DYNAMIC DAMAGE ANALYSIS OF EXTENDED PILES OF BRIDGE STRUCTURES UNDER SEISMIC LOADING

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Abstract

Piles are a type of deep foundations, commonly used in bridge structures. When an earthquake occurs, piles may sustain inertial forces transferred from the structure as well as kinematic loading caused by ground movement. In this study, we perform dynamic analysis to investigate the development of damage of an extended pile of a bridge structure caused by inertial and kinematic ground movement effects during earthquakes. The analysis model combines a structure-pile-soil interaction model and a ground movement model. In the structure-pile-soil interaction model, beam elements are used to simulate the pile, soil springs are used to simulate the soil reaction, and a lumped mass is used to simulate the deck. In the ground movement model, a series of shear springs are used to simulate soil layers at different depths subjected to horizontally upward shear waves. In addition, plastic hinges are placed in the beam elements to simulate the nonlinear flexural behavior of the pile. Through a series of numerical analyses, effects of ground motions of different characteristics, and effects of ground movement and inertial loading on the development of plastic zones in the pile are explored. From this study, the consideration of ground movement appears to increase the inertial forces in the pile and may further increase the range of the plastic zone. The maximum range of the plastic zone occurs when the directions of the inertial and kinematic loading are out of phase. Seismic design for pile foundations only considering inertial loading may be unsafe, and therefore the ground movement effect needs to be included for more rational design.

Keywords: structure-pile-soil interaction; kinematic ground movement; inertial loading; plastic hinges

1. Introduction

Conventional seismic design of pile foundations mainly considers inertial loading from the superstructure. However, according to previous studies [1, 2, 3], in addition to inertial loading, piles may also be subjected to kinematic effect of ground movement, especially for soft ground. Tokimatsu et al. [2] explored the influence of inertial force and ground movement on the pile foundation under the action of seismic force using 1g large shaking table tests. Their study shows that: (1) when the natural period of the superstructure is less than the natural period of the soil layer, the directions of the ground movement effect and the inertial loading are in phase, which would increase the stress in the pile; (2) when the natural period of the superstructure is greater than the natural period of the soil layer, the ground movement effect and the inertial force is out of phase, which tends to reduce the stress in the pile. Hussien [3] conducted a series of 40g centrifuge shaking table tests on single piles and group piles in dry sand to investigate the influence of ground movement and inertial effects. The results of the tests indicate that the pile-head motion is governed by two frequencies: a lower frequency (natural soil-structure interaction frequency, f_{SSI}) where pile-head motion is maximized and a higher one (pseudo natural soil-structure interaction frequency, f_{pSSI}) where the response is minimized with respect to the free-field ground movement [4].

In this study, we attempt to numerically explore the effects of inertial loading from the superstructure and kinematic ground movement on the development of damage in the pile under strong seismic loading. A numerical model considering these two effects is used to analyze an extended pile subjected to two historical earthquake records. To observe the influence of ground movement, analyses without its effect are also conducted.

2. Numerical model

Lee [5] developed an analysis model that combines a ground movement model and a structure-pile-soil interaction model. The model can simulate the pile responses subjected to both the inertial and ground movement effects and was verified using a series of centrifuge shaking table test events.

In this study, we build a numerical model, modified from Lee [5], using SAP2000, to consider both inertial loading and kinematic ground movement. As shown in Fig. 1(a), it is a full model to consider both effects. The full model contains a structure-pile-soil interaction model and a ground movement model. On the other hand, in order to investigate the influence of ground movement, as shown in Fig. 1(b), we remove the ground movement model in the full model and set the boundaries of the soil springs to be fixed to ignore the effect of ground movement.

For the soil springs in the structure-pile-soil interaction model, this study uses a hyperbolic curve proposed by Kondner [6] to define the nonlinear p-y relationship, as shown in Eq. (1):

$$p = \frac{E_{\max} y}{1 + \frac{E_{\max}}{p_u} y} \tag{1}$$

where p = soil reaction, E_{max} = maximum elastic modulus of soil, y = soil displacement, and p_u = ultimate soil resistance.

