Influence of Sand State on Network effect of Micropiles

By

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ABSTRACT

Past studies on micropile behavior on sands have treated the effects of density and confining stress separately. It had often led to conflicting results in many laboratory and field tests and problems associated with the interpretation of network behavior of micropiles. This paper presents the results of the numerical simulation conducted using FLAC3D to study the combined influence of sand density and stress level on micropile network performance. The constitutive model used in the analysis explicitly incorporates the effect of initial state of sand through a state parameter expressed as the difference between the current void ratio and the void ratio at the critical state at the same confining pressure. The numerical simulations show that network effect of micropiles is significantly influenced by initial sand state and sand dilatancy. The study concludes that the use of initial state parameter rather than density or confining stress alone as often done in the current state of practice would lead to a consistent methodology in the interpretation of micropile test results.

Introduction

Micropiles are small diameter (typically less than 300 mm) drilled or cast in-place piles designed with high structural strength by large amount of steel reinforcement. They are rapidly gaining popularity for foundation support and slope stabilization due to their ready access to installation in locations with low headroom and restricted access. Micropile contribution to foundation support is generally derived from two mechanisms: direct structural support and soil reinforcement. These two mechanisms are designated as Case 1 and Case 2 in the literature, respectively (Bruce et al., 1989, Juran et al. 1997, FHWA, 2000). Case 1 micropiles are generally referred to pile groups vertically installed to directly support foundation load whereas Case 2 micropiles are three-dimensional array of reticulated elements, also described by Lizzi as ‘root pile’ (1982), to encompass and internally reinforce soil, resulting in a network or “knot” effect of composite pile-soil foundation. The potential for enhanced engineering behavior of reticulated micropile network systems compared to that of micropile group has been continually investigated by numerous researchers in the past (Lizzi, 1982, Plumelle, 1984, Forever,2002). The results of laboratory and full-scale experiments reported by various investigators, have, however, resulted in significantly different and apparently contradictory effects of group of micropiles. Lizzi and Carnevale (1979) have observed a dramatic positive group effect (220%) on the capacity of reticulated micropile networks over those vertically installed micropile groups with the same number of piles with identical dimensions. This dramatic increase was not observed by other full-scale experiments conducted to re-examine the results of Lizzi (FOREVER 2002).

It is well known that the behavior of sand is influenced by a number of factors including two important ones: relative density and confining stress level. It is believed that the disagreements described above on the behavior of group and network piles are in part due to not accounting for the state of sand in the different test programs and in the interpretation of their results. Most full-scale tests replicate the sand with its field relative density (or the void ratio). Such replication is insufficient to account for the important effects of confinement stress. Thus, it would be difficult to compare the results of laboratory and full-scale experiments from a unified perspective, without accounting for the combined effects of relative density and confining stress level on sand behavior.

The influence of density and confining pressure can be combined through a measure termed state parameter ψ as shown in Figure 1. The state parameter describes the proximity of the initial or the current state of the soil to its critical state line (Been and Jefferies 1985). As seen from Fig. 1, if ψ is negative, the sand is considered in a dilative state, and if ψ is positive, the sand is in a contractive state. In this regard, at small confining stress levels even a loose sand may behave in a dilative manner similar to that of a very dense sand; whereas at a high confining stress a dense sand may in fact behave in a contrive manner as in the case of a loose sand. The state dependent behavior of sand implies that caution should be exerted in the interpretation and extrapolation of experimental results obtained at different test scales. Better interpretation of micropile test results could be achieved if a single measure such as the state parameter is used rather than the current use of density alone.

Numerical analysis is an effective way to study the behavior of micropiles under various states of sand as, once the model is verified, conditions can be changed with little effort to conduct a parametric study on the system variables. Foerster and Modaressi (1995), Estephan and Frank (2001), Sadek (2002), and Sadek & Shahrour (2004) have performed numerical analyses of micropiles under various conditions. Most of them have, however, not focused on the effects of sand state on the performance of a micropile, group, or network.

This paper uses a constitutive model that explicitly accounts for soil state through the state parameter ψ implemented into the widely used commercial 3-dimensional geotechnical software FLAC3D to investigate the effect of sand state on performances of network of micropiles.

Constitutive Model and Its Implementation

Complete details of the constitutive model for sand, its implementation into FLAC 3D, and its validation are presented elsewhere (Li and Dafalias 2000; Li, 2002; Shu, 2005; Shu et al. 2010). Briefly, the constitutive model is formulated within a critical state soil mechanics framework (Schofield and Wroth 1968) and incorporates the concepts of bounding surface plasticity (Dafalias, 1981 & 1986). The model assumes that the dilatancy of sand is dependent not only on the stress ratio $\eta = q/p$ (q and p are the deviator and mean effective normal stresses, respectively) as in other family of critical state models, but also on the state parameter ψ.

The Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D) developed by Itasca Consulting Group, Inc. is a widely used finite difference commercial code in the geotechnical field. It has been successfully used to numerically simulate a number of geotechnical problems. Besides many built-in soil constitutive models, it provides a user interface to implement new constitutive models. The state dependent sand model was implemented into the FLAC3D by the authors for purposes of the micropile analysis presented below. It was verified on some micropile data from the FOREVER test program (for complete details the reader is referred to Shu 2005, Shu et al. 2010) before its use in the parametric analyses presented here.

Simulation of Network of Micropiles

Network Model Setup

Figure 3 shows schematic of a 3-pile group or network. The inclination angle $\alpha = 0°$ indicates that the network is identical to the vertical group, $\alpha > 0°$ constitutes outwardly inclined piles and $\alpha < 0°$ consists of inwardly inclined piles. The latter is similar to the "basket" group of micropiles of Lizzi (1985). A finite difference mesh including a 3-pile group or network was prepared with bottom boundary fixed in both x and y directions and side boundaries fixed in x direction.

The length and diameter of a single pile are chosen to be 6m and 200mm, respectively, corresponding to $L/D = 30$. The piles were placed at a constant spacing of 400 mm on center (2 diameters) in plan at the top. Note that network micropiles are often categorized in practice as reinforcement type (Case 2 as defined previously). However, in order to identify the dominant effects of network on micropile performance, structural elements were used in FLAC 3D to simulate the micropiles. An assumption is made that the grouting of micropiles recovers the stress relief caused by boring process and that the sand state remains relatively unchanged from its initial state before and after pile installation. It is noted that the grouting process has been shown to be significant in pile design (Juran, 1999), however, its significance is ignored in the analyses. Such effects can of course be taken into account properly by modifying the changes to state parameter in a future analysis.

The soil used in the simulation is Toyoura sand for which the constitutive model parameters have been extensively studied by Li and Dafalias (2000) and Li (2002). The parameters used in this study are as shown in Table 1. The initial state parameter of the sand is assumed to be kept uniform (by varying the void ratio distribution) with depth to address the effect of sand state on the performance of micropiles.

Table 1: Model Parameters for Toyoura Sand (Li, 2002)

Elastic parameters	Critical state parameters	Parameters associated with dr-mechanisms[1]	Parameters associated with dp-mechanisms[2]	Default parameters
G_0=125 ν=0.25	M=1.25 c=0.75 e_Γ=0.934 λ_c=0.019 ξ=0.7	d_1=0.41 m=3.5 h_1=3.15 h_2=3.05 h_3=2.2 n=1.1	d_2=1 h_4=3.5	a=1 b_1=0.005 b_2=2 b_3=0.001

(1) The parameters related to sand response upon the change of deviatoric stress ratio.
(2) The parameters related to sand response upon the change of mean effective stress.

Very small values of continuous vertical velocity (less than 10^{-5} m/s) were applied to the top nodes of the pile network to mobilize the side and tip resistances of micropiles from the surrounding soil. The side and tip resistances against displacement were recorded when the pile was pushed downward.

