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Liquefaction Effects on Lateral Pile Behavior for Bridges

Wei Zheng[1] and Ronaldo Luna[2]

Abstract

A coupled pile-soil-structure interaction (SPSI) analysis method is presented to study the liquefaction effects on lateral pile behavior of the highway bridges. Pile-soil interaction is simulated by the dynamic nonlinear p-y method including the effect of gap, soil nonlinearity, and liquefaction. The liquefaction effects to the pile-soil interaction are taken into account by introducing a degradation multiplier to the p-y curve. The degradation multiplier is related to the excess pore water pressure buildup at the pile-soil interface. The SPSI analysis method is implemented into a Missouri highway bridge site near the NMSZ rift complex for future earthquake scenarios of M_w 7.0. Synthetic motions at rock base were developed to the bridge foundation level for SPSI analyses. Results from analysis indicate that the degradation of p-y curve due to the excess pore water pressure significantly increases displacement of superstructure and moment of pile foundation.

Key word: SPSI, Liquefaction, Bridge

Introduction

Based on the recent observations of pile performance during earthquakes, a large amount of bridge foundation (pile foundations) damage and failure were observed in the 1964 Alaska, 1964 Niigata, 1989 Loma Prieta, 1995 Kobe and 1999 Chi-Chi earthquakes. These failures have been found on the pile itself primarily due to the loss of lateral soil support and the lateral soil spreading during or after the soil liquefaction. A coupled pile-soil-structure interaction (SPSI) approach is presented to study the liquefaction effect on lateral pile behavior of the highway bridges. The coupled approach can simulate the soil response and the pile-soil interaction simultaneously. The soil response is represented as a free field soil column simulated by the cyclic soil model with a loosely coupled liquefaction model. The pile soil interaction simulation is based on the dynamic p-y element, which uses a degradation multiplier for the liquefaction effects. The SPSI analysis method was coded as new elements

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into the existing finite element code in OpenSees (http://opensees.berkeley.edu/). Then it was evaluated against the results the dynamic centrifuge tests. Reasonably good agreement was obtained between the calculated and recorded response.

Finally, the approach is implemented into the SPSI analysis at a Missouri highway bridge site in the New Madrid Seismic Zone (NMSZ). The NMSZ has experienced some of the largest magnitude (estimated 8.0 - 8.3) earthquake events in North American recorded history (1811-1812). Based on the evidences of paleoliquefaction in the NMSZ, similar magnitude earthquakes may strike this region again. Shallow sediments in this area consist of silts, sands and low plastic soil that have high potential for liquefaction. Many of the bridges in the NMSZ have been built without seismic design, some date back to the 1940s. The SPSI approach presented will provide a practical tool to understand the seismic behavior of pile foundation and superstructure and can be used to assess seismic retrofit options. Findings from the numerical analyses and their implication to design practice are discussed.

Coupled SPSI Approach

A coupled SPSI approach is illustrated in Figure 1. The whole system includes the free field soil column, the pile-soil interaction element and the structure components. A single input motion is applied at the base of the whole system. Thus, the response of the foundation soils and the pile-soil-structure system were obtained in a single fully-coupled step.

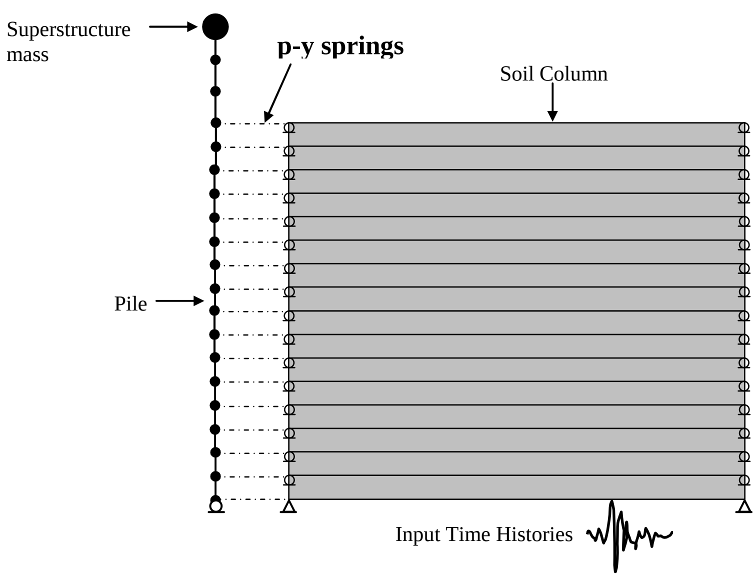

Figure 1. Coupled SPSI Approach

A cyclic soil model has been developed to simulate the free field soil response. The backbone curve of the model is based on the published unified formulas (Ishibashi and Zhang, 1993), which are used to calculate the shear modulus and the damping ratio at different strain levels (Equation 1 and 2).

