INFLUENCE OF SOIL PILE INTERACTION ON SEISMIC BEHAVIOR IN SANDY CONDITION

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TO MY PARENTS

TO MY LOVELY WIFE

TO MY SONS-POUYA& PARHAM

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ABSTRACT

Damages of structures supported by deep foundations due to complete or partial collapse have demonstrated paramount importance of the understanding of Soil-Pile Interaction (SPI). Kinematic interaction is due to the presence of pile foundation in the ground. Several methods are available to determine the kinematic interaction. Among these approaches, the method of Beam on Nonlinear Winkler Foundation (BNWF) is widely used in research practices. In the BNWF method, soil and pile are modeled as nonlinear springs and linear finite elements, respectively. Stiffness coefficient of spring is evaluated based on load-transfer approach, often known as *p-y* curve method. On the other hand, the pile group and the single pile behavior are usually different owing to the impacts of the pile-to-pile interaction known as shadowing effects. Shadowing effects are the condition where there is an overlapping of the stress zones. The *p-y* curve of single pile can be used in pile group based on *p*-multiplier concept. Many investigators have developed *p-y* curves for sandy and clayey soils. However, these developed curves do not account some parameters such as relative density of sandy soil and side friction. This research has developed a new *p-y* curve for single pile under lateral loading through a comprehensive experimental investigation on Johor Bahru Sand. A good estimation of soil properties in the laboratory was required to simulate natural soil condition. In this study, sand samples prepared using new Mobile Pluviator designed to achieve of the desired relative densities ranging from 10% to 98%. A series of 12 different configurations of piles groups investigated in loose and dense sandy conditions to evaluate the piles interaction effects. The *p-y* multiplier factor was determined for the piles in the group based on distribution of load applied among the pile groups. The results of different configurations of pile group showed that the ultimate lateral load increased by 53% in increasing of spacing center-to-center piles (s) from 3D to 6D (D=pile diameter) owing to the reduction of pile group interaction effects that improve the performance of the pile group efficiency. A ratio of s/D more than 6 was large enough to eliminate the effects of pile group interaction. The new p-y curve exhibits a lower initial stiffness compared to the p-y curves from previous researchers. The maximum values of displacement and seismic acceleration of the structure occurred almost at the same time for existing and new p-y curves, but the new p-y curve can determine the seismic behavior under the strong earthquakes more accurate than the existing curves because of the higher ultimate lateral resistance.