Performance of Outward network Piles

The variation of the side, tip and total resistance of outwardly inclined micropile group with inclination angle installed in various states of sand are shown in the sets of Figures 3 to 6. These figures also show comparison of the results with a single identical vertical pile. The set of Figure 3 are for micropiles network installed in a *dilative* sand with state parameter of ψ = - 0.1; the set of Figure 4 are for those at *critical* state sand with state parameter of ψ = 0.0, and set of Figures 5 are for those installed in a *contractive* sand with state parameter of ψ = 0.1. Within these set of figures, the figures marked (a) are for variation of side resistance, (b) are for tip resistance, and (c) are for variation of the total resistance.

Performance of Outward Network in Dilative Sand

It is seen that for dilative sand the side resistance is a maximum in the case of a vertical group piles or (Figure 3a). Generally the side resistance is found to decrease with increase in inclination angle α from 0^0 to 15^0. This decrease is higher at smaller inclinations ($\alpha < 5^0$) with only a modest drop observed from 5^0 to 15^0 (Figure 3a). Note that side resistance of a micropile is higher in both vertical group and inclined network compared to that of an individual pile. This positive effect of side resistance of group piles and network piles observed may have been due to the induced shear dilation along the interface between the micropile and the surrounding dilative sand resulting in an increased normal stress on the pile perimeters.

The tip resistance of a micropile in the dilative sand is higher in a network than that of a corresponding micropile in a vertical group or a single vertical pile; the maximum value of tip resistance is reached for a micropile in the network with an inclination of around 10^0. Notice that the tip resistance of vertical piles in group is also less than that of single vertical pile (Figure 3b).

The combination of side and tip resistances resulted in a positive effect of total or ultimate resistance for both network piles and group piles (Figure 3c) and all of the total resistance curves for inclined network piles plot above both the vertical micropile group (α = 0°) and the single vertical pile. Moreover, the ultimate resistances of the network piles reach a maximum with an inclination around 10°. Further increase in angle of inclination, however, appears to result in a slightly lower value for the ultimate total resistance as seen in the case for α = 15°.

Performance of Outward Network in Sand at critical state

Sand at the critical state has no possibility for dilatancy. The variation of side resistance of the outward network micropiles installed in critical state sand with inclination is different from that in dilative sand in that it reaches a maximum at an inclination angle of about 10^0 (Figure 4a). The skin friction of all inclined network piles is larger than that of vertical group piles and individual vertical pile, moreover, the skin friction of vertical group piles is less than that of individual vertical pile.

Tip resistance of network piles installed in sand at critical state shows very similar variation with inclination angle as found in dilative sand (Figures 4b), even though the magnitudes of tip resistance are much lower in the sand at critical state than in dilative sand. It also reaches a maximum at inclination angle of 10^0 (Figure 4b), then slightly decreases towards inclination angle of 15^0. The tip resistance of a micropile in vertical group and that of a single pile is about a fourth from a similar pile in network with inclination angle of 10^0.

The combination of tip resistance and skin friction results in a positive increase in total resistance variation similar to that found in dilative sand (Figure 4c).

Performance of Outward Network in Contractive Sand

Contractive sand when subjected to shear leads to volume contraction. Performance of the three-micropile outward network installed in contractive sand is different from those in dilative sand and critical state sand.

The side, tip, and total resistance of a micropile in network all increased with pile inclination angle (Figures 5a, 5b and 5c). However, all three resistances of a micropile in vertical group were less than those that of a single vertical pile. This indicates a negative group effect by the vertical group of piles in contractive sand, as opposite to the positive group effect of vertical group piles in dilative sand. This negative group effect may have been contributed by shearing contraction effect of the contractive sand surrounding the piles leading to reduced normal stress on the pile perimeter.

Performance of Inward Network Piles

The variation of the side, tip and total resistance of inwardly inclined micropile network with inclination angle are shown in Figures 6a through 8c for the different sand states.

Performance of Inward Network Micropiles in Dilative Sand

For inward network micropiles in dilative sand, the side resistance is a maximum in the case of a micropile in vertical group arrangement. The side resistance of micropile in an inward inclined network is observed to be larger than that of a single vertical pile. This was similar to that observed in the case of outward group piles. The variation of the side resistance, however, was not consistent with pile inclination angle (Figure 6a).

The tip resistance of a micropile in dilative sand in an inward network reaches a maximum at an inclination angle of 15^0 and drops to lowest at inclination angle of 0^0. The tip resistances are very close at inclination angles of 10^0 and 5^0. The tip resistance of a single vertical pile is larger than that of one in vertical group but is less than that in all inward inclined networks (Figure 6b).

The total resistance of piles in dilative sand is observed to increase with pile inclination angle consistently (Figure 6c). The total resistance of single vertical pile is less than a micropile in all inward inclined network or group vertical piles.

Performance of Inward Network Micropiles in Sand at Critical State

The variation of side resistance of piles installed in critical state sand with inclination is mixed and different from that in dilative sand in that it reaches a maximum at an inclination angle of 10^0 (Figure 7a).

The variation of the tip resistance of piles installed in this sand was not consistent either (Figure 7b). As in the case of tip resistance of inwardly inclined network piles in dilative sand, the tip resistance here is a maximum at an inclination angle of 15^0 and drops to lowest at inclination angle of 0^0. The tip resistance of single vertical pie is less all inwardly inclined network piles but larger than vertical group piles.

The behavior of the total resistance of piles showed the same variation as found in inwardly inclined network piles in dilative sand (Figure 7c).

Performance of Inward Network Micropiles in Contractive Sand

In the case of inwardly inclined network piles installed in contractive sand, total, side and tip showed a consistent pattern of increase with pile inclination angle (Figures 8a, 8b and 8c). For side resistance, the single vertical pile is less than of a micropile in all inclined networks but larger than vertical group piles. However for tip resistance, the single vertical pile is very close to group vertical pile but less than all inclined piles. Combination of side resistance and tip resistance results in that total resistance of single vertical pile is larger than that of a pile in vertical group, but again less than those of all inclined piles.

Conclusions

This paper presents some numerical analyses of the performance of network and vertical group micropiles is the various state of sand. FLAC3D implemented with a comprehensive sand constitutive model explicitly accounting for sand state parameter was used to investigate the effect of the sand state on network effect and group effect of micropiles. The following conclusions are drawn:

1. For piles installed in dilative sand with inclination angle less than 15^0 (individual, inward and outward network), ultimate shaft resistance is less than that of vertical piles. However, the behavior is opposite for piles installed in contractive sand.
2. The tip resistances of inclined piles are always larger than those of vertical piles for both contractive sand and dilative sand.
3. Group effect of side resistance of micropiles installed in dilative sand is positive, but becomes negative when they are installed in contractive sand. Tip resistance group effect is negative in dilative sand but there is no obvious group effect in contractive sand.
4. Based on these analyses, it is implied that the network and group effects of micropiles and piles in sand depends on types of installation, sand state, pile spacing, ratio of length over diameter, properties of pile-sand interface. Therefore, it is difficult in practice to compare the performance of micropiles and groups from one test program to other without consideration of the state of sand. Use of relative density alone as has been done in the past experiments and model studies would lead to conflicting results. The FLAC3D model developed here is a useful means of quantifying the effects of state of sand for design.

