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Inelastic seismic behavior of soil–pile raft–structure system under bi-directional ground motion

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ABSTRACT

Performance based design of structure requires a reasonably accurate prediction of displacement or ductility demand. Generally, displacement demand of structure is estimated assuming fixity at base and considering base motion in one direction. In reality, ground motions occur in two orthogonal directions simultaneously resulting in bidirectional interaction in inelastic range, and soil–structure interaction (SSI) may change structural response too. Present study is an attempt to develop insight on the influence of bi-directional interaction and soil–pile raft–structure interaction for predicting the inelastic response of soil–pile raft–structure system in a more reasonably accurate manner. A recently developed hysteresis model capable to simulate biaxial interaction between deformations in two principal directions of any structural member under two orthogonal components of ground motion has been used. This study primarily shows that a considerable change may occur in inelastic demand of structures due to the combined effect of such phenomena.

1. Introduction

In the present seismic design strategy, structures are allowed to undergo an acceptable limit of damage avoiding collapse due to severe earthquake shaking. The same structure is designed in such a way that it behaves elastically under minor to moderate earthquakes. The design philosophy, therefore, related to both serviceability and ultimate limit states are categorized as performance based design. The development of such design philosophy has been made focusing on multiple limit states or multiple performance levels [1,2] and explicitly addressed in various seismic design guidelines. However, the available guideline for performance based design is based on the idealization of seismic shaking in one principal horizontal direction of the structure, though in reality shaking occurs simultaneously in both the mutually perpendicular horizontal principal directions. Few previous studies [3–5] have indicated that simultaneous action of ground motions along the two orthogonal principal directions may have a considerable effect on inelastic demands. Hachem et al. [6] shows the impact of bi-directional interaction based on an experimental study. In fact, simultaneous action of orthogonal horizontal components of bidirectional ground motions will invite bi-directional interaction between hysteresis behavior of the load resisting members which is generally not considered for the estimation of inelastic seismic demand. In this context, the present seismic codes [7–9] suggest to consider the effect of bi-directional interaction of ground motion by combining the 100% and 30% of response obtained for two orthogonal horizontal ground motions recorded at a particular site through square root sum square (SRSS) method. This superposition method may be valid for elastic analysis but is not acceptable for inelastic analysis as it cannot recognize the effect of interaction between inelastic responses in both directions.

However, a recent study in this direction [10] has shown that the effect of biaxial interaction of inelastic deformations along two principal directions of the structure may be important to account for, with a proposed reasonably accurate and computationally efficient bidirectional hysteresis model. The influence of such effect is investigated obtaining response only in fixed base condition, while, a realistic situation incorporating the effect of soil flexibility is not considered in this study. Hence, the present study makes an attempt to highlight the effect of bi-directional interaction on inelastic response of structures supported on piled-raft foundation incorporating soil–pile raft–structure interaction. Hysteresis behavior of structure and foundation element is

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characterized by this recently developed biaxial model [10]. This bi-directional hysteresis model is capable of incorporating strength and stiffness degrading features of reinforced concrete structural elements and elastoplastic features for steel elements with easily implementable algorithm having relatively less computational rigor. Because of reasonable accuracy achieved along with lesser computational rigor, this model may be conveniently used for large range parametric study involving both concrete as well as steel structure.

Different representative natural period of structures supported on piled raft system, embedded in different consistencies of homogenous clay deposit is primarily chosen for assessing the interaction effect of bi-directional ground motions along with soil–structure interaction (SSI). Conventionally, piled raft supported structures are designed on the basis of fixed base assumption under unidirectional ground motion. Incorporation of SSI is ignored due to its involvement of complex modeling and the notion of beneficial attributes on response of structure [11]. However, this conventional perception is not proved to be always true and non-consideration of SSI may be detrimental to the system as a whole, evidenced in a few recent case studies e.g., [12,13]. Several studies on shallow foundation performed by the first author along with other co-workers [14–16] have also pointed out underestimation of seismic design forces in structural elements. Moreover, soil–pile foundation–structure interaction is considered as an important phenomenon in evaluating the seismic response of pile-supported structures in various types of soil as suggested by various researchers e.g., [17–27]. The importance of SSI is also anticipated in different design guidelines e.g., [8,9,28]. Further, a recent study by the authors [29] has indicated that lateral shear force increases at pile head due to consideration of interaction among soil, pile, raft and structure under dynamic loading as compared to what is obtained in fixed base condition. The additional inertia force contributed by relative acceleration of heavy raft mass with respect to adjacent soil mass lead to such increase in pile head shear even counterbalancing the beneficial effect of SSI. This preliminary study clearly signifies the importance of consideration of SSI while estimating inelastic demand of such heavy structure supported on piled raft foundation. Hence, a realistic and reasonably accurate evaluation of response of soil–pile foundation–structure system requires consideration of bi-directional interaction of inelastic deformations due to two orthogonal horizontal ground motions incorporating SSI through introducing a simplified and computationally efficient model. However, the studies are yet to be made in this direction.

