Soil-structure interactions analysis for vertical and lateral loaded pile foundations

Analyse des interactions sol-structure dans le cas des fondations en pieux chargées verticalement et latéralement

M. N. Hussien, T. Tobita & S. Iai
Disaster Prevention Research Institute, Kyoto University,Japan

K. M. Rollins
Department of civil and Environmental Engineering , Brigham Young University

E. H. Ramadan
Faculty of Engineering, Assiut University,Egypt

ABSTRACT

The effect of vertical loads on the lateral response of group pile is studied on the basis of soil-pile interaction nature. Coupled soil-pile system is idealized through two dimensional finite elements with soil models idealized by multiple shear mechanism of hyperbolic type. The developed numerical model has been verified by comparing the results with full scale pile group test results. Through comparative studies, it has been found that for a single pile and at a given lateral load, the lateral deflection decreases with the combination of vertical load. For the group pile, the vertical load effect depends basically on pile position and pile spacing to diameter ratio.

RÉSUMÉ

L'effet des chargements verticaux sur la réponse d'un groupe de pieux est étudié sur la base de la nature de l'interaction sol-pieux. Le couple du système sol-pieux est modélisé par la méthode des éléments finis à deux dimensions avec un model du sol représenté par un mécanisme de cisaillement multiple de type hyperbolique. Le model numérique développé a était vérifié en comparant les résultats obtenus avec les résultats des tests réalisés à l échelle réelle d'un groupe de pieux. A travers les études comparatives, il a était trouvé que pour un pilier et un chargement latéral donné, la déviation latérale diminue avec la combinaison du chargement vertical. Pour un groupe de pieux, l'effet du chargement vertical dépend principalement sur la position du pilier et du ratio de l'espacement entre les pieux et le diamètre du pilier.

Keywords : full scale, pile group, axial loading, lateral loading

1 INTRODUCTION

Recently, Pile foundation has become the preferred foundation system for high-rise buildings in urban area. These foundations are not only used to support vertical loads, but also lateral loads and combination of vertical and lateral loads. Several investigators attempted to study the behavior of pile groups under the application of axial loads (Xu & Poulos 2000; Zhu & Chang 2002; Wang & Sitar 2004), others attempted to study the behavior under pure lateral loads (Rollins et al. 2005; Tobita et al. 2006) among others. The results of these extensive studies have formed the basis for the current design practice of pile group. According to the current design codes, piles are independently analyzed first for axial load to determine their bearing capacity and settlement and then for the lateral load to determine the stresses and deflections (Anagnostopoulos & Georgiadis 1993). The laboratory and field data on the response of piles under the combined action of vertical and lateral loads is rather limited. In view of the above stated issues, this paper uses a two dimensional finite element analysis based on multi-shear mechanism constitutive relationship, **FLIP** (**F**inite element analysis program for **LI**quefaction **P**rocess) (Iai et al. 1992), to investigate the behavior of group pile under the application of lateral loading and further to study the effect of the vertical load on the lateral loaded group pile response.
A series of full scale pile tests performed at a clayey site in the Salt Lake City International Airport (Snyder 2004) is used to verify the validity of the proposed FE model employed in this study. The full scale tests consist of a combination of a single and 3 by 5 group piles under lateral loads. This comprehensive combination allows rigorous study and restricts the arbitrary parameter back-fitting that would be often possible if only a partial combination of the test data were available.

2 VALIDATION BY COMPARISON WITH FULL CALE TEST RESULTS

2.1 *Full scale tests of a single and 3×5 group pile*

The test pile has a 0.324 m outside diameter with a 9.5 mm wall thickness. Steel pipe piles were driven closed end to an embedment depth of 11.6 m. The piles in the group were driven in a 3×5 pattern with a nominal spacing of 3.92 pile diameters center to center in the loading direction and of 3.29 pile diameters perpendicular to the loading direction. The test piles in the group had the same properties as the single pile. The load was applied at 495 mm above the ground surface. The piles and the load frame are pin-connected so that the rotation is free at the pile head (Snyder 2004).

