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Experimental investigation of the seismic performance of bridge models with conventional and rocking pile group foundations

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ABSTRACT

This experimental study assesses the seismic performance of a rocking pile group foundation system for bridges. Two large-scale mass-column-foundation bridge models with a rocking pile group foundation and a conventional foundation were designed, constructed, and tested under quasi-static cyclic loading. An effective pile model with a short pile length and an additional end plate was proposed that provided approximate foundation flexibility and pile responses. Special consideration was taken for the pile-to-cap connection details. The test results show that the model with the rocking foundation led to similar hysteretic cycles compared to those with the conventional foundation at small lateral loading (e.g. functional load), while at large cyclic drift ratios (e.g. induced by strong earthquakes), flag-shaped hysteretic loops and excellent resilient capability were achieved. Compared to the conventional foundation, the rocking foundation resulted in much less damage in the piles, decreased the residual drift ratio by up to 88%, and retained nearly 60% of the initial stiffness following a maximum drift cycle of 6%. The traditional definition of stiffness degradation based on the secant stiffness that corresponds to the peak forces and displacements for each loading cycle was found unsuitable for evaluating the residual stiffness of resilient structures. A new index was then proposed, based on the secant stiffness that corresponds to the critical functional load.

1. Introduction

Pile group foundations are prevalent in highway bridges because of the high resistance to gravity loads for different soil types. However, in the event of an earthquake, a significant dynamic shear force and an overturning moment are induced at the top of the foundations that consequently result in the exertion of a large axial force and a bending moment on the piles. The fluctuation of the axial force is often larger than the gravity-induced compression, and causes concentrated tensile failure in the piles frequently at the pile-to-cap connection, settlement, punching, or pull-out failure. During previous strong earthquakes (e.g. the Hyogo-Ken Nanbu earthquake of 1995, Chi–Chi earthquake of 1999, and Tohoku earthquake of 2011), many pile group foundations for bridges experienced considerable damage and failure [1–6], as shown in Fig. 1a and b.

The Capacity design strategy requires bridge foundations to be designed for over-strength capacity so that inelastic flexural behaviour will only develop in ductile regions of the piers [7]. This procedure increases the strength demand on the foundations and is sometimes economically unfeasible when non-ductile piers with high lateral loading bearing capacity are used. Guan et al. [8] indicated that additional piles were required to the minimum number for non-seismic actions, and that high-longitudinal reinforcement ratios were often necessary to accomplish a seismic design for conventional urban viaducts within a capacity design framework.

According to the National Earthquake Hazards Reduction Programme (NEHRP) guidelines for the seismic rehabilitation of buildings and Building Seismic Safety Council (BSSC) [9], mobilization of the ultimate capacity and rocking behaviour of shallow footings can reduce the ductility demand on structures (Fig. 2a). Thus far, numerous studies have been carried out on the responses of shallow foundations allowing uplift and rocking through numerical or experimental methods (Psycharis and Jennings [10]; Gazetas and Apostolou [11]; Gajan et al. [12]; Mergos and Kawashima [13]; Harden and Hutchinson [14]; Sakellaraki and Kawashima [15]; Fujita et al. [16]; Pollinoa and Bruneaub [17]; Gajan and Kutter [18]; Michaltsos and Raftoyiannis [19]; Roh and Reinhorn [20]; Deng et al. [21]; Kourkoulis et al. [22]; Anastasopoulos et al. [23]). The results of these studies showed that bridge piers with rocking mechanisms can remain elastic and free of damage during a seismic event. The rocking spread footings also provide a re-centering mechanism and consequently enhance post-earthquake functionality. Different from the rocking bridge piers with pre-

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(a) Flexural/tensile failure near pile head

(b) Pile-to-cap connection failure

Fig. 1. Seismically induced pile failures [5,6].