ABSTRAK

Kerosakan struktur-struktur yang disokong oleh cerucuk asas dalam yang disebabkan oleh keruntuhan sepenuhnya atau keruntuhan separa menunjukkan bahawa adalah amat penting untuk memahami Interaksi antara Tanah-Cerucuk (*Soil-Pile Interaction*-SPI). Interaksi Kinematik dalam SPSI adalah disebabkan oleh kehadiran cerucuk asas di dalam tanah. Beberapa kaedah boleh digunakan untuk mengenalpasti interaksi kinematik berkenaan. Antara kaedah-kaedah ini, Kaedah Rasuk pada Asas Bukan Linear Winkler (*Beam on Nonlinear Winkler Foundation*-BNWF) merupakan kaedah yang paling meluas digunakan dalam kajian. Dalam Kaedah BNWF, tanah dimodelkan sebagai spring bukan linear manakala cerucuk pula dimodelkan sebagai elemen terhingga linear. Pekali kekukuhan dinilai berdasarkan pendekatan pemindahan beban, kerapkali dikenali sebagai kaedah lengkungan *p-y*. Sifat cerucuk berkumpulan dan cerucuk tunggal selalunya berbeza disebabkan kesan bayang disebabkan interaksi dalam cerucuk berkumpulan. Kesan bayang ini merupakan satu keadaan di mana terdapat pertindihan zon-zon tekanan. Lengkungan *p-y* untuk satu cerucuk tunggal boleh digunakan untuk cerucuk berkumpulan berdasarkan konsep pendaraban beban, *p*. Ramai penyelidik telah membina lengkungan *p-y* untuk tanah berpasir dan tanah liat. Walaubagaimanapun, lengkungan-lengkungan ini tidak mengambil kira ketumpatan relatif dan geseran sisi tanah berpasir. Kajian ini telah menghasilkan satu lengkungan *p-y* baru untuk cerucuk tunggal di bawah bebanan mengufuk melalui kajian eksperimen yang komprehensif pada pasir di Johor Bahru. Satu anggaran yang tepat berkenaan sifat-sifat tanah dalam makmal diperlukan untuk mengsimulasikan keadaan tanah yang semula jadi. Dalam kajian ini, penyediaan sampel pasir dilakukan menggunakan *Mobile Pluviator* yang direka khas bagi mencapai ketumpatan relatif antara 10% ke 98%. Satu siri yang terdiri dari 18 konfigurasi berbeza cerucuk berkumpulan dalam pasir yang longgar dan padat dikaji untuk menilai kesan interaksi dalam cerucuk berkumpulan. Faktor pendarab *p-y* untuk cerucuk-cerucuk di dalam kumpulan dikenalpasti berdasarkan agihan beban antara cerucuk berkumpulan berkenaan. Keputusan dari konfigurasi yang berbeza menunjukkan bahawa beban mengufuk muktamad meningkat sebanyak 53% dalam peningkatan jarak pusat-ke-pusat cerucuk dari 3D kepada 6D (D=garispusat cerucuk) disebabkan oleh pengurangan kesan interaksi cerucuk berkumpulan yang meningkatkan keberkesanan cerucuk berkumpulan berkenaan. Nisbah *s/*D melebihi 6D adalah cukup besar untuk menyingkirkan kesan-kesan cerucuk berkumpulan. Lengkungan *p-y* baru yang dihasilkan mempamerkan nilai pekali kekukuhan awal yang lebih rendah berbanding lengkungan-lengkungan *p-y* daripada penyelidik-penyelidik terdahulu. Lengkungan *p-y* yang lama dan baru menghasilkan nilai pesongan dan pecutan seismik yang sama tempohnya bagi sesebuah struktur. Lengkungan *p-y* yang baru walaubagaimana pun mampu menghasilkan sifat seismik yang lebih tepat dibawah gegaran yang kuat berbanding lengkungan *p-y* yang lama kerana mampu mengambil kira rintangan sisi muktamad yang lebih tinggi.