Acknowledgements:

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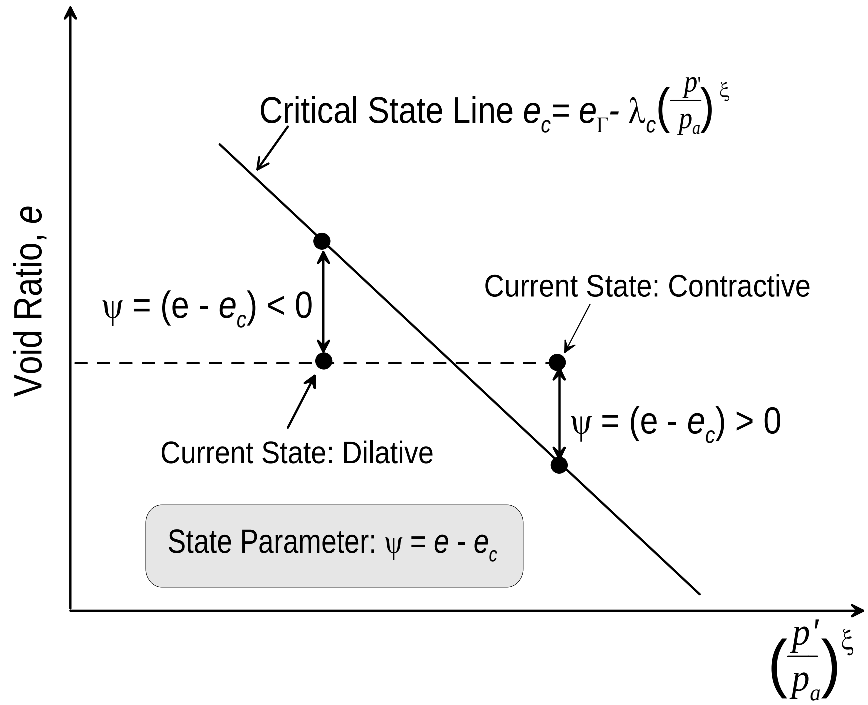

Figure 1. State Parameter and Critical State Line

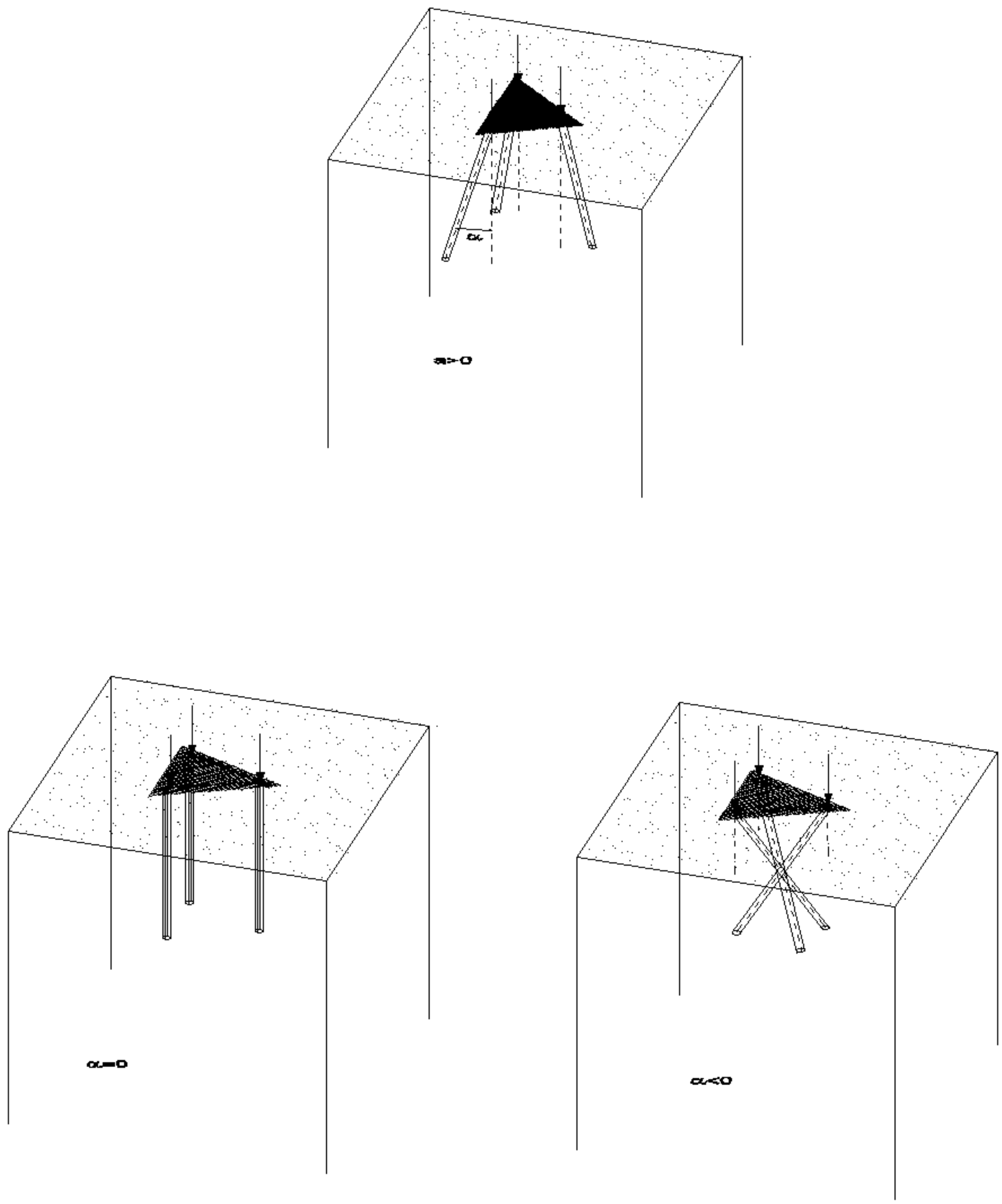

Figure 2: Model setup for network Micropiles

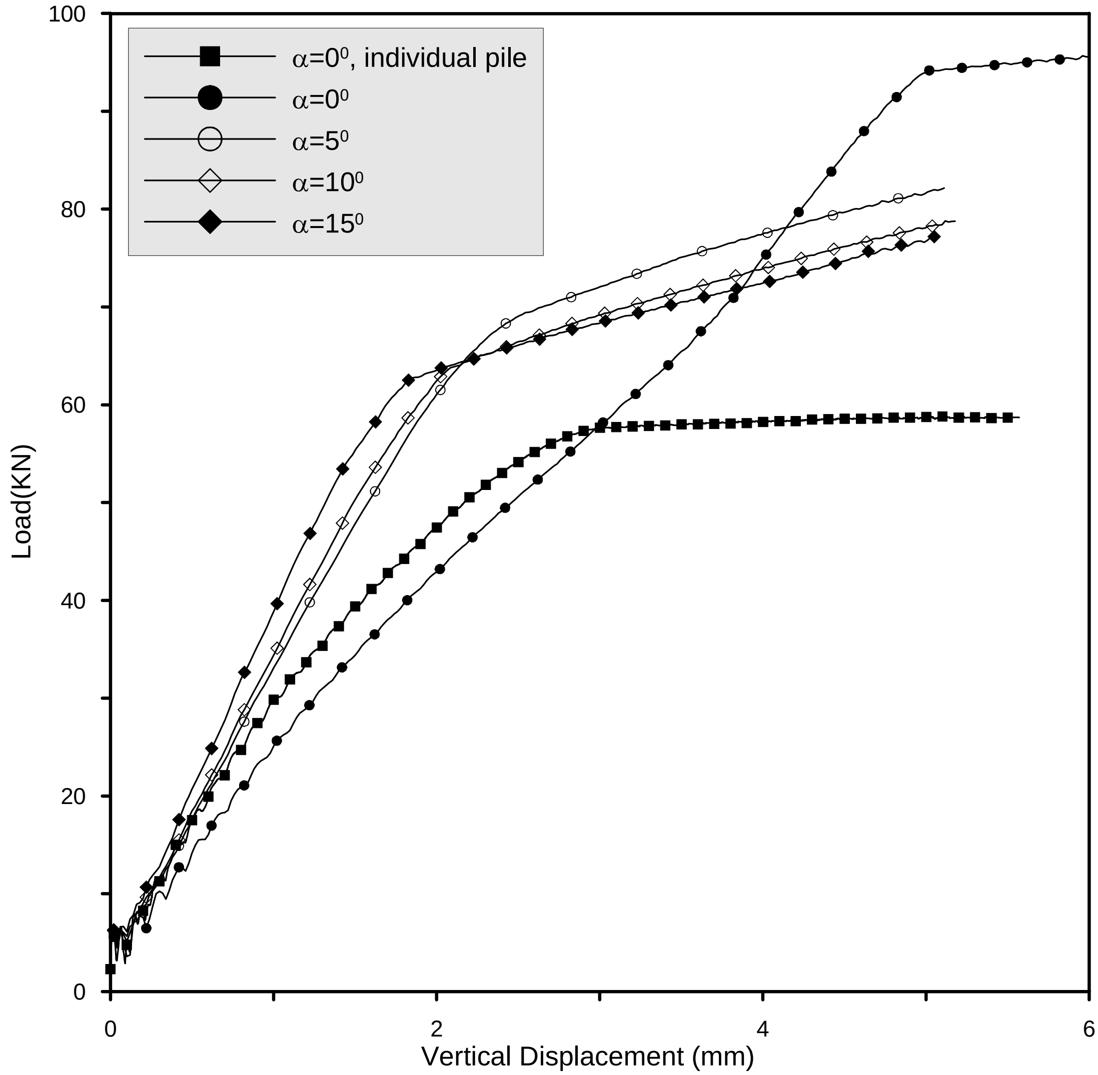

Figure 3a Side Resistance Variation with Network Pile Outward Inclination (ψ=-0.1)

