Ocean Engineering 115 (2016) 1–18

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Multi-directional cyclic *p–y* curves for soft clays

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ARTICLE INFO

Article history:
Received 12 April 2015
Accepted 28 January 2016
Available online 10 February 2016

Keywords:
p–y springs
Lateral loading
Piles
Soil–structure interaction
Soft clay behavior

ABSTRACT

Currently there is a lack of information and experimental data to formulate *p–y* curves in multi-directional loading conditions for soft clays. Experimental evidence has shown that uni-directional *p–y* curves are not able to represent correctly the near field soil response to multi-directional earthquake loading. This paper presents the results of an experimental study aimed at characterizing soil–pile interface response for multi-directional pile trajectories in soft clay. Series of multidirectional *p–y* test were performed including circular, elliptical, parabolic, and figure-8 pile transit paths. These tests provide information regarding the force–displacement relationship dependence on the loading path, the evolution of the soil stiffness during multi-directional cyclic loading, the effect of loading history on the near field soil stiffness, and the variation of the lateral load with pile depth. The tests results showed that the multi-directional movement of the pile produces loading induced anisotropy, which can significantly affect the behavior of the near field soil. From the results gathered it is clear that the soil–pile interaction in soft clay during multi-directional loading, is complex and cannot be modeled with methods based on the traditional concept of *p–y* curves simply applied in two orthogonal directions.

1. Introduction

Seismic soil–pile–structure-interaction analyses very often rely on the concept of non-linear discrete spring elements to simulate the effect of the soil surrounding the pile (Bea et al., 1984; Lok et al., 2000; Mayoral et al., 2002). In particular for lateral soil–pile interaction, the so-called *p–y* curves are used to describe the response of non-linear springs connected to structural elements (i.e. pile), which represent the soil immediately adjacent to the pile (i.e. near field). The *p–y* approach was proposed by McClelland and Focht (1958) to describe the relationship between the lateral forces developed on a pile, "*p*", by the adjacent soil, when the pile moves a lateral displacement, "*y*", at a given elevation. Procedures to obtain this relationship fall into one of two categories: (a) in situ testing of full-scale single piles or pile groups (Kim and Brungraber, 1976; Brown and Reese, 1987; Reese et al., 1974; Cox et al., 1974) and (b) laboratory testing using scale model testing or element testing, commonly referred as pot testing (Matlock, 1962,1970; Lok et al., 2000, Mayoral et al., 2005). Full-scale pile testing is costly, and in many cases the results are proprietary (i.e. Bea, 1988). As a result, significant effort has been made over the last two decades to develop reliable laboratory-based techniques. In model testing (e.g. 1-g or centrifuge testing), the actual soil–pile system is modeled using appropriate similitude laws for both soil and pile to correctly simulate the actual field conditions (Riemer and Meymand, 1996; Meymand, 1998; Finn and Gohl, 1987; Wilson et al., 1995). In the so-called "pot" testing, it is assumed that the soil–pile system can be divided into units where the force vs. displacement distribution on a given segment of pile is uniform with depth (e.g. Matlock, 1962; Lok, 1999). Although empirical *p–y* curves are soil specific, generic uni-directional *p–y* curves have been proposed by a number of authors for both clays (e.g., Matlock, 1970; Reese et al., 1975) and sands (e.g., Bogard and Matlock, 1980; Reese et al., 1974; Neill and Murchison, 1983). Some specific uni-directional *p–y* curves have been incorporated into computer programs that are widely used in offshore engineering applications (e.g. Reese, 1977; Matlock et al., 1978), as well as in the design of important onshore structures such as tall bridges and buildings subjected to seismic loading (e.g. Matlock et al, 1979; Bea, 1988; Wang and Reese, 1993). A major advantage of using *p–y* curves is the ability to capture key features of soil–pile–structure interaction, such as (a) progressive gapping, (b) cyclic degradation of the soil, and (c) pile slippage with less computational effort than solutions based on continuum models. These results have led to the American Petroleum Institute recommended method for constructing *p–y* curves (API, 1993). Most of this work has involved either monotonic or cyclic loading along a single loading axis. Accordingly, there is a lack of information (experimental data) to formulate and calibrate *p–y* curves in multi-directional loading

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http://dx.doi.org/10.1016/j.oceaneng.2016.01.033
0029-8018/

