Assessment of Pile Group Response under Lateral Load

Mohamed Ashour
University of Nevada, Reno, NV

Patrick Pilling
Black Eagle Consulting, Inc., Sparks, NV

Gary Norris
University of Nevada, Reno, Reno, NV

ASSESSMENT OF PILE GROUP RESPONSE UNDER LATERAL LOAD

Mohamed Ashour
University of Nevada, Reno
Reno, Nevada-USA-89557

Patrick Pilling
Black Eagle Consulting, Inc.
Sparks, Nevada-USA-89431

Gary Norris
University of Nevada, Reno
Reno, Nevada-USA-89557

ABSTRACT

Assessment of the response of a laterally loaded pile group based on soil-pile interaction is presented in this paper. The behavior of a pile group in uniform and layered soil (sand and/or clay) is predicted based on the strain wedge (SW) model approach that has been developed to predict the response of a flexible pile under lateral loading. The pile group is characterized in terms of three-dimensional soil-pile interaction and then transformed into its one-dimensional beam on elastic foundation equivalent with associated parameters (modulus of sugrade reaction). Therefore, the interference among the piles in a group is determined based on the geometry of the mobilized passive wedge of soil in front of the pile in addition to the pile spacing. The overlap of shear zones among the piles in the group varies along the length of the pile and changes from one soil to another in the soil profile. Also, the interference among the piles grows with the increase in lateral loading. The modulus of subgrade reaction determined will account for the additional strains (i.e. stresses) in the adjacent soil due to pile interference within the group.

INTRODUCTION

As presented by Ashour et al. (1996 and 1998) and Norris (1986), the prediction of single pile response to lateral loading using the SW model correlates traditional one-dimensional beam on an elastic foundation (BEF) response to the three-dimensional soil-pile interaction. In particular, the Young's modulus of a soil is related to the corresponding horizontal subgrade modulus; the deflection of the pile is related to the strain that exists in the developing passive wedge in front of the pile; and the beam on an elastic foundation line load for a given deflection is related to the horizontal stress change acting along the face of the developing passive wedge. The three-dimensional characterization of the laterally loaded pile in the SW model analysis provides an opportunity to study the interference among the piles in a pile group in a realistic way. The influence of the neighboring piles on an individual pile in the group will be a function of soil and pile properties, pile spacing, and the level of loading. These parameters are employed togther in the SW model analysis to reflect the soil-pile interaction on pile group behavior. The paper presented illustrates the links between the single pile and the pile group analysis.

The pile group procedure commonly used today employs the p-y multiplier technique (Brown et al. 1988). Such procedure is based on reducing the stiffness of the traditional (Matlock-Reese) p-y curve by using a multiplier ($f_m < 1$), as seen in Fig. 1. The value of the p-y curve multiplier should be assumed and is based on the data collected from full-scale field tests on pile groups which are few (Brown et al. 1988). Consequently, a full-scale field test (which is costly) is strongly recommended in order to determine the value of the multiplier (f_m) of the soil profile at that site. Moreover, the suggested value of the multiplier (f_m) is taken to be constant in the same soil at any level of loading.

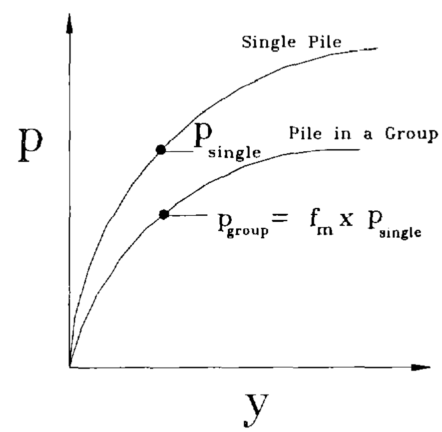

Fig. 1. p-multiplier (f_m) concept for pile group (Brown et al. 1988)

As seen in Fig. 2, the interference among the piles in the group varies with depth, even in the same uniform soil, and increases with level of loading as the wedges grow deeper and fan out farther. Therefore, the use of a single multiplier that is both constant with depth and constant over the full range of load/deflection would seem to involve significant compromise.