In the ground movement model, a shear beam using a series of shear springs with lumped masses is used. Similar to the structure-pile-soil interaction model, a hyperbolic curve proposed by Hardin and Drnevich [7] is used to describe the nonlinear relationship between shear modulus and shear strain of soil, as shown in Eq. (2):

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$$\frac{G}{G_{\max}} = \frac{1}{1 + \frac{G_{\max}}{\tau_f}\gamma} \tag{2}$$

where G = dynamic shear modulus corresponding to dynamic shear strain, G_{max} = maximum shear modulus of soil, γ = shear strain, and τ_f = shear stress at failure.

In order to simulate the hysteretic response for the soil springs in the structure-pile-soil interaction model and the shear springs in the ground movement model, the Masing rule [8] is adopted. Besides, the distributed plastic hinge model is applied to simulate the nonlinear flexural behavior of the pile [9].

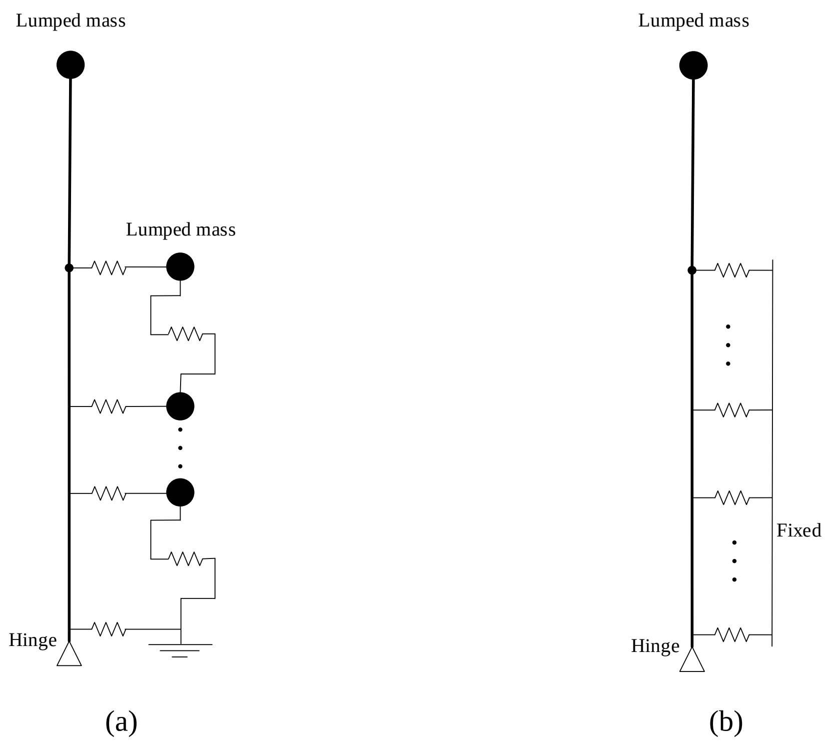

Fig. 1 – Numerical model: (a) with ground movement, (b) without ground movement

3. Analysis example and results

This study uses an example that a bridge structure supported by an extended pile foundation for numerically exploring effects of inertial loading and ground movement on the development of plastic hinge zone. The example is based on [10]. Fig. 3 displays the bridge structure and the moment-curvature curve of the pile cross-section in the example. According to Fig. 3, the yield and ultimate moments of the pile cross-section are 15000 kN-m and 23000 kN-m respectively. The pile is in a medium dry sand with an effective friction angle of soil ϕ = 33° and an effective unit weight of γ = 17.5 kN/m^3. The rate of increase of modulus of horizontal subgrade reaction n_h is 1500 kN/m^3. Two historic seismic events are analyzed in this study: Kobe earthquake (Case I) and ChiChi earthquake (Case II). The time histories of the input motions of Cases I and II and the associated acceleration spectra are shown in Figs. 4 and 5, respectively. The amplitude of acceleration is doubled in order to develop a wider plastic hinge zone. The results for these two events are described below.