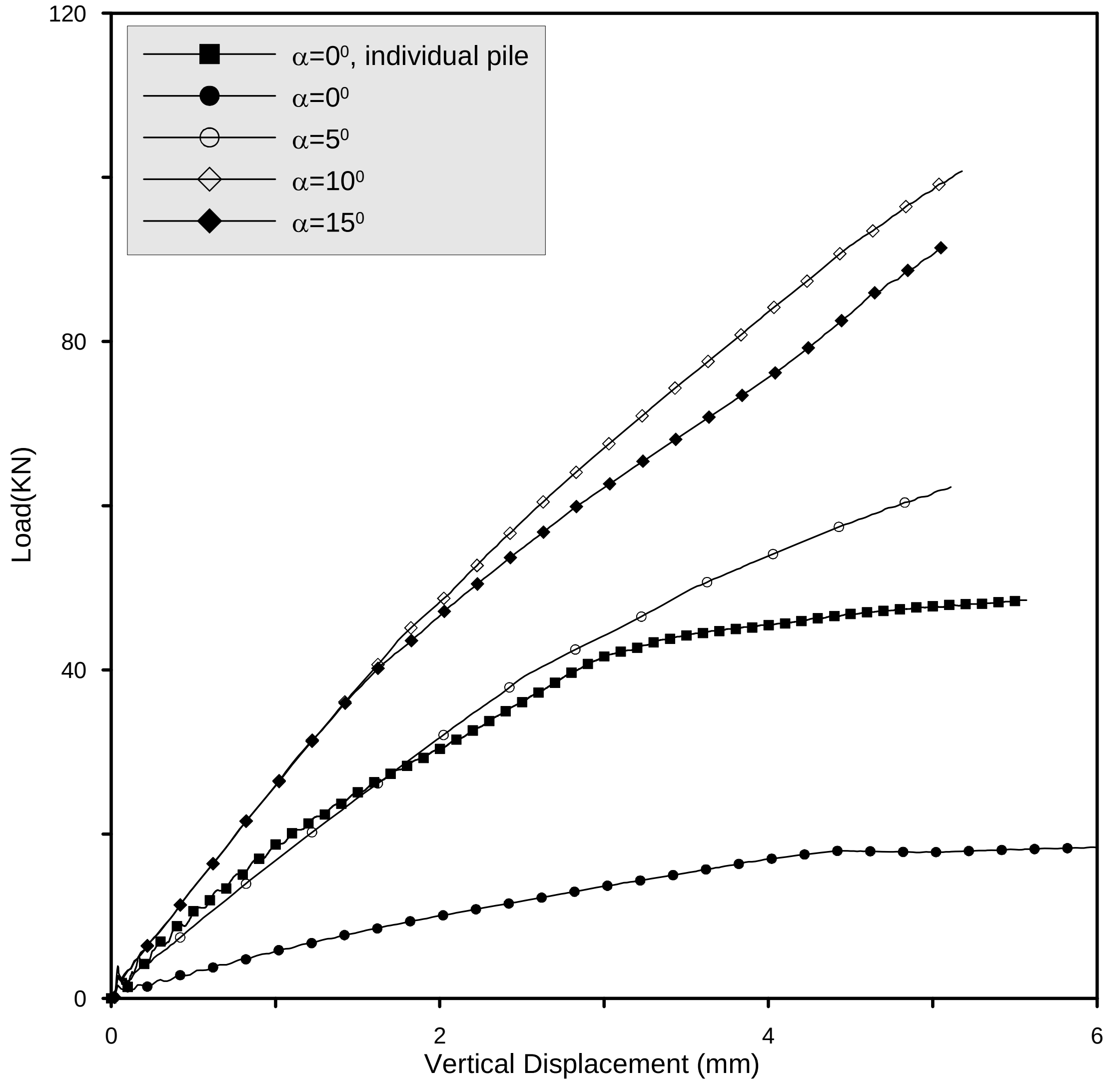

Figure 3b Tip Resistance Variation with Network Pile Outward Inclination (ψ=-0.1)

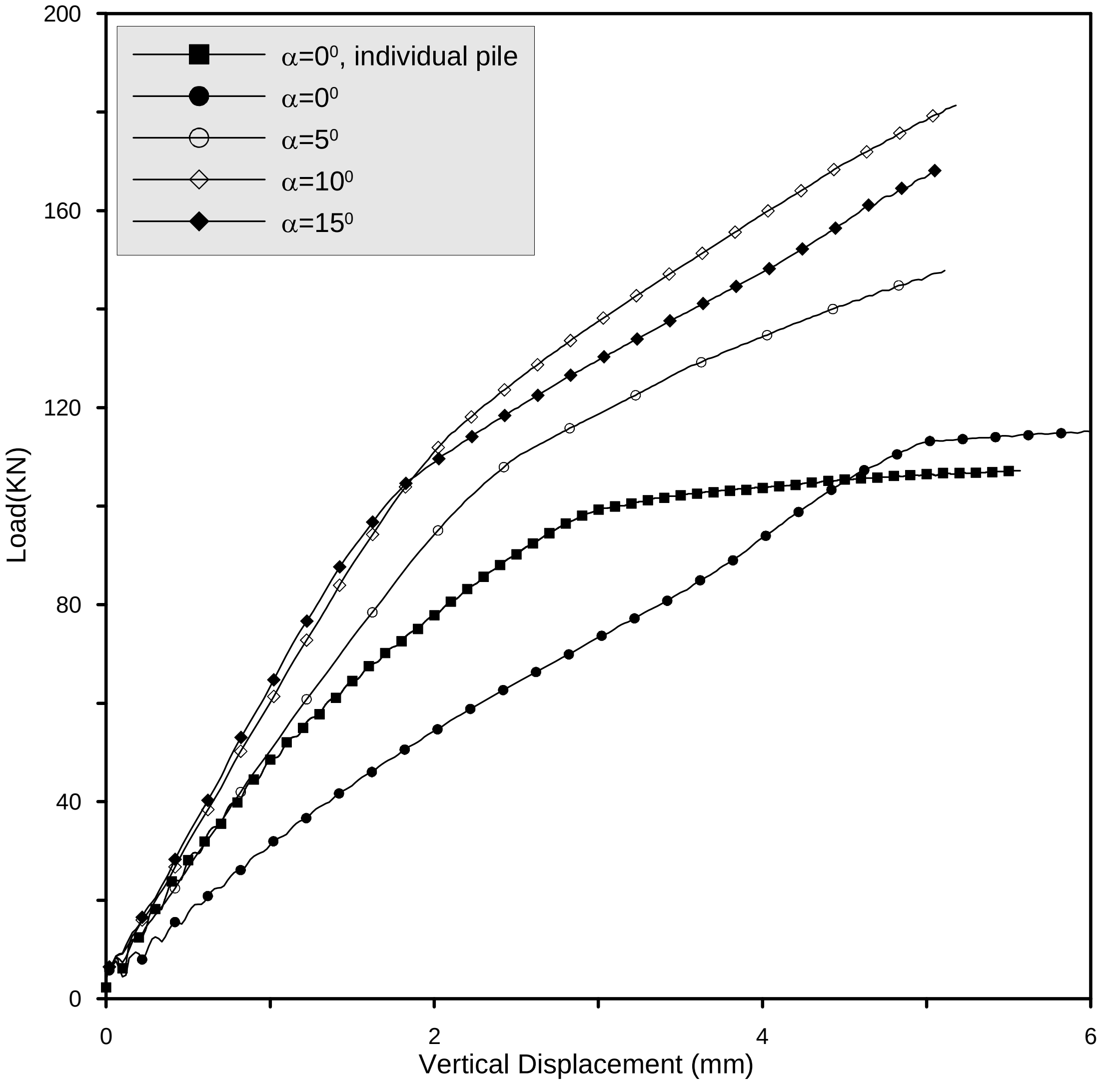

Figure 3c Total Resistance Variation with Network Pile Outward Inclination (ψ=-0.1)

