at large total displacements. This is the reason why the global ductility factor, in this case, indicates yielding of the pier while local ductility factor indicates no yielding. Therefore, in such cases, the global ductility factor can be a misleading indicator of the inelastic response of the pier. Figure 5b shows a case for which global ductility demand is greater than 1.0 while the local ductility demand is less than 1.0 with no yielding of the pier. In general, Figure 5b demonstrates the shortcoming of the pushover analysis in accurate prediction of the relative contribution of the pier and the foundation to the total displacements of the soil-foundation-pier system when SSI is significant.

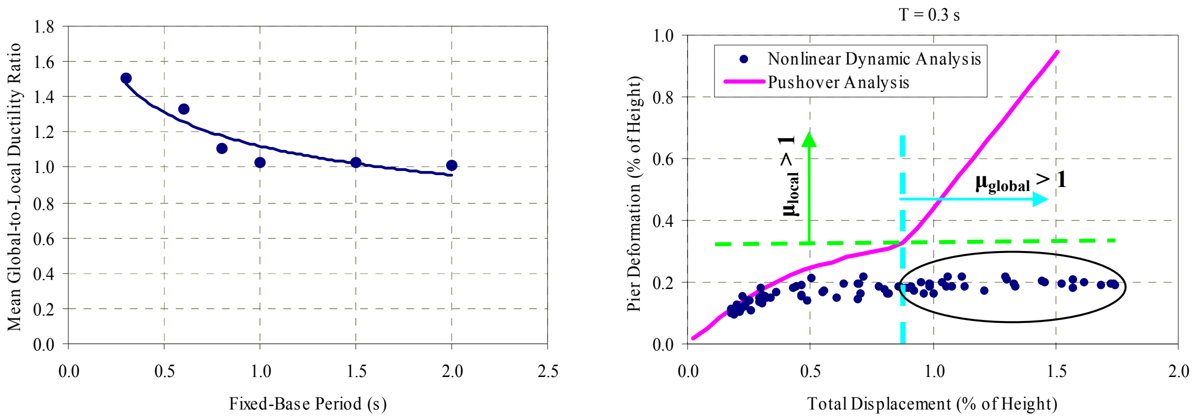


Figure 5: (a) Mean ratio of the global ductility to the local ductility factors; (b) Pier deformations vs. total displacements: comparison of results from pushover and nonlinear dynamic analyses of piers with T = 0.3 s

7. CONCLUDING REMARKS

Response databases of prototype soil-foundation-structure systems were constructed for a range of structure's period and varying soil layer thickness subjected to an ensemble of input rock motions. The data was generated by performing nonlinear dynamic analyses of both flexible-base (with SSI) and fixed-base structures (without SSI). The input ground motions for the fixed-base structure were the free field motions obtained from site response analyses. Comparison of flexible-base and fixed-base responses provided insight into the importance and the effects of SSI on the response of structures of which the effects on the ductility and total displacement demands were presented as functions of the structure's natural period. Results of the nonlinear dynamic analysis were also used to check the accuracy of the seismic demands estimated using pushover analysis. It was observed that pushover analysis might not properly capture the dynamic soil-structure interaction when the interaction is significant and may predict greater contribution of the deformation of the pier to the total displacements when compared to that predicted by the dynamic analysis. In such cases, pushover analysis overestimates the base shear of the piers and the global ductility factor overestimates their ductility demand.

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