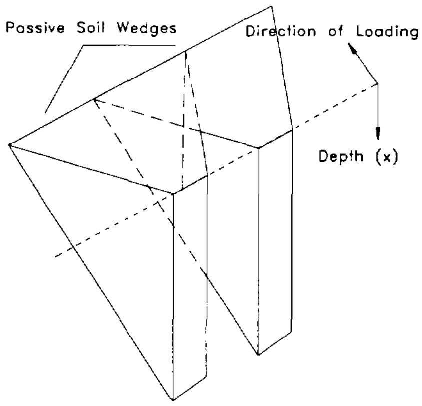

Fig. 2. Lateral Interference between two neighboring piles.

The assessment of the response of a laterally loaded pile group based on soil-pile interaction is presented in this paper. . The strain wedge (SW) model approach, developed to predict the response of the flexible pile under lateral loading (Ashour et al. 1998; and Ashour and Norris 2000), is extended in this paper to analyze the behavior of the pile group in uniform or layered soil. Several field and experimental tests reported in the literature are used to demonstrate the validity of the approach.

CHARACTERIZATION OF PILE GROUP INTERFERENCE

The pile group is characterized in terms of three-dimensional soil-pile interaction and then converted into its equivalent one-dimensional beam on elastic foundation model with associated parameters (modulus of sugrade reaction). Therefore, the interference among the piles in a group is determined based on the geometry of the passive wedge of soil in front of the pile in addition to the pile spacing. A fundamental concept of the SW model is that the size and shape (geometry) of the passive wedge of soil changes in a mobilized fashion as a function of both soil and pile properties at each level of loading and is expressed as follows:

$$\Theta_m = 45 - \frac{\varphi_m}{2} \qquad (1)$$

$$\beta_m = \Theta_m + \varphi_m = 45 + \frac{\varphi_m}{2} \qquad (2)$$

$$\overline{BC} = D + (h - x)\ 2\tan\beta_m\ \tan\varphi_m \qquad (3)$$

As seen in Fig. 3, $\overline{BC}$ is the width of the wedge face at any depth (x). D is the width of the pile cross section, h is the current depth of the passive wedge which depends on the lateral deflection of the pile and, in turn, on the pile properties such as pile stiffness and pile head fixity. φ_m is the mobilized fan angle of the wedge (also the mobilized effective stress friction angle of the soil) which is a function of the current stresses/strains in the soil as presented by (Ashour et al. 1998).

The overlap of shear zones among the piles in the group varies along the length of the pile (as shown in Figs. 3 and 4). Also, the interference among the piles grows with the increase in lateral load. The modulus of subgrade reaction which is determined based on the SW model approach will account for the additional strains (i.e. stresses) in the adjacent soil due to pile interference within the group (Fig. 4). Thus the modulus of subgrade reaction (i.e. the secant slope of the p-y curve) of an individual pile in the group will be reduced in a mobilized fashion according to pile and soil properties, pile spacing and the level of loading. As a result, no reduction factor for the p-y curve (currently, assumed to be a constant value at any depth or level of loading) is needed in order to treat the pile in the group as an equivalent single pile. The SW model allows the direct evaluation of the pile-group stiffness reduction as required, for instance, in the assessment of the stiffness of the bridge foundations for the seismic analysis of a highway bridge.

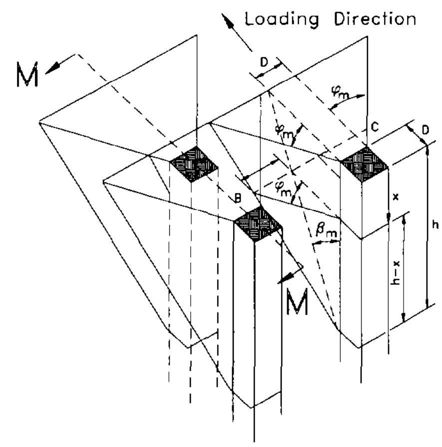

Fig. 3. Configuration of the mobilized passive wedges, and associated pile group interference.