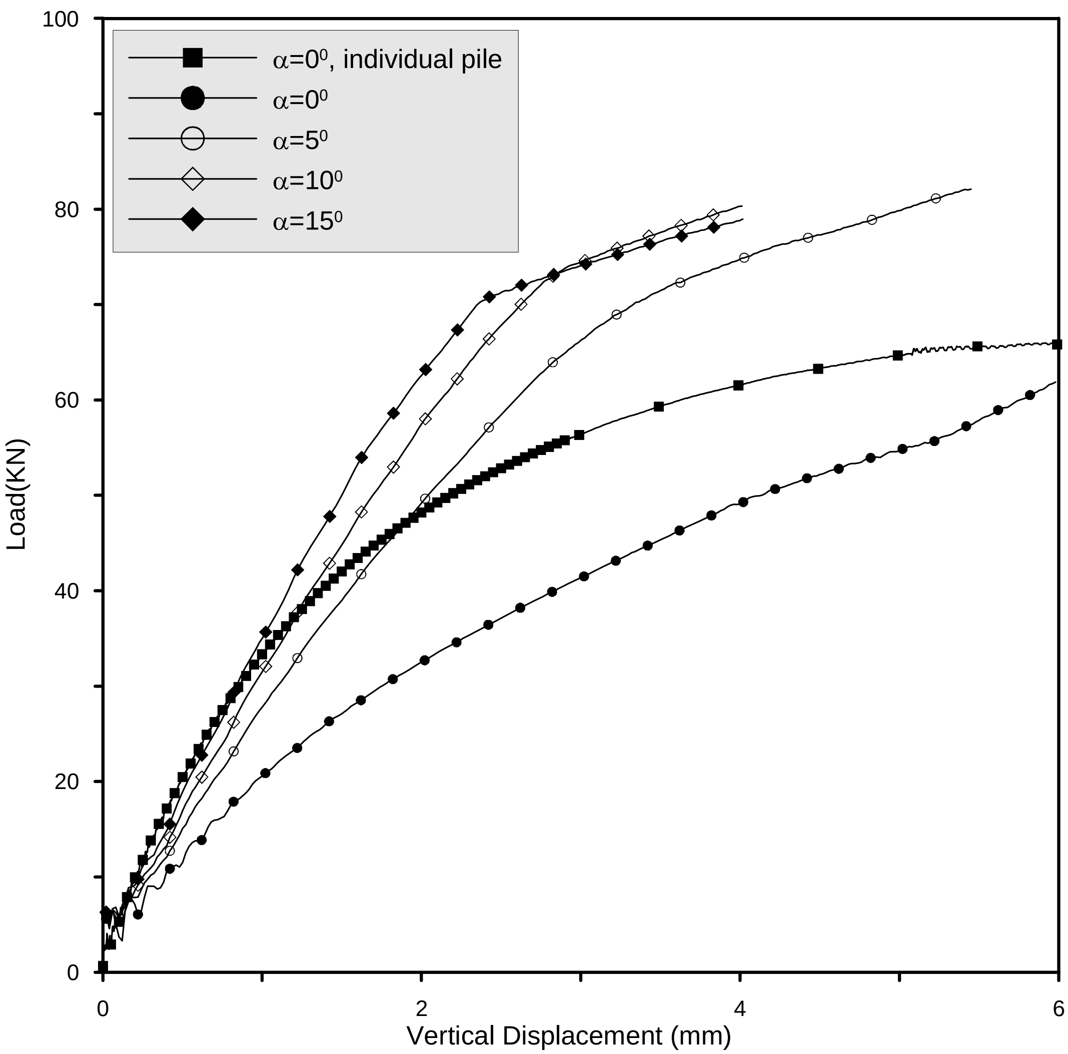

Figure 4a Side Resistance Variation with Network Pile Outward Inclination (ψ=0.0)

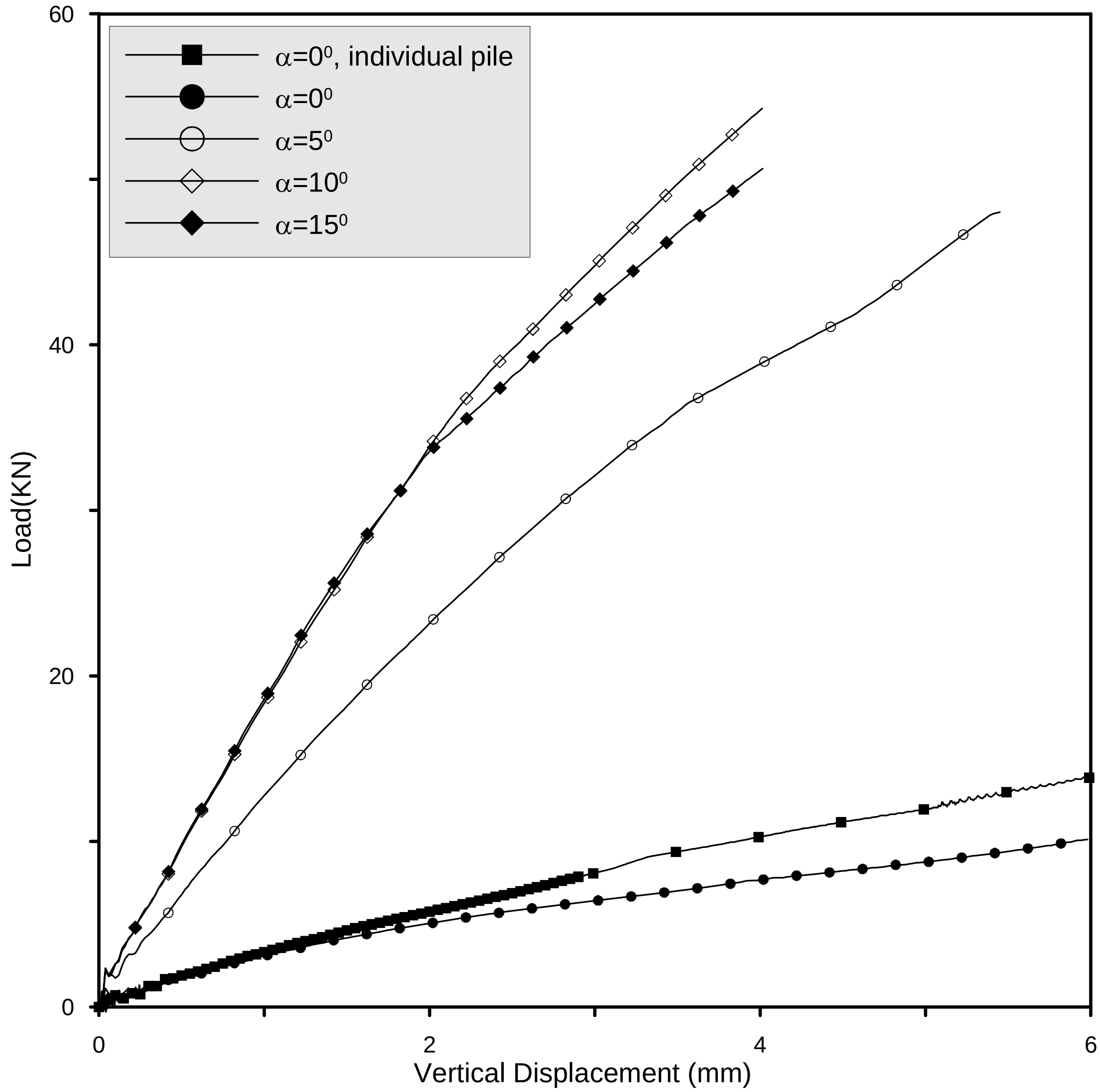

Figure 4b Tip Resistance Variation with Network Pile Outward Inclination (ψ=0.0)