$$G/G_{\max} = K(\gamma, PI)(\bar{\sigma}_0^{'})^{m(\gamma,PI)} \quad (1)$$

$$\lambda = \frac{0.333(1+\exp(-0.0145PI^{1.3}))}{2}\left\{0.586\left(\frac{G}{G_{\max}}\right)^2 - 1.547\left(\frac{G}{G_{\max}}\right)+1\right\} \quad (2)$$

Where, $G_{\max}$ is the initial shear modulus; γ is the shear strain; λ is the damping ratio; G is the shear modulus at the shear strain γ; PI is the plasticity index of the soil; $\bar{\sigma}_0^{'}$ is the mean effective confining pressure. Based on the plasticity index, K and m are two functions used to control the shape of the shear modulus degradation curve. The advantage of this model is to provide reasonable results with simple inputs $G_{\max}$ and PI (Zheng and Luna, 2004). Those soil properties can be directly measure from the field and lab tests, which is good for engineering practice. A two-parameter pore water pressure generation model, based on widely used Byrne's model (1991), is loosely coupled into the soil model to calculate the excess pore water pressure of each soil element during the earthquake.

The pile-soil interaction element is simulated as the dynamic nonlinear p-y element (Boulanger et al. 1999). In this method, the pile-soil contact is discretized to a number of points where combinations of springs and dashpots represent the pile-soil stiffness and damping at each particular layer. The nonlinear *p-y* behavior is conceptualized as consisting of elastic, plastic, and gap components in series. Radiation damping is modeled by a dashpot in parallel with the elastic component. The gap component consists of a nonlinear closure spring in parallel with a nonlinear drag spring. The effect of liquefaction on the pile-soil interaction is considered as applying a degradation multiplier based on the excess pore water pressure buildup at the pile-soil interface. Based on the centrifuge test results (Liu and Dobry, 1995 and Wilson, 1998), the degradation multiplier is found linearly with the excess pore pressure ratio. The following equations were used to calculate the degradation multiplier for loose and medium dense sands, respectively:

$$Cu = 1 - 0.9r_u \text{ (loose sand)} \quad (3)$$

$$Cu = 1 - 0.65r_u \text{ (medium dense sand)} \quad (4)$$

Where, Cu is the degradation multiplier and r_u is the excess pore pressure ratio. In the numerical simulation, the excess pore pressure ratio of the p-y springs is obtained by averaging the excess pore pressure ratios of the adjacent soil elements.

The pile foundation is modeled as the linear-elastic beam elements with its own mass and the superstructure mass. The whole procedure was coded into the existing finite element code and evaluated against the results of a series of dynamic centrifuge model tests performed in U.C. Davis (Wilson, 1998). The centrifuge tests were simulated by using the same soil profile, pile foundation and earthquake events. The calculated and recorded peak moments and displacements are compared in Figure 2. When comparing several ground motions to the recorded centrifuge, the model predicts better at lower magnitudes and as the deformation increases the predictions are less reliable. The results indicate that the presented numerical approach can provide reasonable good agreement for earthquake events.