The multi-sublayer technique developed by Ashour et al. (1996 and 1998) provides a good means to determine the interference among the passive wedges of the piles in the group and the additional stress/strain induced in the soil in these wedges. As seen in Fig. 3, the soil around the piles in the group interferes with that of adjacent piles horizontally by an amount that varies with depth. The multi-sublayer technique allows the SW model to determine the overlap of the wedges of neighboring piles in different sublayers over the depth of the interference as shown in Fig. 4.

This provides a great deal of flexibility in the calculation of the growth in stress (and, therefore, strain) in the overlap zones which increases with the growth of the passive wedges. The main objective in the calculation of the area of overlap among the piles is to determine (with increased load) the increase in soil strain in the passive wedge of the pile in question.

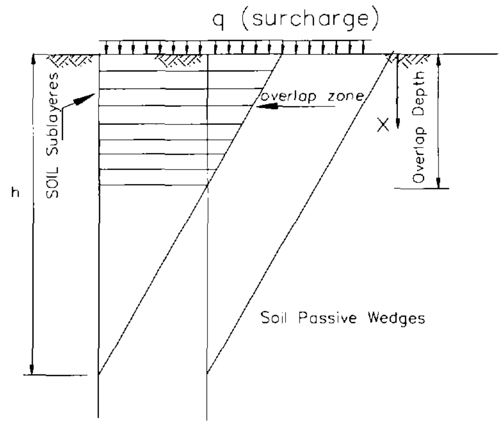

Fig. 4. Front overlap among soil sublayers in two adjacent passive wedges (Section M-M in Fig. 3)

A value of soil strain (ε) (at a particular load level) in the passive wedge is assumed for a given soil profile. The response of a single pile (similar to the piles in the group) in the same soil profile will be determined at this value of soil strain. The shape and the dimensions of the developed passive wedge is then assessed (i.e. $\overline{BC}$, φ_m, and β_m in Fig. 3) as presented by Ashour et al. (1998). This will include the values of stress level in each soil sublayer i (SL_i), Young's modulus (E_i), and corresponding modulus of subgrade reaction $(E_s)_i$.

Considering a group of single piles under the same previous conditions (SL, $\overline{BC}$, h, φ_m, and β_m), the passive wedges of soil in front of the piles will interact and overlap the neighboring ones, as seen in Figs. 3 and 4. Therefore, overlap zones of stress will exhibit larger values of soil strains and stresses. The increase in soil strain in the passive wedge depends on the number of the interfered passive wedges over the same area as shown in Fig. 5. Such interference also depends on the location of the pile in the group.

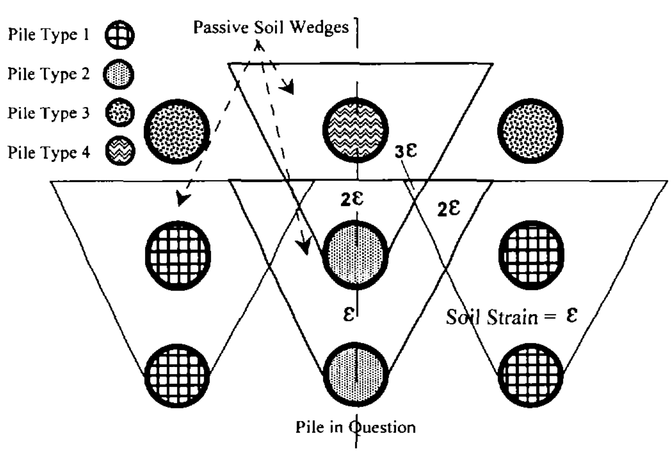

Fig. 5. Horizontal (lateral and frontal) interference for a particular pile in the pile group at a given depth.