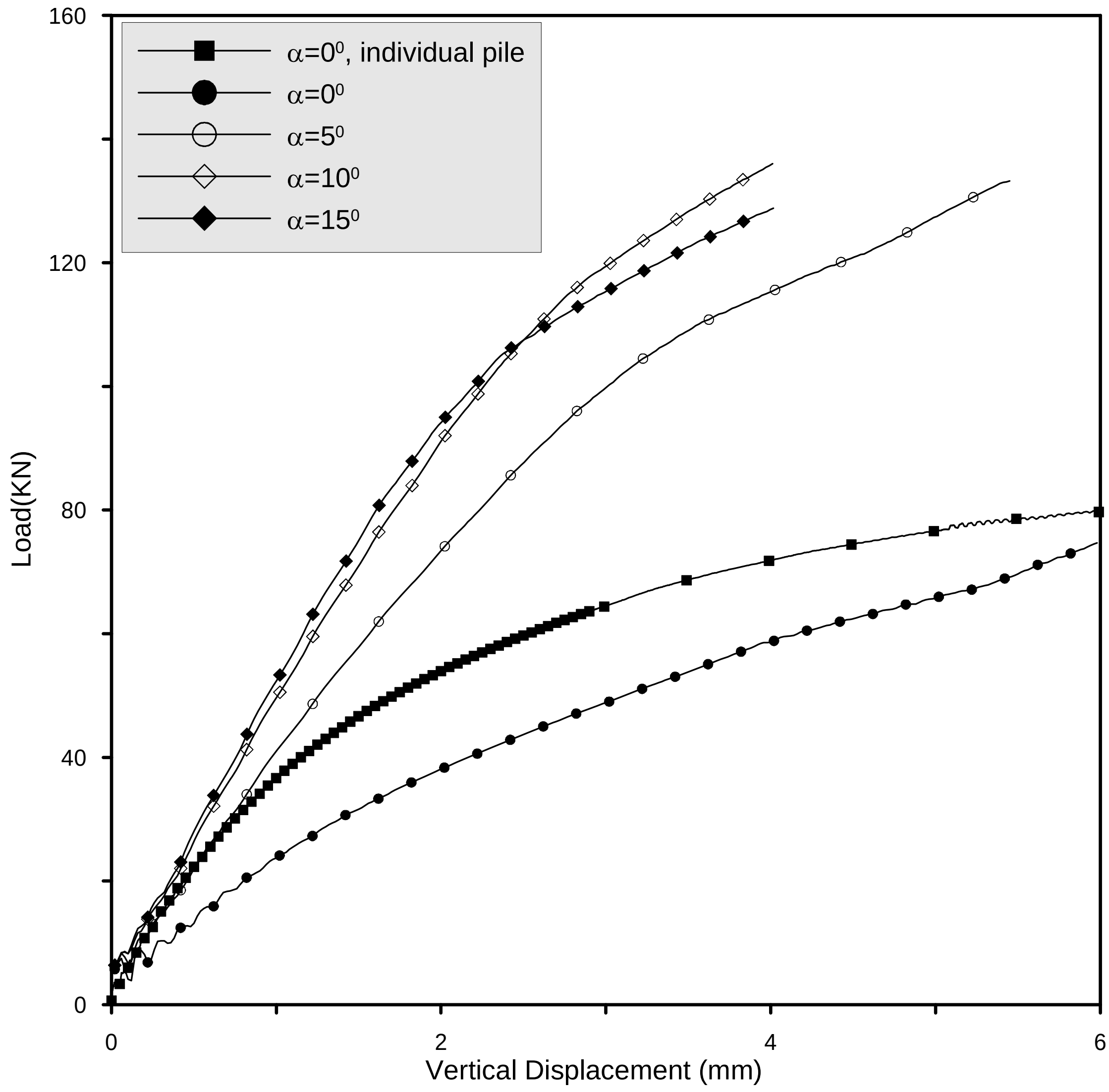

Figure 4c Total Resistance Variation with Network Pile Outward Inclination (ψ=0.0)

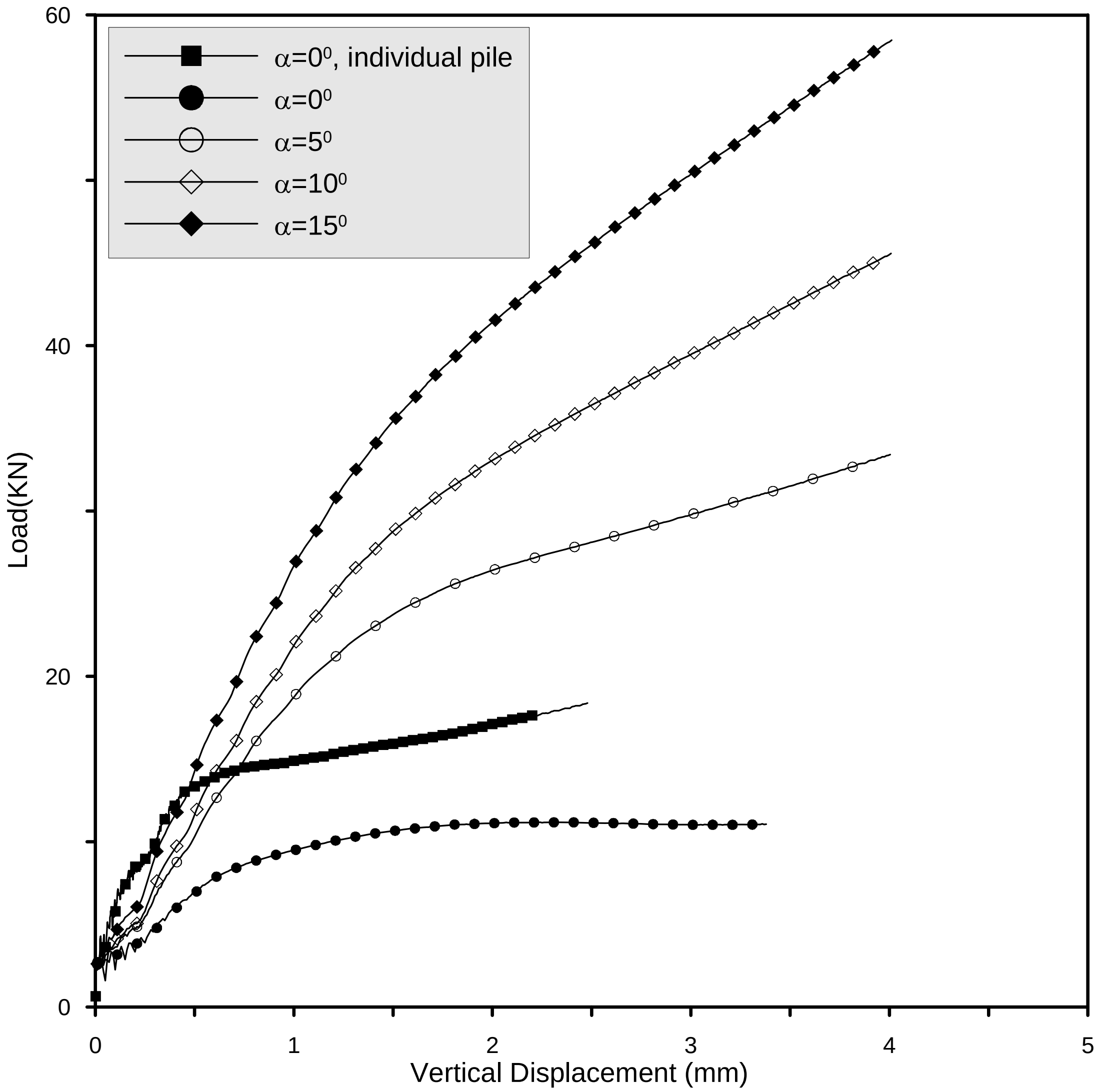

Figure 5a Side Resistance Variation with Network Pile Outward Inclination (ψ=0.1)