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V_s - Shear wave velocity

G_{max} - Maximum shear modulus

$\gamma_{d\ max}$ - Maximum dry unit weight

$\gamma_{d\ min}$ - Minimum dry unit weight

P_u - Ultimate lateral resistance

p - Soil-pile reaction

y - Pile deflection

SPI - Soil pile interaction

BNWF - Beam on Nonlinear Winkler Foundation

l_a - Active length

E_s - Young's modulus of soil

E_p - Young's modulus of pile

D - Pile diameter

y_c - One-half the ultimate soil resistance

ε_{50} - Strain for 50% of the ultimate stress

C_u - Undrained shear strength

USCS - Unified Soil Classification System

z - depth

ν - Poisson's ratio

K^e - Initial elastic stiffness

φ - Friction angle

σ_p - Passive earth pressure

C_r - Radiation damping coefficient

V_s - S-wave

V_p - P-wave

ρ_s - Density of soil

V_{la} - Lysmer's wave velocity

LVDT - Linear Variable Differential Transducers

a_0 - Dimensionless frequency factor

C_m - Material damping

ζ - Material damping ratio

f_m - p-multiplier factor

ω - Frequency of loading

ELM - Equivalent linear method

NLM - Nonlinear method

γ_{eff} - Effective shear strain

e - Void ratio

γ_{max} - Maximum shear strain

σ_0 - Principal effective stress

f-f - Free-Field

FEM - Finite element method

BEM - Boundary element method

EI - Flexural rigidity

D_{50} - Mean size of soil particles

S - Distance between hopper and diffuser system

H - Distance between diffuser system and sand surface

H_{crit} - Critical falling height

M(z) - Bending moment curve

k_{ini} - Initial stiffness

P_i - Number of shutter plate

D_r - Relative density of soil

C_u - Uniformity coefficient

SR - Spacing ratio

η - Group efficiency

Q_{LG} - Ultimate lateral capacity of pile group

Q_{LS} - Ultimate lateral capacity of single pile

λ - Gauge constant

M - Moment

ε - Strain

k_p - Passive earth pressure

API	-	American Petroleum Institute
EQ1	-	Earthquake number 1
EQ2	-	Earthquake number 2
EQ3	-	Earthquake number 3
f	-	Fundamental frequency
I	-	Inertia moment
PGA	-	Peak Ground Acceleration

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Many great cities are built on flat lands containing a thick layer of sediment such as basins, river, deltas or valleys. Superstructures such as tall buildings, important structures and bridges sometimes in these cities are founded on fluvial and alluvial soil deposits that are weak and/or inherently soft (Chau *et al*., 2009). For this reason, the superstructures are supported by deep foundations to transfer dead and dynamic loads through shallow deposits of loose soils to deeper and denser soils which have enough strength without excessive ground settlements. Therefore, the evaluation of the superstructure's behavior subjected to lateral loads is known as a key concern for the designers. Obviously, the superstructure behavior supported by pile and rigid foundations differs because of the soil-pile-superstructure interaction (Finn . *et al*., 2011).

Piles transfer vertical and horizontal forces. On the type of superstructure supported by piles, there are different causes of lateral loads. For examples, wind gusts are common causes of lateral load for transmission towers and tall buildings. In these structures, the lateral loads are known as the primary cause. In cases of bridge piers, the horizontal forces are due to wind movement and traffic. Seismic motions are the most important lateral loads since pile damages have demonstrated during earthquake.

The mechanism's load transfer vertically and horizontally is necessary for design. In the transfer of lateral loads, pile behaves as a loaded beam in a transverse manner. In such conditions, a part of pile moves horizontally in the load direction. The soil in front of the pile resists against the pile's press so as strain and stress are developed in soil and consequently the Soil-Pile Interaction (SPI) occurs. Therefore , the Soil-Pile Interaction (SPI) plays a very important role in the superstructure's behavior subjected to lateral excitations because in most studies on superstructure, the foundation is assumed as rigid (embedded in solid rock) while it is supported by piles foundations. Consequently, the mechanism of SPI for the pile damages need to be further examined (Tseng and Penzien, 2003).

As mentioned above, the seismic motions are the most important lateral load in the SPI. Earthquake waves propagate through the soil deposit and affect the pile foundations and structures resting on the ground surface. The effects of soil-superstructure interaction and local soil conditions on the pile's motion have been observed during the major earthquakes (Figure 1.1). The strong earthquakes have demonstrated the role of soil-structure interaction on the piles. Observations of the major earthquake of Loma Prieta Earthquake in 1989 are other learning options. The piles' Cypress Freeway were founded in stiff to the soft soils. The local soil conditions were the main reason for the failure mechanisms. The San Francisco Oakland Bay Bridge collapsed due to structural failure. The spectral accelerations were amplified four times and damaged the structures and foundations (Housner, 1989).