The average value of strain accumulated in a particular soil sublayer (i) in the passive wedge of an individual pile will be calculated, $(\varepsilon_g)_i$.

$$(\varepsilon_g)_i = \varepsilon_i + \Delta\varepsilon_i \tag{4}$$

where Δε is the growth in soil strain in that soil sublayer due to the overlap of adjacent pile wedges. ε_g will be assessed for each soil sublayer in the passive wedge of each pile in the group. The type of pile in the group is based on the location of the pile by row (leading/trailing row) and the location of the pile in its row (side/internal pile) as seen in Fig. 5. Δε is determined as a function of the area of overlap.

Thereafter, the change in the soil Young's modulus and, consequently, the moulus of subgrade reaction in each sublayer will be assessed. Once the profile of the modulus of subgrade reaction along the individual pile is predicted, the pile will be analyzed as an equivalent single pile (with all piles in the group to have the same pile head deflection). It should be noted that the angles and dimensions of the passive wedge that are obtained from Eqns. 1 through 3 will be modified according to the calculated value of ε_g.

EVALUATION OF THE YOUNG'S MODULUS, E_g

Based on the value of soil strain assessed in the overlapped sublayers at the current level of loading, the value of Young's modulus, $(E_g)_i$, of the soil sublayer i is expressed as

$$(E_g)_i = \frac{SL_i\,(\Delta\sigma_{hf})_i}{(\varepsilon_g)_i} \tag{5}$$

where stress level (SL_i), associated with ε_g in a given sublayer i, is determined based on the stress-strain relationship developed by Norris (1986) and modified by Ashour et al. (1998). The relationship between the corresponding stress level (SL) in sand, for instance, and the associated mobilized effective stress friction angle (φ_m) in a soil sublayer i is

$$SL_i = \left(\frac{\Delta\sigma_h}{\Delta\sigma_{hf}}\right)_i = \frac{\tan^2\left(45 + (\varphi_m)_i\right) - 1}{\tan^2\left(45 + \varphi_i\right) - 1} \tag{6}$$

where $\Delta\sigma_h$ and $\Delta\sigma_{hf}$ are the current horizontal stress change (due to pile-head lateral load and pile group interference) and the deviatoric stress at failure, respectively. The stress level calculated in Eqn. 6 reflects the stresses in the soil around the pile in question due to the pile head load and the stresses from the neighboring piles (Fig 5).

It should be noted the Young's modulus (E_g) calculated using Eqn. 5 results from the original strain in the passive wedge (ε) as a single pile, and the additional soil strain (Δε) which develops in the overlap zones between the pile in question and the neighboring piles. Based on the amount of interference among the piles in the group, the value of the Young's modulus (E_g) should be less or equal to the associated modulus (E) for the single pile.

EVALUATION OF THE MODULUS OF SUBGRADE REACTION, E_{sg}

Based on the concepts of the SW model, the modulus of subgrade reaction for an individual pile in the group can be expressed as

$$\left(E_{sg}\right)_i = \frac{p_i}{y_i} = \frac{A_i\, D\, (\varepsilon_g)_i\, (E_g)_i}{\delta_i \left(h - x_i\right)} \tag{7}$$

where x is the depth of a soil sublayer i below the pile head. δ is the linearized deflection angle of the deflection pattern as shown in Fig. 6. A is a parameter that governs the growth of the passive wedge and the flow around failure, and is a function of soil and pile properties (Ashour et al. 1998). Compared to the case of the single pile, the developing passive wedge of a pile in a group will be larger or equal to that of the single pile (depending on the amount of pile interference). However, the criteria presented by Ashour et al. (1998) and Ashour and Norris (2000) continue to govern the development of flow around failure, and variation of the BEF soil-pile reaction (p) and lateral deflection (y) in the single pile analysis continue be employed with the pile group analysis.