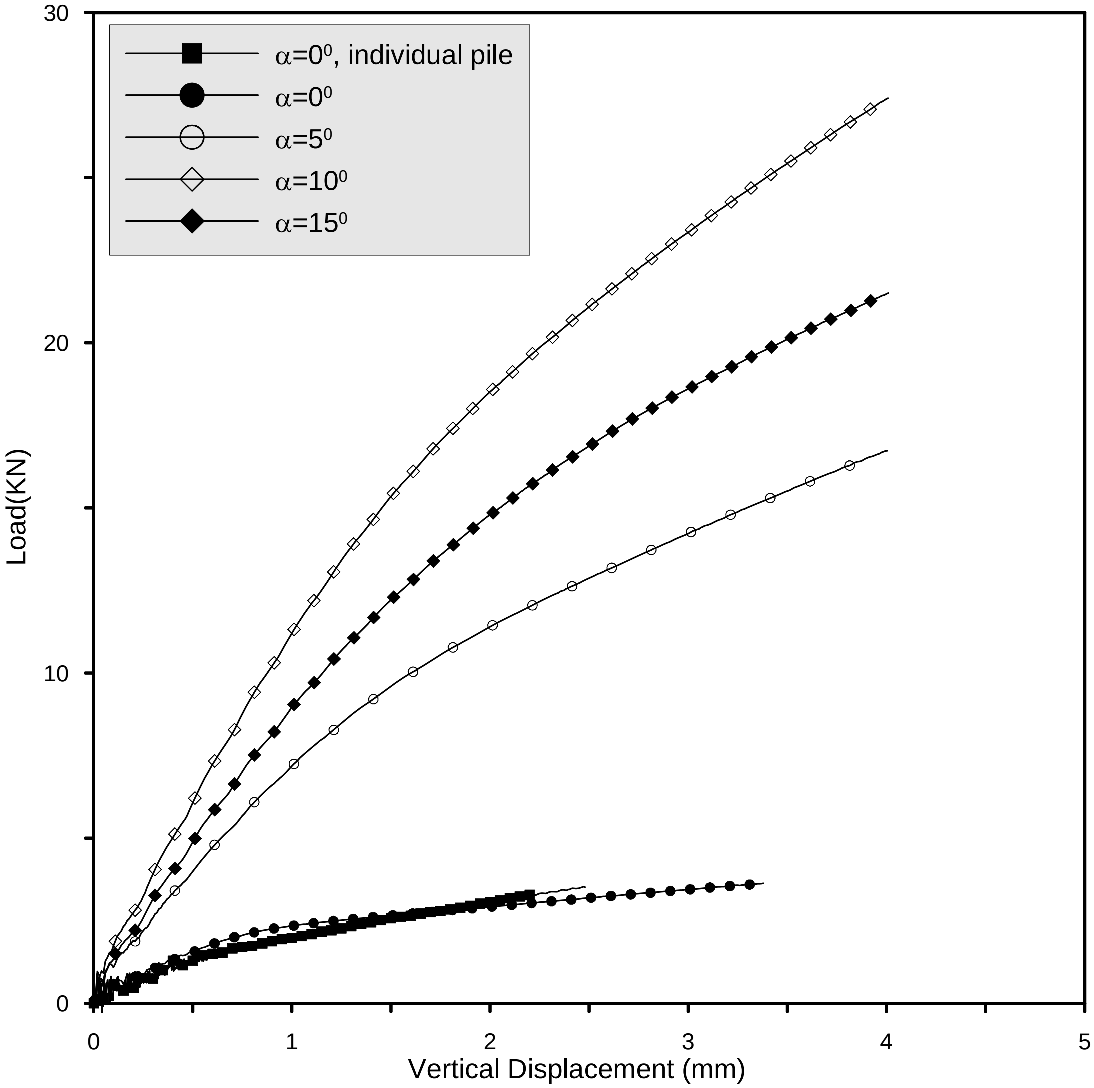

Figure 5b Tip Resistance Variation with Network Pile Outward Inclination (ψ=0.1)

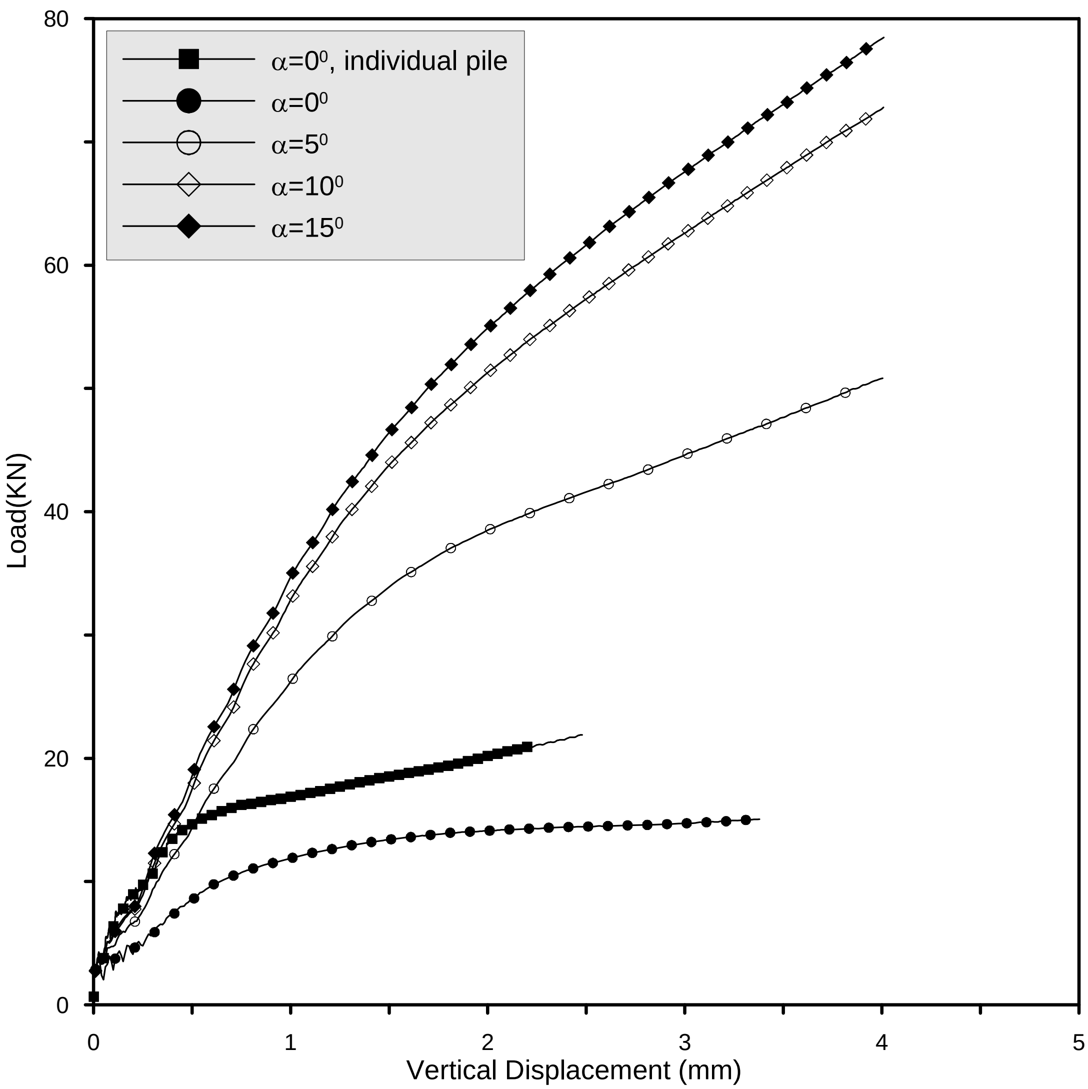

Figure 5c Total Resistance Variation with Network Pile Outward Inclination (ψ=0.1)