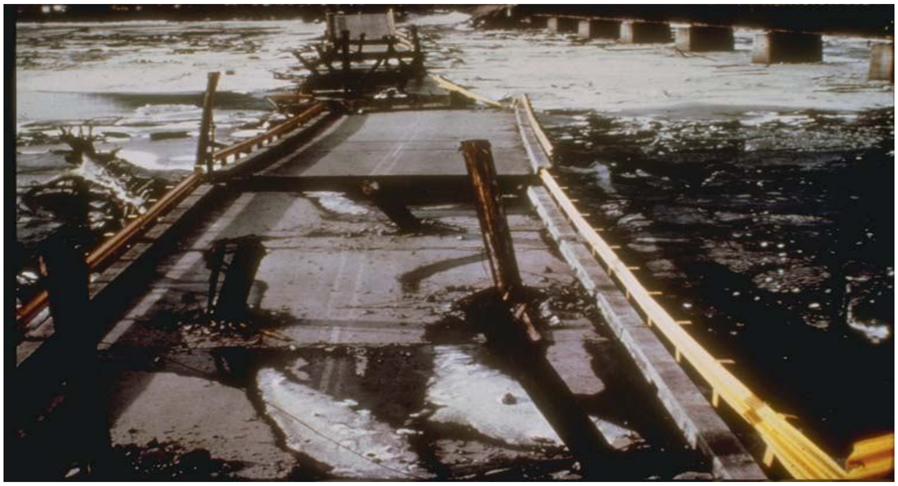

Figure 1.1 Collapse Twenty nine mile River Bridge supported on Timber Piles in the 1964 Alaskan Earthquake (after Meymand,1998)

The behavior of the structure under dynamic loads depends on the interaction between the structure, pile foundations and local soil. The effects of this interaction were highlighted in the early 1960s where the foundations of equipment were designed. The influence of soil-structure interaction can be more significant when the structure is supported by pile foundations in sand with different densities. So that, the modern structure codes consider the dynamic soil and structure interaction in the structure supported by pile foundations in cohesionless soils. Therefore, the effects of different relative densities and soil-pile interaction are important in complete understanding of the seismic behavior in sandy conditions. Briefly, much is yet to be learned analytically on the subject before having a complete important insight of the parameters in SPI problems.

1.2 Statement of the Research

The importance of SPI can be demonstrated through the observations of damages in the structures owing to partial or complete collapse under lateral loads.

Generally, it is common to ignore the SPI effects for simplifying design of structures due to a series of reasons. For example, flexibility pile is considered as a conservative design assumption because the period of structure is lengthened and the structural forces decrease in comparison with a fixed base case (Figure 1.2). Although this assumption may be correct in some cases, in 1985 Mexico City earthquake, the acceleration values were higher than the spectral values related to some building codes at the high periods (NEHRP, 1997b) (Figure 1.3).

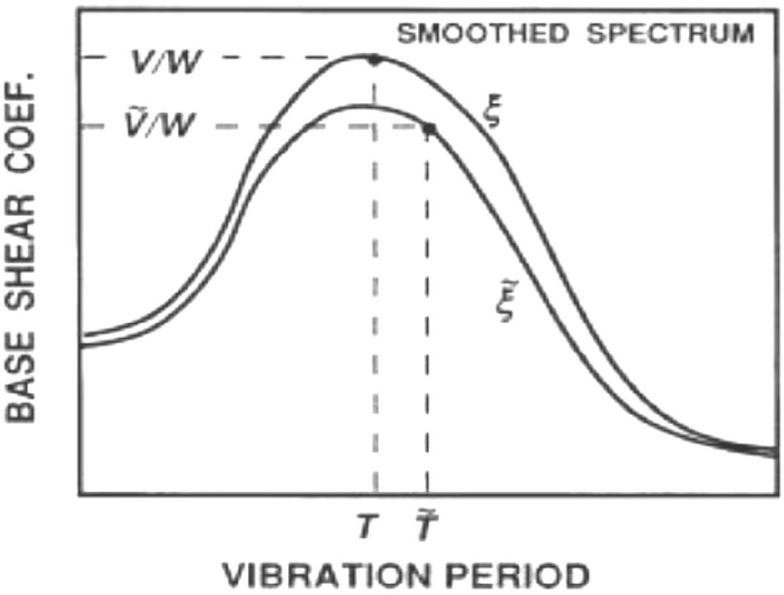

Figure 1.2 Effect of Soil-Structure Interaction on Seismic Coefficient for Base Shear (after Fenves *et al.,*1992)

It is somewhat more common that the free field response is predicted on the ground surface and these predicted motions are applied to the fixed base of the structure (Figure 1.4). In fact, the soil's response to foundation or the foundation's response of soil is not taken into account. Although recently building and bridge codes, state that the soil-pile-structure interaction shall be considered in design, it requires a substantial amount of expertise in idealizing the actual system.