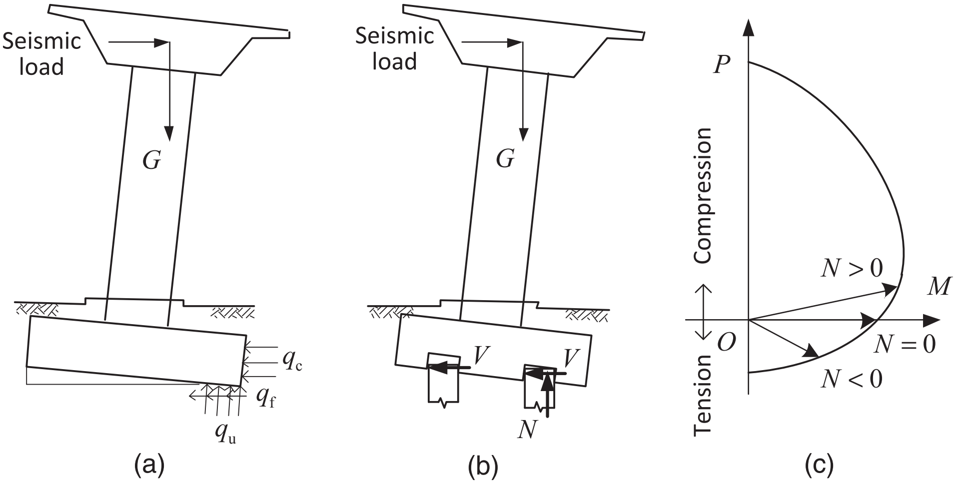

Fig. 2. Rocking foundations: (a) Footing foundation, (b) Pile group foundation, and (c) Typical *P*–*M* interaction for reinforced concrete members.

stressed tendons in which the recentering force is mainly provided by the pre-stressed tendons, the re-centering capacity of a rocking spread footing is provided by the gravity of the structure. When uplift of the footing occurs and the centre of gravity of the structure is located on the inside of the edges of the footing, the gravity load provides a re-centering moment to bring the structure back toward a vertical orientation. Housner [24], Ishiyama [25], and Apostolou et al. [26] investigated the stability of structures allowing rocking motion under earthquake actions, and indicated that large-scale structures were more stable against overturning than expected. Spread footings for bridges are often several metres wide, while the displacement spectra of the historical records have shown that the considered seismically induced lateral displacements are mostly less than one metre [27]. This indicates that the rocking systems actually have sufficient stability against overturning.

Similar rocking behaviour can be achieved for bridges with pile group foundations if the piles are not attached to the pile caps (Fig. 2b), i.e. no tension is transferred from the pile caps to the piles while resisting compressive actions induced by gravity and traffic loads, vertical acceleration, and base overturning moments. When the seismic overturning moment exceeds the restoring moment provided by gravity, the pile caps can rock intermittently like the case of previous spread footings [28]. To prevent overturning of the bridge in earthquakes, the gravity centre of the rocking body should be restricted within the region enclosed by the outer piles during the excitation. Without the action of a tensile force on the top of the piles, the section bending moment capacity can be significantly increased (Fig. 2c), and therefore, damage to the piles could be decreased.

While numerous studies have been devoted to the nonlinear responses of spread footings, a limited number of studies have been performed specifically with regard to pile group foundations allowing uplift and rocking. Allmond and Kutter [29] conducted two series of centrifuge tests to investigate the use of unattached piles in poor soil conditions with liquefaction potential, primarily focusing on the settlement control of the piles. Antonellis and Panagiotou [28] numerically analysed the seismic response of bridges with rocking pile foundation at a near-fault site, based on an idealised pile-to-cap constraint. According to Gajan et al. [12], the response of a rocking foundation to seismic shaking can be reasonably predicted by slow cyclic tests. Wang [30] tested a small-scale physical model subject to static cyclic loading in which the piles were modelled as short cantilever shafts fixed onto a rigid reinforced concrete end plate, referred to as the ‘equivalent fixed base’ in according to Veletsos and Meek [31]. The test showed a significant seismic isolation effect for the bridge model with a rocking pile group foundation. However, the responses of the piles cannot be properly simulated without surrounding soil. An unexpected failure mode occurred in the piles and led to an overestimated damping effect on the elicited hysteretic responses. Moreover, local damage was found at one of the four pile-to-cap connections, most likely caused by an unexpected rotation constraint owing to an insufficient free space between the pile head and the socket in the pile cap.

In this study, two large-scale, physical bridge models with rocking