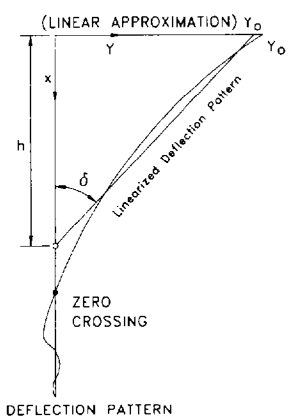

Fig. 6. Deflection pattern of a laterally loaded pile in the SW model analysis (Ashour et al. 1998)

It should be expected that the resulting modulus of subgrade reaction of a pile in a group, E_{sg}, is equal to or softer than the E_s of the single pile at the same depth (Fig 7). The value of E_s will vary with the level of loading and the growth of the soil stress in the developing passive wedge. Thus, there is no constant variation or specific pattern for changes in E_s of the individual piles in the pile group.

The modulus of subgrade reaction of a pile in a group should reflect the mutual resistance between the soil and the pile. However, a portion of the pile deformation (Δy_i) results from the additional stresses in the soil (and, therefore, strains, $\Delta\varepsilon$) which result from the effect of the neighboring piles (Fig. 5). Therefore, under a particular lateral load, the pile in the group will yield deflections more than those of the single pile. The additional deflection at any pile segment, (Δy_i), due to $\Delta\varepsilon_i$ does not contribute any additional resistance for the pile in question. Also, the soil-pile reaction (p) is affected by the changes in stress and strain in the soil, and the varying geometry of the passive wedge.

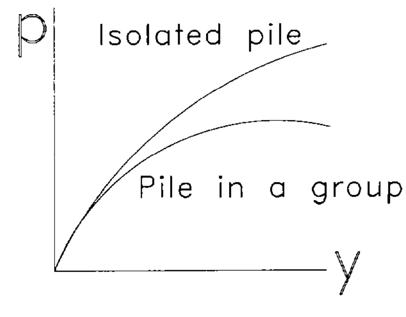

Fig. 7. Change in the modulus of subgrade reaction (i.e. the p-y curve) due to pile interference in the pile group at different levels of loading according to SW model.

Having reduced values of E_s along the individual piles in the group, the piles in the group will be analyzed as equivalent single piles by BEF analysis. The pile head load and deflection of the piles in the group can be predicted and compared to that of the single pile response.

CASE STUDIES

Full-Scale Load Test on a Pile Group in Sand

A full-scale lateral load test on a 3 x 3 pile group in sand overlying an overconsolidated clay was conducted at the University of Houston, Texas (Morrison and Reese, 1986). The results obtained from this load test were used to develop an approach (the f_m multiplier) to predict the response of laterally loaded pile groups in sand (Brown et al. 1988). This pile group of three diameter pile spacing was embedded in approximately 3 m of a dense to very dense uniform sand overlying an overconsolidated clay. The piles consisted of steel pipe with an outside diameter of .275 m, a wall thickness of 9.3 mm, a 13 m embedded length, and a bending stiffness (EI) of 1.9×10^4 kN-m^2. The soil properties (the effective unit weight, and the angle of internal friction) suggested by Morrison and Reese (1986) were used in the SW model analysis.

Figures 8 and 9 show a comparison between the field data and the results obtained by using the SWM program (Ashour et. al. 1997 and 1998). As seen in Figs. 8 and 9, the observed and predicted response of an average pile in the tested pile group are in good agreement. Before a comparison between pile group response can be made in this case, it is important that the strain wedge model accurately predicts the response of an isolated pile embedded in the same soil profile as shown in Figs. 8 and 9.

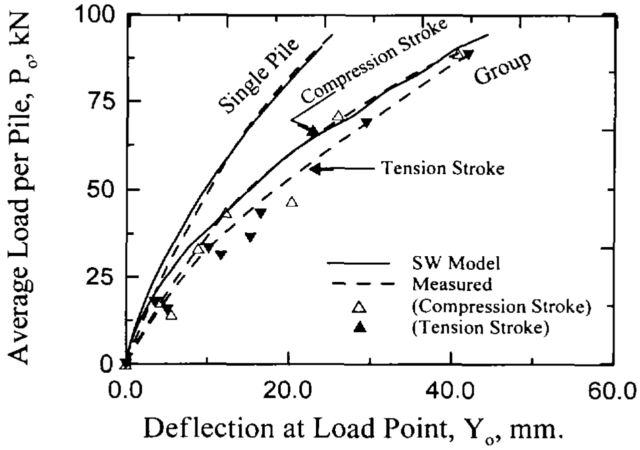

Fig. 8. Average pile-head lateral load vs. deflection for a pile group (3 x 3) in sand.