2.2 *Finite element modeling and parameter identification*

2.2.1 *Finite element*

The two dimensional finite element FLIP is employed to simulate the full scale lateral load tests of a single and 3×5 group pile. Five piles in the middle row out of 3x5 pile group are the target of the analysis. Figure 1 shows the general layout and meshing of the FE model. The same meshing of soil profile is used for the analysis of a single pile. In the analysis,

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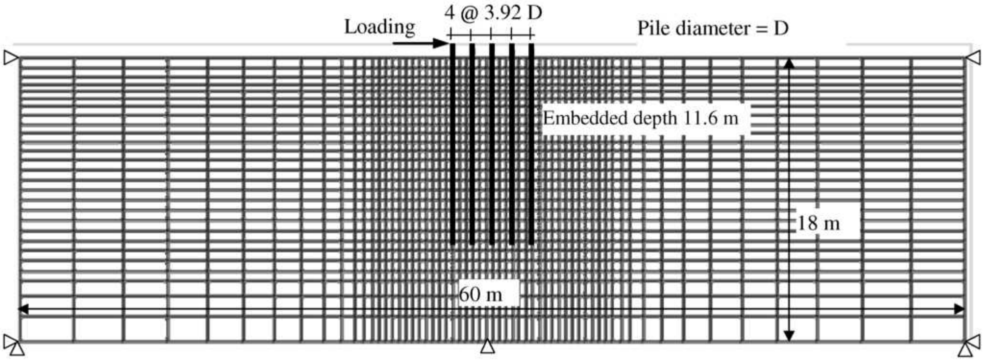

Figure 1. General layout and meshing of the FE model.

displacements at side boundaries are fixed in horizontal direction, while that of the bottom boundary are fixed both in horizontal and vertical direction. Top and bottom of piles are set as displacement and rotation free to simulate the condition at the full-scale tests.

2.2.2 *Soil model*

Soil model was idealized by multiple shear mechanism constitutive relationship of hyperbolic type (Iai et al. 1992). In the analysis, Idealized soil layers derived in Snyder (2004) are adopted. Soil properties are obtained from the geotechnical investigation data at the site, including standard laboratory tests of soil mechanics such as Atterberg limits, shear strength tests, consolidation tests, and In-situ tests such as cone penetration testing, pressure meter testing, and standard penetration testing. Idealized soil layers and model parameters for soil elements used in this study are defined in Table 1.

2.2.3 *Pile model*

Bilinear beam elements are used for modeling piles. Model parameters of pile element are defined in Table 2. Parameters for piles are taken from industrial standard (Tobita et al. 2006).

2.2.4 *Soil-pile interface model*

Joint elements are used at the soil-pile interface to represent slide and separation between them. As shown in Fig.2, the separation-contact model in the compression side is idealized using a high rigidity spring (Kn) between the pile and soil elements to avoid the overlapping of the elements during compression. In the tension side, no stress will transfer between the pile and the soil at any tension stress value. Model parameters for joints element are defined in Table 3.

2.2.5 *End bearing spring*

The axial soil reactions at pile tips are simulated using nonlinear spring element (Q-Z curve). The nonlinear spring at pile tip is represented according to Zhang et al. (1999).

2.2.6 *Pile-soil interaction spring*

The interaction between a pile and the surrounding soil in three dimensional type is idealized in the two dimensional analysis as follows. A nonlinear-spring element as shown in Fig. 3 is used to represent the soil-pile interaction. Underlying concept of this spring is to analyse the soil deformation between the piles in a row perpendicular to the direction of load. Parameters of the spring element were determined by parametric studies on soil-pile interaction in 2-D horizontal plan (detail can be found in Hussien et al. 2008).

2.3 *Comparison of measured and computed results*

2.3.1 *Single pile under lateral load*

lateral load is statically applied at the pile head (0.495 m above the ground surface) until the displacement of 90 mm at the loading point is achieved. Figure 4 shows computed and measured load deflection curves at pile head. The computed curve agrees well with the field results.

Table. 1. Idealized soil layers and model parameters of soil elements.