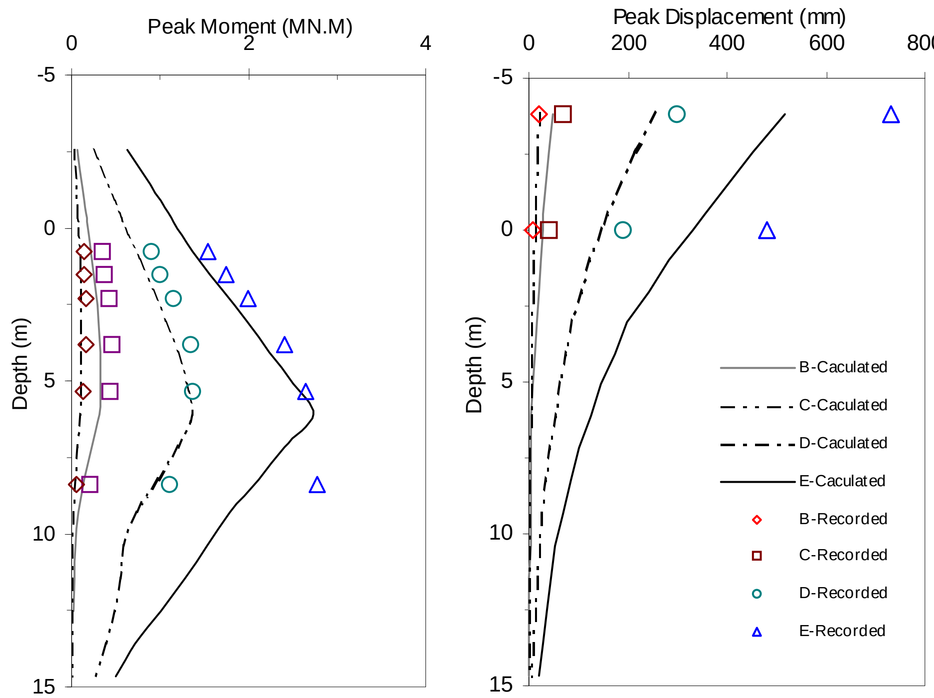

Figure 2. Calculated and Recorded Peak Moments and Displacements

Application in the NMSZ

The presented SPSI analysis approach is applied to an I-55 highway bridge L472 site located in the NMSZ. This bridge was a multi-span simply supported steel girder bridge built in the early 1950s. The superstructure is supported on four intermediate bents and two end abutments through TYPE "C" fixed and expansion steel bearings. Each bent consists of a reinforced concrete cap beam and three reinforced concrete columns. Pile foundations of length 7.62-9.14 m (25-30 ft) support both bents and abutments and are installed in medium dense to dense sand layers. In the simulation, elastic beam elements are used to model the reinforced concrete columns and pile foundation. The mass of the reinforced concrete cap beam is evenly distributed into each column and simulated as a mass point at the top. The pile cap is also simulated as the beam element with the mass of the cap (Figure 3). The pile group effects were taken into account by the concept of *p* multipliers. Due to lack of the strong motion records in the NMSZ, the composite source model program (Zeng at el., 1994) was used to develop the synthetic ground motions at the study site.

The bridge is subjected to a future earthquake event of M_w 7.0 for the preliminary study. The simulations with (analysis #1) and without (analysis #2) the liquefaction effect to the pile-soil interaction are performed for comparison (Figure 4). The comparison indicates that the peak displacements at the pile cap are increased when the liquefaction effect is considered. The significant cycles in the displacement time history also increased due to the softening of the p-y springs, which makes the peak moments increase significantly, especially near the pile cap. Large inertia force and relative displacement are applied to the columns and nonlinear analysis should be considered in the subsequent studies. Preliminary evaluation of the reinforcement details in columns and their connections with cap beams and pile caps indicated that retrofitting is required to ensure that a plastic hinge can be fully developed at the bottom and top of each column. The poor performance reflects the fact that the bridge was designed in compliance with the 1949 AASHO specifications without consideration of earthquake loads.

