ABSTRACT

The seismic response of pile foundations is a complicated soil-structure interaction (SSI) problem. The problem of soil-pile interaction during earthquake in liquefiable soil gets further intricate than non-liquefiable soil because of degradation of strength and stiffness of soil over time, soil nonlinearity and development of excess pore water pressure. A significant number of damages and/or collapses of pile foundations and pile-supported structures are reported in liquefiable soil after past major earthquakes such as San Francisco (1906), Niigata (1964), Northridge (1994), Kobe (1995), Chi-Chi (1999), Bhuj (2001), Sumatra (2004), Tohoku (2011) and Sikkim (2011). So, it is challenging job for geotechnical earthquake engineers to ensure safe and economical design of pile foundation and pile-supported high-rise structures in liquefiable soil. As the soil behaves nonlinearly during strong seismic event, nonlinear SSI is extremely necessary for the analysis of soil-pile interaction in liquefiable soil.

In the present study, 1D effective stress-based nonlinear ground response analysis (GRA) has been conducted using the finite element program Cyclic1D for Kolkata metropolitan city in India, where population and infrastructure are growing rapidly. Two different sites of Kolkata city having two distinct soil formations as Normal Kolkata Deposit (NKD) and River Channel Deposit (RCD) are selected for ground response analysis. The input motions considered for present analysis are 1940 Imperial Valley, 2001 Bhuj and 2011 Sikkim earthquakes whose PGA are well within the reported range of Kolkata city. The validation of the present model is performed by comparing the results of peak ground acceleration (PGA) and its magnification factor profile with that predicted using SHAKE 2000 computer program. Further, liquefaction potential of Kolkata soil has been assessed using the results obtained from the present analysis. Then a well-documented case study on liquefaction-induced damages of Kandla port building (Gujarat) during 2001 Bhuj earthquake has been analysed and presented in this paper. The results of the present analysis are compared with the post-earthquake observations as well as the analyses reported in the literature. It has been observed from nonlinear GRA that PGA at surface ranges from 0.109g to 0.119g for NKD soil and 0.072g to 0.091g for RCD soil. The range of variation of peak spectral acceleration for 5% damping ratio is 0.51g to 0.67g for NKD soil and 0.33g to 0.46g for RCD soil of Kolkata. It is also found that top 12 m of RCD soil is susceptible to liquefaction if these considered input earthquake motions are experienced at bedrock.

Next, beam on nonlinear Winkler foundation (BNWF) model is developed using open-source finite element-based code OpenSees for pseudo-static analysis of nonlinear soil-structure interaction in non-liquefiable homogenous cohesionless soil and liquefiable multi-layered sloping ground using results obtained from nonlinear GRA. Pile and soil are simulated by displacement-based beam element and nonlinear spring element respectively. The present numerical model has been validated with the established theoretical solution and past case study. The effects of relative density of cohesionless soil, length to diameter (L/d) ratio of pile and fixity of pile head on pile and soil responses are investigated. The simplified BNWF numerical model is then used to investigate the seismic response of single piles in liquefiable multi-layered sloping ground taking into account of both kinematic and inertial interaction effects. The parametric studies have been performed for evaluating the influence of various parameters on seismic response of layered soil-pile system. The results from pseudo-static analysis show that the peak lateral displacement and bending moment of piles are significantly influenced by ground slope, L/d ratio of pile, pile head fixity condition, depth of liquefiable layer and pile embedment depth. The peak bending moment occurs near the interface between liquefiable and non-liquefiable layer when the depth of liquefiable layer is almost 22% and embedment depth is almost 45% of total length of pile. It is also observed that peak lateral displacement of pile reduces and peak kinematic pile bending increases in liquefiable sloping ground with increasing of embedment depth of pile.

Then, an advanced nonlinear finite-element based 3D numerical study has been carried out to investigate the effects of axial loading on dynamic response of soil-pile system in liquefiable layered level and sloping ground of Kolkata city. An advanced soil constitutive law based on multi-yield surface plasticity model implemented in fully-coupled u-p formulation is adopted for soil-fluid interaction and pore water pressure development reasonably. The present model is validated with the past experimental results. Then, a detailed systematic parametric study is performed for numerical simulation of pile failures in layered level and sloping ground under axial loading by taking into account various soil conditions, pile and ground motion parameters. Parametric studies of dynamic analysis reveal that the bending moment response of pile under axial loading can be higher in non-liquefiable condition, with reference to the liquefiable condition. The peak lateral displacement and bending moment decreases in both non-liquefiable and liquefiable condition due to decrease of axial load. So, the designer should consider both extreme scenarios for safe and economical design. Also, it is noticed that the buckling capacity of pile is improved significantly

by using larger diameter pile and the bending capacity is increased by selecting higher grade of concrete. The amplification factors of bending moment for sloping ground with respect to level ground due kinematic and combined loading increases significantly with an increase of ground slopes. The combined peak lateral displacement and bending moment co-efficient decreases when L/d ratio decreases. Also, the peak combined lateral displacement decreases by 48.7% and combined bending moment co-efficient increases by 14.3% when soil condition changes from liquefiable state to dry condition. So, it is recognised from the present study that the bending and buckling failure mode may be avoided in liquefiable level and sloping ground under combined loading condition by selecting a suitable combination of material strength and pile geometry.

Keywords: Cyclic1D; Nonlinear; Liquefaction; Laterally Loaded Pile; BNWF; OpenSees; Finite element; Soil-Structure Interaction; Sloping ground; Pseudo-static; Bending-buckling interaction

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