Soil layer	Depth (m)	γ_{sat} (t/m^3)	G_{ma} (kPa)	υ	K_a (kPa)	ϕ_f (degrees)	c (kPa)
Soft clay	0-1.22	1.92	12,200	0.33	31,720		27
Soft clay	1.22-2.14		18,000		46,800		40
Soft clay	2.14-3.06		15,800		41,080		35
Sand	3.06-4.80	1.83	161,000		418,600	38	
Soft clay	4.80-5.33	1.92	34,100		88,660		56.9
Soft clay	5.33-5.87		15,000		39,000		25
Soft clay	5.87-6.48		32,400		84,240		54
Sand	6.48-11.6	1.83	127,000		330,200	33	
Sand	11.6-18.00		40,600		105,560	31	

Table. 2. Model parameters for pile element.

Gs (kPa)	υ	ρ (t/m^3)	Initial flexural rigidity (kPa)	Flexural rigidity after yield (kPa)
77,500,000	0.29	7.9	108,67	65,200

Table 3. Model parameters for joint element.

Interface angle of friction (ϕ_J)	Cohesion(c_J)	Normal stiffness (kN/m^3)	Tangential stiffness (kN/m^3)
2/3 ϕ_f	c	1,000,000	1,000,000

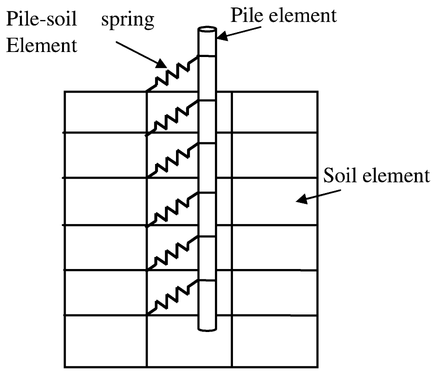

Figure 3. Concept of pile-soil spring element.

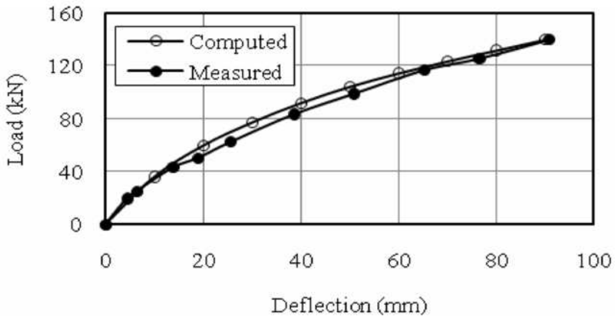

Figure 4. Single pile response: Measured and computed load versus pile head deflection curve

2.3.2 *Group pile under lateral load*

In the analysis of group pile under lateral load, lateral load is statically applied in the same manner as single pile. The same model parameters as those for the single pile are used without arbitrary adjustment or back-fitting to the measured data of group pile test. Computed and measured average load per pile versus deflection for no 1, 3, and 5 pile are shown in Figs. 5a, 5b, and 5c respectively. Both of the measured and the computed results indicate that the load distribution in the pile group is not uniform but is a function of the pile position. The FE analysis slightly overestimates the load carrying capacity of the leading pile (pile no 1) while the computed loads of third and Fifth piles are in good agreement with the measured ones.

From the above results, it can be concluded that, there was a reasonable agreement between full scale and FE simulation results thus the developed FE model can model the behavior of lateral loaded pile group with the accuracy required to design practice, accounting for the pile-soil interaction and the nonlinearity of material, and It would be possible to use the developed model to further investigate of group pile behavior.

3 NUMERICAL STUDY

Because of the high cost and logistical difficulty of full scale tests on pile groups, it is desirable to benefit from the proposed FE simulation to further study the actual behavior of pile groups with an acceptable accuracy. In this section, the same FE model with replacing all soil layers by a uniform layer of sand will be used to study the effect of vertical load on the response of the lateral loaded piles embedded in sand. Model parameters for the sand layer element are shown shaded in Table 1. In the analysis, vertical displacement of 0.1d (d = pile diameter) was applied prior to the application of lateral load for both a single and group piles then lateral loads are statically applied until a target horizontal displacment of 3d is achieved. The maximum vertical applied displacment at pile head was kept constant during the application of the lateral displacement. To study the effect of vertical load on