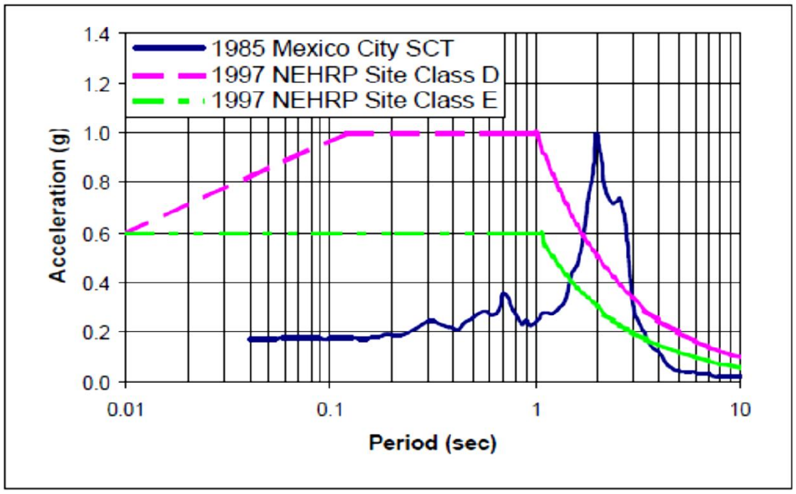

Figure 1.3 Comparison of 1985 Mexico City Earthquake SCT Response Spectra with NEHRP (1997) Code Recommendations

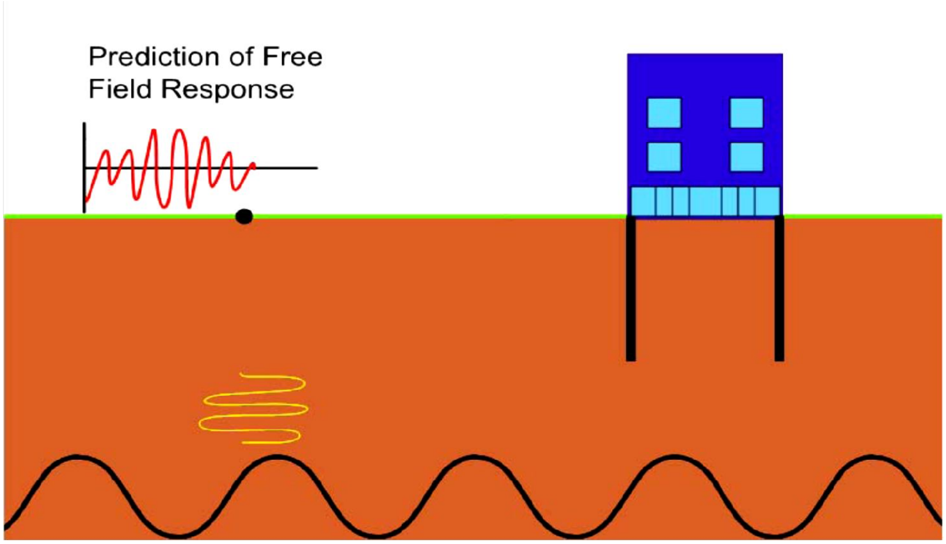

Figure 1.4 Free Field Site Response Analyses

The pile movement under axial load is simply because it moves downward. Base and shaft resistances increase the limit values so that the pile suffers excessive vertical deflection. On the other hand, piles under lateral loads may bend or rotate. In addition, the rigid and flexible pile behavior is different owing to the applied load. Therefore, the flexible pile subjected to lateral load is more complex. Unfortunately, there is a lack of well-documented soil-pile interaction case histories during the earthquakes in cohesionless soil(Finn, 2005). For fulfillment of this goal, it is essential to carry out the soil-pile interaction in cohesionless soil with different relative densities.