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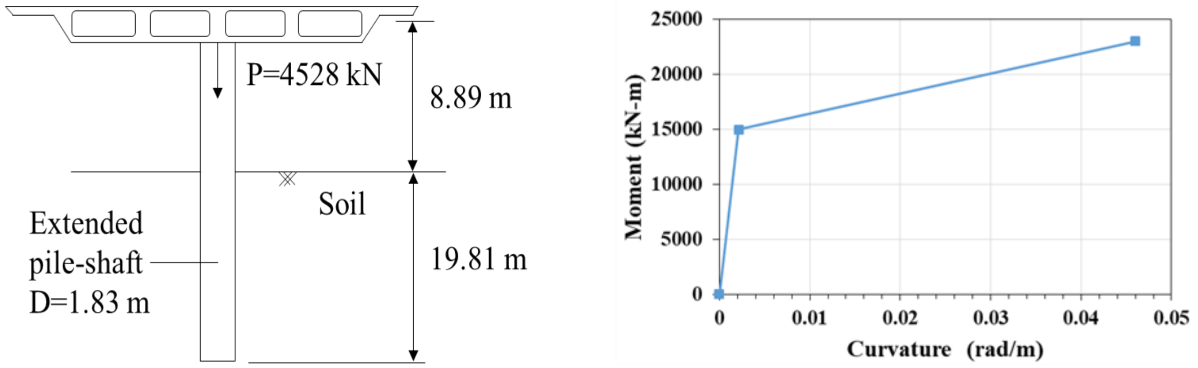
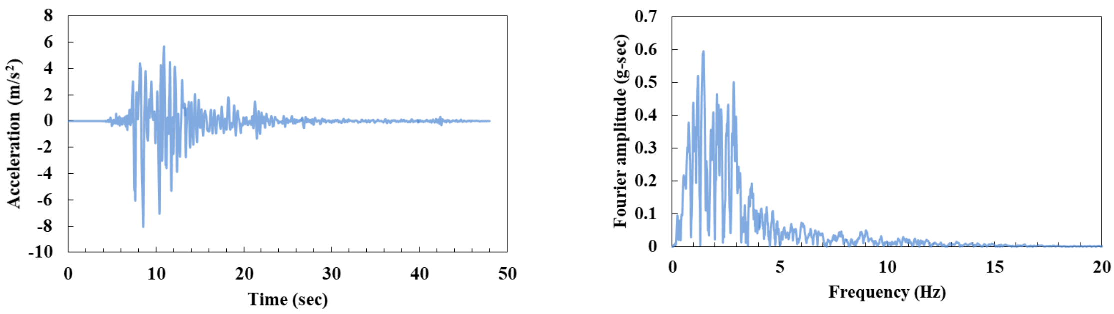


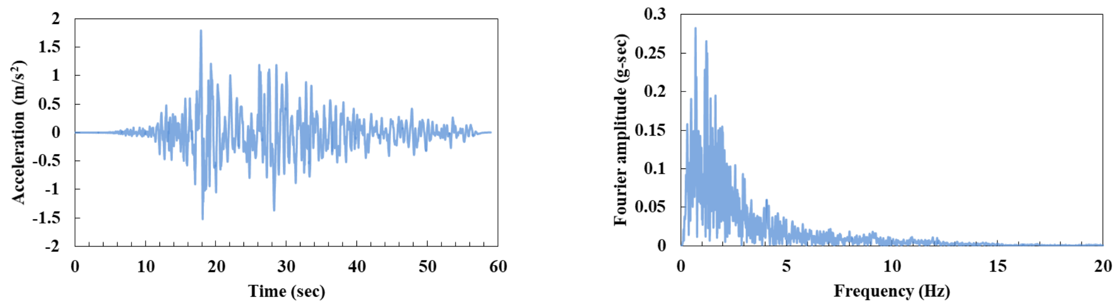
(a) (b)

Fig. 3 – (a) Example bridge structure supported on an extended pile, (b) moment-curvature response of pile cross-section (redrawn after Chai (2002))



(a) (b)

Fig. 4 – Input motion of Case I (Kobe earthquake): (a) time history, (b) acceleration spectrum



(a) (b)

Fig. 5 – Input motion of Case II (ChiChi earthquake): (a) time history, (b) acceleration spectrum