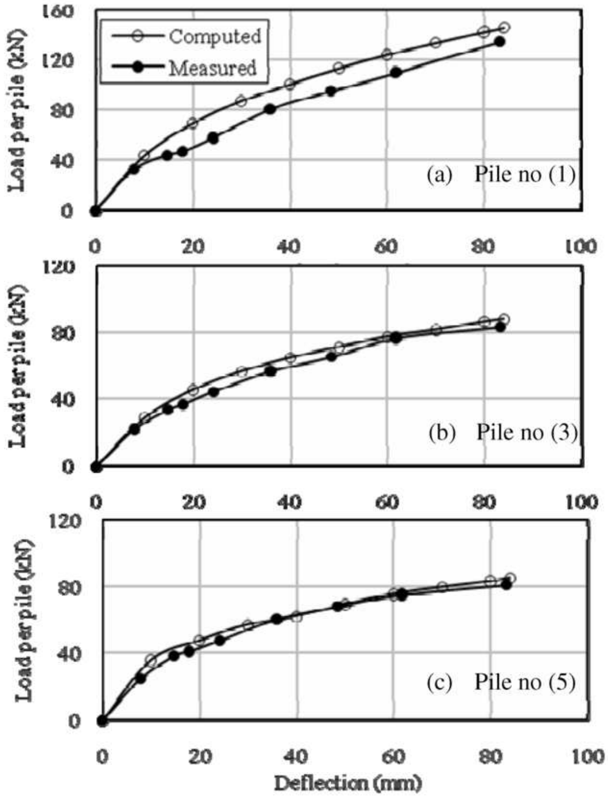

Figure 5. Group pile response: Measured and computed load versus pile head deflection of no 1, no 3, and no 5 pile

the response of each pile in the lateral loaded group pile and its relation with the group effect., a total of 10 cases with different pile spacing to daimeter ratios were considered. Pure lateral load is considered in half of these cases while a comination of vetical and lateral load is considerd in the others.

3.1 *Single pile response under combined load*

Figure 6 shows load versus pile head deflection computed with and without the effect of vertical load for single pile. It could be observed that for a given lateral load, the lateral deflection decreases with the combination of vertical loads. At maximum target deflection of 3d (97.2 mm), a vertical applied displacement of 0.1d (32.4 mm) leads to 6 % increase of the ultimate lateral load-carrying capacity of the pile.

3.2 *Group pile response under combined load*

Figure 7 shows load versus pile head deflection computed with and without the effect of vertical load for no 1, 3, and 5 pile at constant pile spacing to diameter ratio of 3.92. It could be

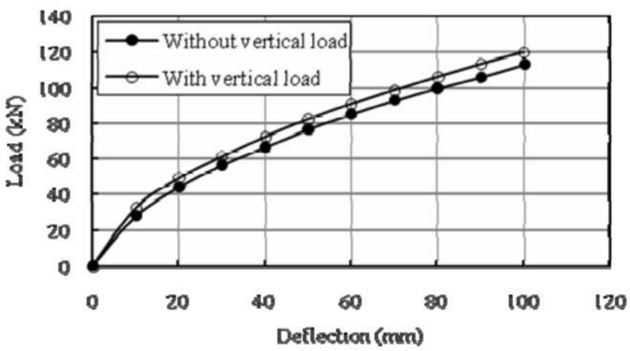

Figure 6. Single pile response: Measured and computed load versus pile head deflection curve

observed that the effect of vertical load on the response of each pile in a group is not the same but is a function of the pile position. At any lateral deflection level, the load carried by the leading pile (pile no 1) is reduced when the vertical load is introduced. For no 3, and 5 pile, introducing vertical load prior to the application of lateral load leads to a noticeable increase of the load carrying capacity of these piles.

Figure 8 shows the variation of the load multiplier (ratio of pile load when vertical load is considered to pile load when vertical load is not considered) with pile spacing to diameter ratio. This figure indicates that at closed spacing pile group, the effect of vertical load on the lateral response of the group is clear and this effect decreases with the increase of pile spacing. Load multiplier value approaches a constant value of 1.06 at widely spaced groups. This value is identical to the corresponding single pile value.