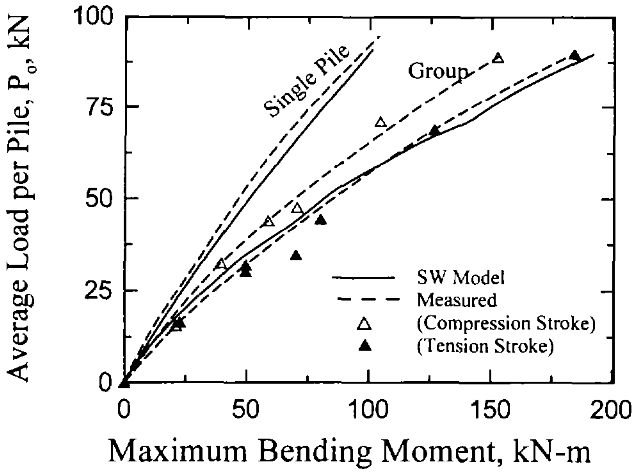

Fig. 9. Average pile-head lateral load vs. maximum bending moment for a pile group (3 x 3) in sand.

<u>Full-Scale Load Test on a Pile Group in Layered Clay</u>

A full scale 3 x 3 pile group was driven in overconsolidated clay layers (Brown and Reese 1986; and Brown et al. 1987). The pile group tested had a three diameter pile spacing and was laterally loaded 0.3 m above ground surface. The nine pipe piles tested had the same properties as the piles used in the previous case study. The soil properties (ε_{50}, the soil unit weight, and the undrained shear strength of clay) evaluated by Brown and Reese were employed in the SW model analysis.

Compared to the observed field data for the lateral response of an average pile in the group, the SW model provides good prediction for pile-head load versus deflection, and pile-head load versus maximum bending moment (Figs. 10 and 11). The assessed behavior for an isolated pile is also in very good agreement with the field data. It should be noted that this case represents a layered soil profile which has different levels of wedge interference in each soil layer at every level of loading along the depth of wedge overlap.

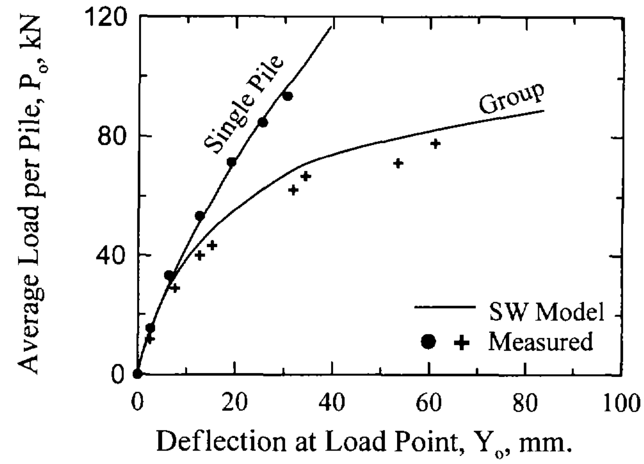

Fig. 10. Average pile-head lateral load vs. deflection for a pile group (3 x 3) in clay.