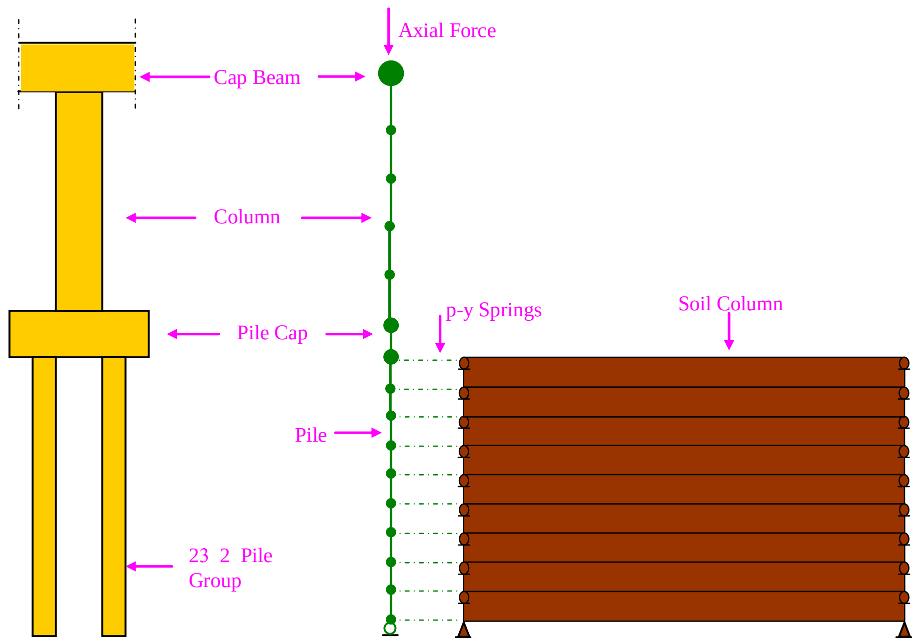

Figure 3. Finite Element Model for the Coupled SPSI Analysis

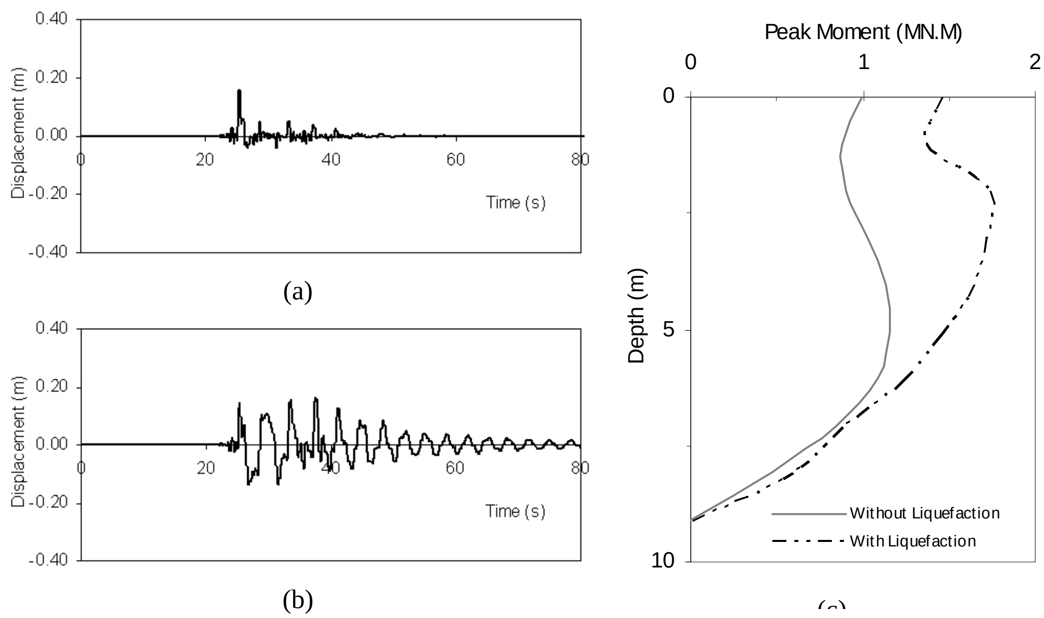

Figure 4. Displacement Time Histories at Pile Cap for (a) Analysis #1 and (b) Analysis #2, and (c) Peak Moment Diagram Comparison.

Conclusion

A coupled SPSI analysis approach is presented to study the liquefaction effect on lateral pile behavior of the highway bridges. The liquefaction effect is considered by applying a degradation multiplier to the p-y element on the basis of the pore water pressure buildup at the pile-soil interface. The SPSI approach is applied to a highway bridge foundation system in the NMSZ. The analysis results indicate that the degradation of soil spring due to the pore water pressure greatly influences the foundation and superstructure response. The results indicate that nonlinear analysis for bridge components should be performed in the future. The bridges, designed in compliance with the 1949 AASHO specifications without seismic consideration, need to be retrofitted at the columns and their connections with the pile caps.

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