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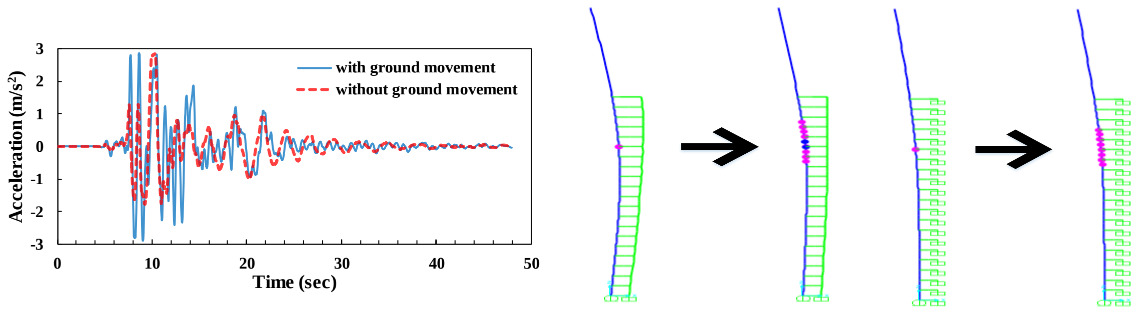
Case I:

Fig. 6 displays the analysis results for Case I, including top mass acceleration history and development of the plastic hinge zone. In Fig. 6, a phase lag occurs between the two models with and without ground movement. The model with ground movement tends to produce a phase lead in top mass acceleration and increase the acceleration amplitude, which implies that the pile will be subjected to a larger inertial force. For the model without considering the ground movement, the initial plastic zone occurs at a depth of 4.95 m, and the range of the final plastic zone is from 2.48 to 6.44 m. When the ground movement is considered, the initial plastic zone occurs at a depth of 4.95 m, and the range of the final plastic zone is from 2.97 to 6.44 m.

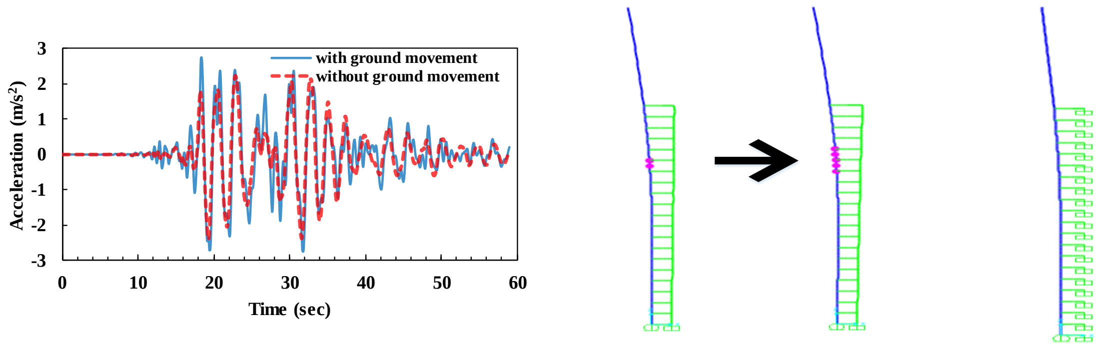
Case II:

Fig. 7 displays the analysis results for Case II, including top mass acceleration history and development of the plastic hinge zone. In Case II, a slight phase lag occurs between the two models with and without ground movement. The effect of ground movement also increases the acceleration amplitude. Without considering the ground movement, the plastic zone does not occur during the entire time history. When the ground movement is considered, the initial plastic zone occurs at a depth of 4.95 to 5.45 m, and the range of the final plastic zone is from 3.96 to 5.94 m.



(a) (b) (c)

Fig. 6 – Analysis results of Case I: (a) top mass acceleration history, (b) plastic zone with ground movement, and (c) plastic zone without ground movement



(a) (b) (c)

Fig. 7 – Analysis results of Case II: (a) top mass acceleration history, (b) plastic zone with gorund movement, and (c) plastic zone without ground movement (no plastic hinge occurs)

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The aforementioned analysis results show that in the model of considering the ground movement, the amplification effect on the acceleration of the top mass is significant, which implies the inertial force is increased. Because of the ground movement, the soil pushes the pile to generate a large internal force in the pile, which leads to a deeper and wider plastic zone.

4. Conclusions

This study numerically explores the effects of inertial loading and ground movement on the development of the plastic zone in an extended pile of a bridge structure under strong earthquakes. The consideration of ground movement tends to increase the inertial force and internal forces in the pile and further the range of the plastic zone. From this preliminary study, seismic design for pile foundations only considering inertial loading may be unsafe, and thus the ground movement effect needs to be considered for more reasonable design.

5. Acknowledgements

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