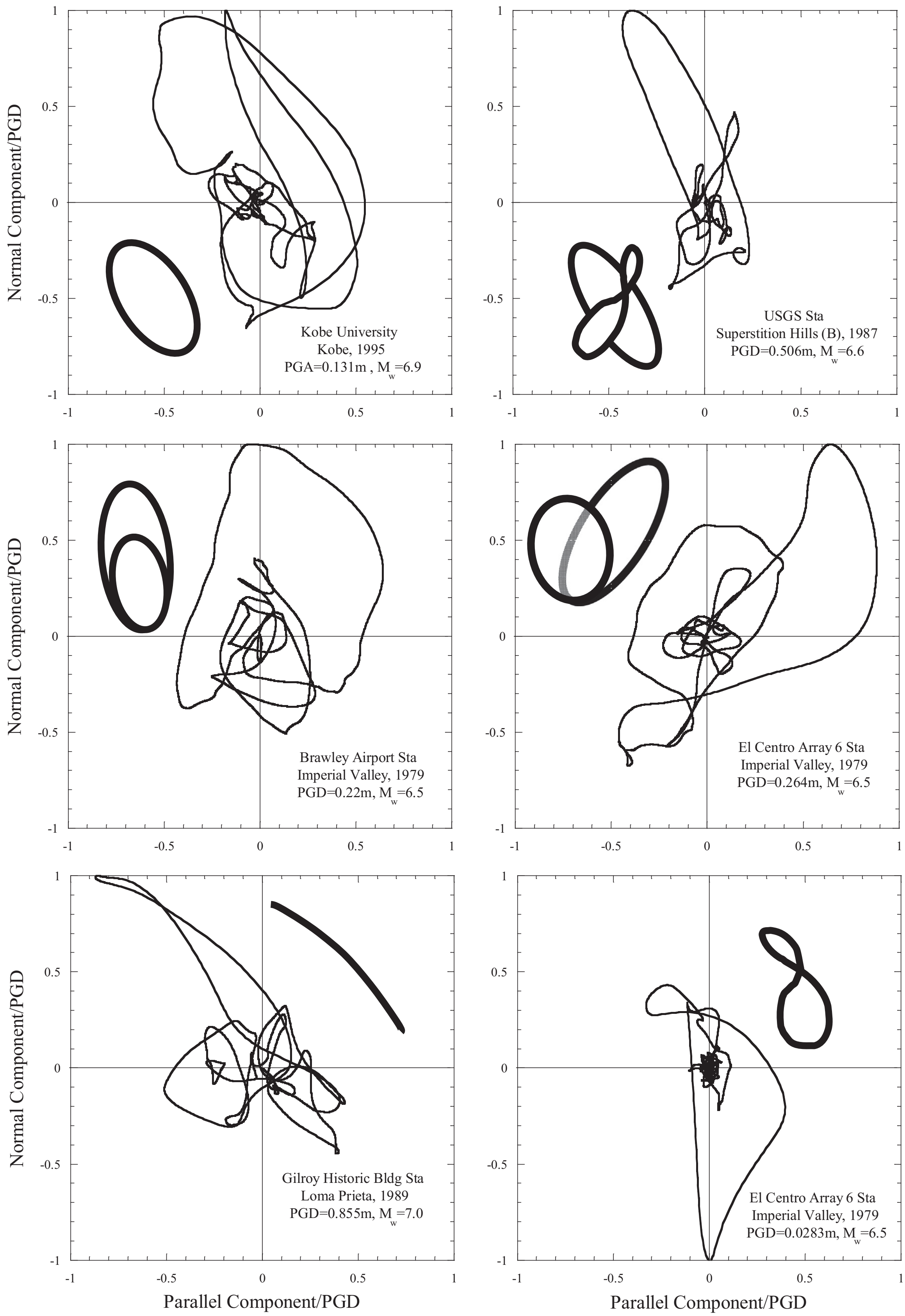

Fig. 1. Examples of "free-field" ground displacement paths observed during recent earthquakes.

conditions. Many procedures used to evaluate the seismic response of pile foundations subjected to two-directional and three-directional components of strong shaking generally assume that the soil foundation can be substituted by a system of orthogonal non-linear inelastic springs, with force–displacement properties given by uni-directional *p*–*y* curves. However, experimental