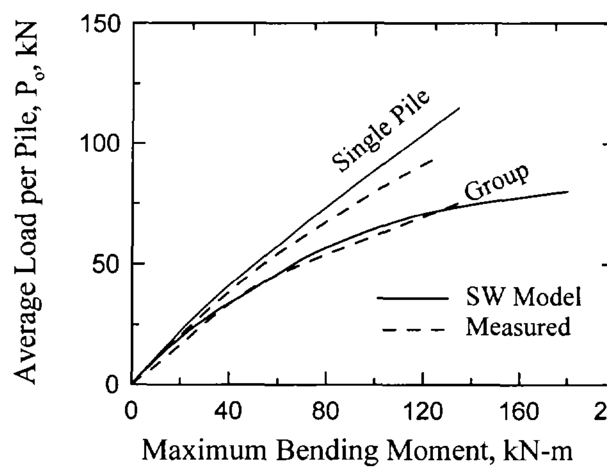

Fig. 11. Average pile-head lateral load vs. maximum bending moment for a pile group (3 x 3) in clay.

It should be noted that the procedure presented here has the capability to predict the pile head response, deflection, and maximum bending moment for every individual pile in the group (type 1 through type 4 based on pile location, as seen in Fig. 5) not just the average pile response. Also, the additional contribution to pile group resistance due to the existence of an embedded pile cap (not presented in this paper) can be evaluated at any level of lateral loading.

SUMMARY

As presented in this paper, the SW model has the capability to assess the response of a laterally loaded pile group. The SW model characterizes the interference among the piles in the group based on the envisioned three-dimensional interaction of the associated passive wedges, in order to then calculate the associated BEF modulus of subgrade reaction for each pile in the group. Thereafter, each individual pile in the group is analyzed by BEF analysis. This procedure allows the calculation of the amount of interference among the piles in the group according to soil and pile properties, and the level of loading. No reduction factor or a multiplier is needed in this procedure. This procedure reduces the uncertainty of the analysis of laterally loaded pile groups.

REFERENCES

Ashour, M., Pilling, P., Norris, G., and Perez, H. [1996]. *Development of Strain Wedge Model Program for Pile Group Interference and Pile Cap Contribution Effects.* @, CCEER, Report No. 96-4, Civil Engrg Dept., University of Nevada, Reno.

Ashour, M., Norris, G., and Pilling, P. [1998]. *Lateral Loading of a Pile in Layered Soil Using the Strain Wedge Model.*.@, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 124, No. 4, pp. 303-315.

Ashour, M. and Norris, G. [2000]. *Modeling Lateral Soil-Pile Response Based on Soil-Pile Interaction.*@, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 126, No. 5, pp. 420-428.

Ashour, M., Pilling, P., and Norris, G. M. [1998]. *Updated Documentation of the Strain Wedge Model Program for analyzing Laterally Loaded Piles and Pile Groups.* @, 33rd Engineering Geology and Geotechnical Engineering Symposium, March 25-27, Reno, Nevada, pp. 177-178.

Ashour, M., Pilling, P., and Norris, G. M. [1997]. *Documentation of the Strain Wedge Model Program for analyzing Laterally Loaded Piles and Pile Groups.* @, 32nd Engineering Geology and Geotechnical Engineering Symposium, March 26-28, Boise, Idaho, pp. 344-359.

Brown, D. A. and Reese, L. C. [1985]. *Behavior of a Large-Scale Pile Group Subjected to Cyclic Lateral Loading.* @, U. S. Department of Interior, Reston, Virginia; Dept. of Research, Federal Highway Administration, Washington, D. C.; U. S. Army Engineer, Waterways Experiment Station, Vicksburg, Mississippi..

Brown, D. A., Morrison, C., and Reese, L. C. [1988]. *Lateral Load Behavior of Pile Group in Sand.* @ *Journal of Geotechnical Engineering*, ASCE, Vol. 114, No. 11, pp. 1261-1276.

Morrison, C. and Reese, L. C. [1986]. *Lateral-Load Test of a Full-Scale Pile Group in Sand.* @, US Department of Interior, Reston, Virginia; Department of Research, Federal Highway Administration, Washington, D. C.; U. S. Army Engineer, Waterways Experiment Station, Vicksburg, Mississippi.

Norris, G. M. [1986]. *Theoretically Based BEF Laterally Loaded Pile Analysis.* @, Third International Conference on Numerical Methods in Offshore Piling, Nantes, France, pp. 361-386.