1.3 Objectives of the Study

With this background and statement, the main goals are to understand the effects of sand densities on the seismic behavior of the structure supported by pile foundations. The main objectives of this study are as follows:

- To develop the physical model of the soil-pile interaction in sand with different relative densities using Mobile Pluviator.
- To investigate the effects of piles' spacing on the pile-soil-pile interaction.
- To establish new static p-y curves from the physical model in sandy soil.

1.4 Scope of the Study

The majority of the piles that have been damaged during the lateral loads such as earthquake and wind were due to the soil-pile-structure interaction (SPSI). However, the number of the investigations about SPSI is few and they are mostly focused on the liquefaction problems. The reported herein attempts to develop new load-deflection relationship for single pile. A series of different configurations of piles were performed to evaluate the single and grouped pile behavior at two different relative densities. The tests were conducted in dried sand with loose and dense densities. Flexible pile behavior was considered in this study. The preinstalled piles were subjected to statically lateral loads applied at the level of the ground model. The new soil-pile reaction against deflection curves (known as p-y curve) were developed for single pile in the two relative densities of sand in Johor Bahru. Due to the lack of shaking table in a physical model of soil-pile-structure interaction subjected to dynamic loads, the interaction was modeled in numerical analysis under the seismic motions. Beam on Nonlinear Winkler Foundation (BNWF) was used to model the soil-pile-structure interaction and the seismic behavior of the superstructure was estimated based on new and existing p-y curve. The acceleration and displacement time histories of the structure were considered in numerical analysis for the evaluation of the structure's behavior. In this thesis:

- To model the soil-pile interaction a new model of BNWF method was simulated by ANSYS code.
- To spread out the experimental data, a series of the static tests were performed in the laboratory scale.
- Model piles were scaled with the Penang Second Crossing' piles.
- Sandy soil properties from Johor Bahru. were used for the numerical part and the laboratory tests.
- To develop the new p-y curve, the two relative densities of sandy soil (loose and dense) were considered.
- The sand samples were prepared using pluviation method by new designed mobile pluviator.
- The three seismic motions were selected as input motion from Sumatra Island and Kobe-Japan.
- The new p-y curves were verified by API curves in the numerical model.

1.5 Significance of the Study

Significant damages of the piles due to partial or complete collapse of piers have been observed. A large number of the pile foundations have been found to be damaged and failed under lateral loads such as wind and seismic motions. The following benefits from the study may be included:

- A more realistic design with SPI considering, may reduce damages of structure thus can reduce cost.
- This study evaluates the effect of density changes on the SPI.

- This study provides the alternative methods to develop the SPI by other researchers.

1.6 Organization of Thesis

The thesis is organized into 8 chapters. The first chapter presents a brief background on the soil-pile interaction and the necessity to understand the mechanisms associated with this process. In additional, the Chapter 1 provides a description of the problem, scope and layout of this dissertation.

Chapter 2 consists of a comprehensive survey of soil-pile interaction and the effects of this interaction on the seismic behavior of the superstructure. It provides a review on Beam Nonlinear Winkler Foundation (BNWF) method and the effects of pile spacing on the pile group behavior. In addition, the existing methods the sand sample's preparation is presented in Chapter 2. The research methodology, theory and application of the proposed data are discussed in detail in Chapter 3.Chapter 4 describes the used method to prepare the sand sample using the new apparatus in this research. The method is suitable to prepare the samples in large area. In Chapter 5, the behavior of single pile and grouped are described. The different parameters such as the sand density and the different configurations of piles in group are discussed. Chapter 6 describes the behavior of single pile under the lateral loading. The new p-y curve are developed to evaluate the seismic behavior of the structure. Chapter 7 presents the numerical analysis of the SPI using a finite element method. The structure behavior is evaluated by using the new p-y curve and the existing curves. Finally, Chapter 8 summarizes the experimental and numerical findings and make recommendations for future research.

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