In this context, the present study makes an attempt to examine the influence of both the effects through comparing the inelastic response of structures supported on pile foundation incorporating the proposed model developed on the basis of a modification of the earlier biaxial hysteresis model [10] incorporating SSI parameter under a set of bidirectional ground motions and their unidirectional counterparts. Hysteresis model proposed by Dutta and Das [30] is considered to compute the response under unidirectional ground motion. The effect of various idealizations, parameters and factors such as, superstructure idealized as single storey systems with typical representative lateral periods of different multistorey structures, elastic and inelastic behavior of pile group, different values of response reduction factors and elasto-plastic and strength stiffness degrading features are also accounted for this analysis. At first, inelastic displacement of selective periods of structures are obtained for bidirectional and unidirectional ground motions in fixed base condition. Responses are also obtained for the similar systems attached with piled raft foundation incorporating soil flexibility. The calculated responses are presented in normalized form at various combinations in order to identify the combined effect of bidirectional interaction incorporating SSI. However, soil–pile foundation–structure interaction is modeled by using simplified impedance based approach as reported in literature [25,31]. Impedance based modeling is further validated through direct approach (often referred to as Direct Soil–Structure Interaction (DSSI) which is considered as another detailed and well accepted modeling procedure for SSI). The limitation of linear pile–soil behavior generally considered in impedance approach is attempted to be modified in present study by incorporating the proposed biaxial hysteresis model which is capable to simulate the non-linear pile–soil behavior along with bidirectional interaction between deformations in two principal directions. Moreover, the effect of excitation frequency on determination of pile head stiffness is also investigated for the sake of obtaining maximum response of the structure, since an earthquake force exhibits different frequencies of motion during its history. Comparisons of maximum responses are made among the following cases: (a) bidirectional ground motions incorporating SSI, (b) unidirectional motion with fixed base condition, and (c) unidirectional motion with SSI condition. This would help to gaze the influence of individual and combined effect of bidirectional interaction along with SSI on inelastic seismic response of structures. The observations and understanding developed from the present study may provide valuable insight on inelastic seismic behavior of structures supported on piled raft foundation. Hence, this study may help to fine tune the guidelines for performance based design leading to a reasonably accurate estimation of inelastic seismic demand of pile raft supported structures.

2. System modeling

In the present study, the term “system” refers to a structure supported on a piled raft foundation which is embedded in homogenous deep clay deposit underlain by a rock layer situated at a higher depth. Seismic excitation is considered to be triggered at rock layer and wave traveling through the clay deposit introduces dynamic loading to the structure. The schematic representation of the system is presented in Fig. 1(a). The SSI phenomenon is incorporated in the analysis using two-step impedance based approach [25,31] to calculate the inelastic response of piled raft supported structure. However, direct modeling exhibited through beam on nonlinear Winkler's foundation (BNWF) approach is also utilized in a limited form to validate the adopted impedance based modeling in order to check the accuracy of results.

2.1. Idealization of superstructure

Seismic response of the structure supported on soil–piled raft foundation is obtained by idealizing the superstructure as single storey and multi-storey systems. Single storey and multi-storey systems are considered which consists of rigid diaphragms at floor levels and the floor slabs are supported by four columns of similar dimensions at each storey. Total three degrees of freedom (two translations in two mutually orthogonal horizontal directions and one rotational in horizontal plane about vertical axis) is assumed at each storey level. Four representative lateral periods (T_{fixed}) under fixed base condition namely 0.3 s, 0.5 s, 1.0 s and 2.0 s are chosen to characterize the typical single storey systems in short, medium and long period ranges, respectively. Storey level mass and lateral stiffness of each column is adjusted to arrive at the stipulated fundamental lateral period of the system, same in both lateral directions. Further, the response of a five storied system is also studied to compare with single storey estimates. The effect of participation of higher modes is assessed through idealizing