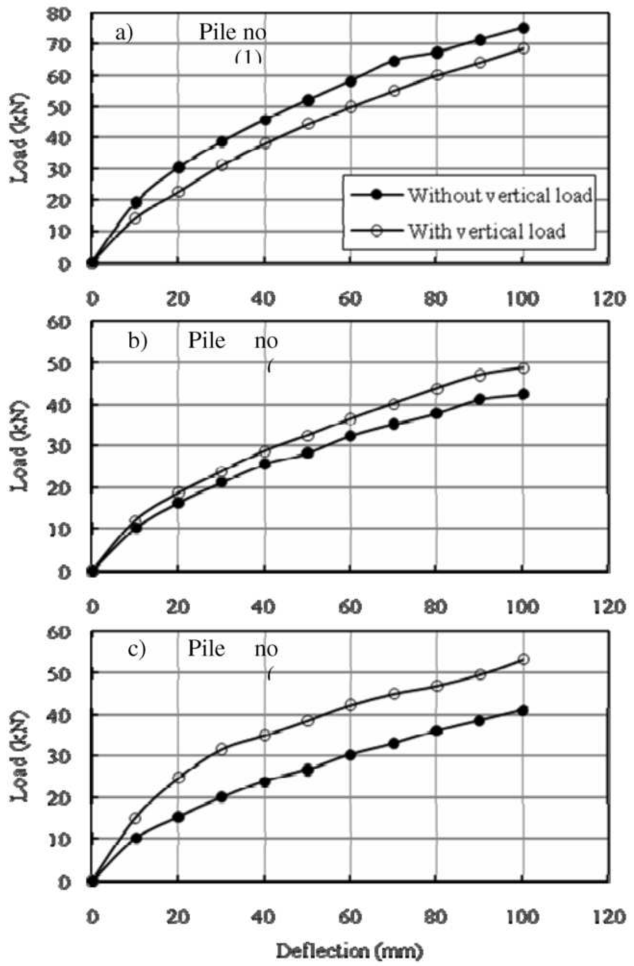

Figure 7. Group pile response: Measured and computed load versus pile head deflection curve, pile spacing/ diameter = 3.92

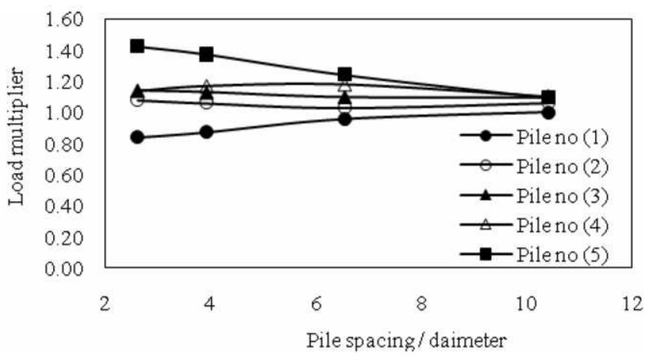

Figure 8. Load multiplier versus pile spacing to diameter ratio.

3.3 *Conclusions*

A two dimensional finite element analysis based on multi-shear mechanism constitutive relationship, **FLIP** is employed to investigate the behavior of group pile under the application of lateral loading and to further study the effect of the vertical load on the lateral loaded group pile response. From the findings of this study, the following conclusions can be drawn:

1. Both of the measured and the computed results indicate that the load distribution in the laterally loaded group pile is not uniform but is a function of the pile position.
2. For single pile and at a given lateral load, the lateral deflection decreases with the combination of vertical loads. At maximum target deflection of 3d, a vertical applied displacement of 0.1d leads to 6 % increase of the ultimate lateral load-carrying capacity of the pile.
3. The effect of vertical load on the response of each pile in a group is not the same but is a function of the pile position.
4. At any lateral deflection level, the load carried by the leading pile is reduced when the vertical load is introduced. For trailing piles, introducing vertical load prior to the application of lateral load leads to a noticeable increase of the load carrying capacity of these piles.

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