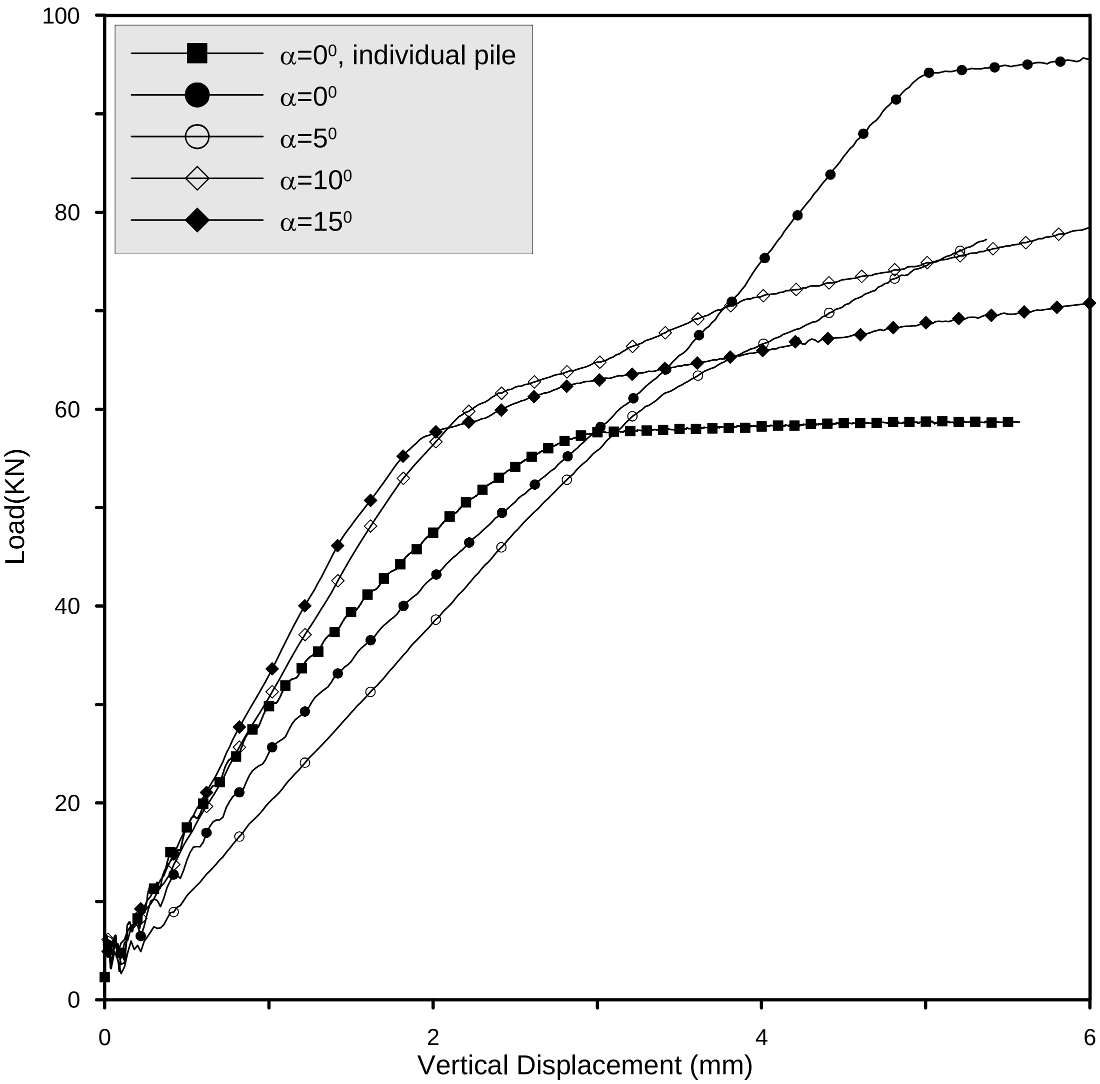

Figure 6a Side Resistance Variation with Network Pile Inward Inclination (ψ=-0.1)

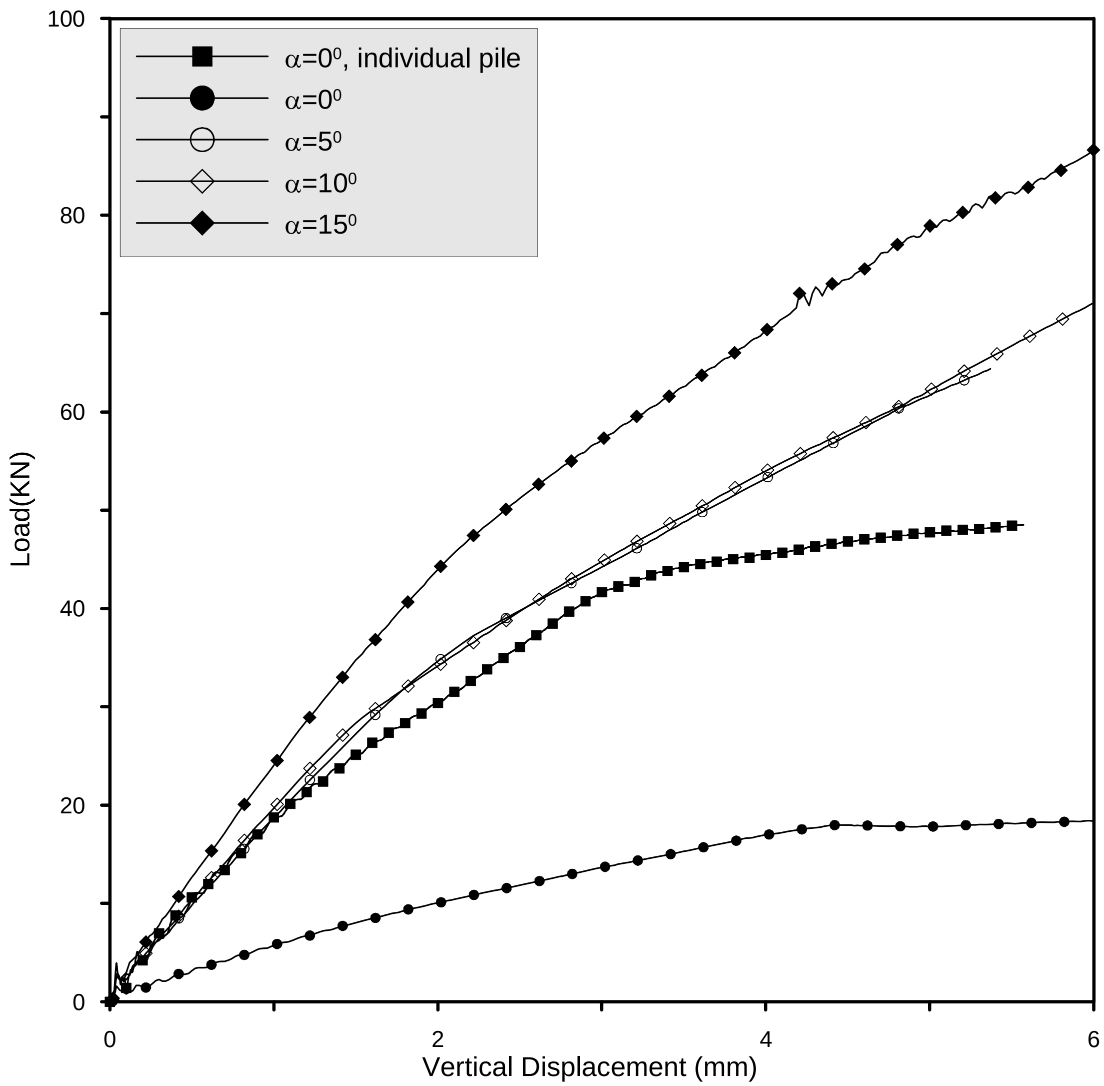

Figure 6b Tip Resistance Variation with Network Pile Inward Inclination (ψ=-0.1)

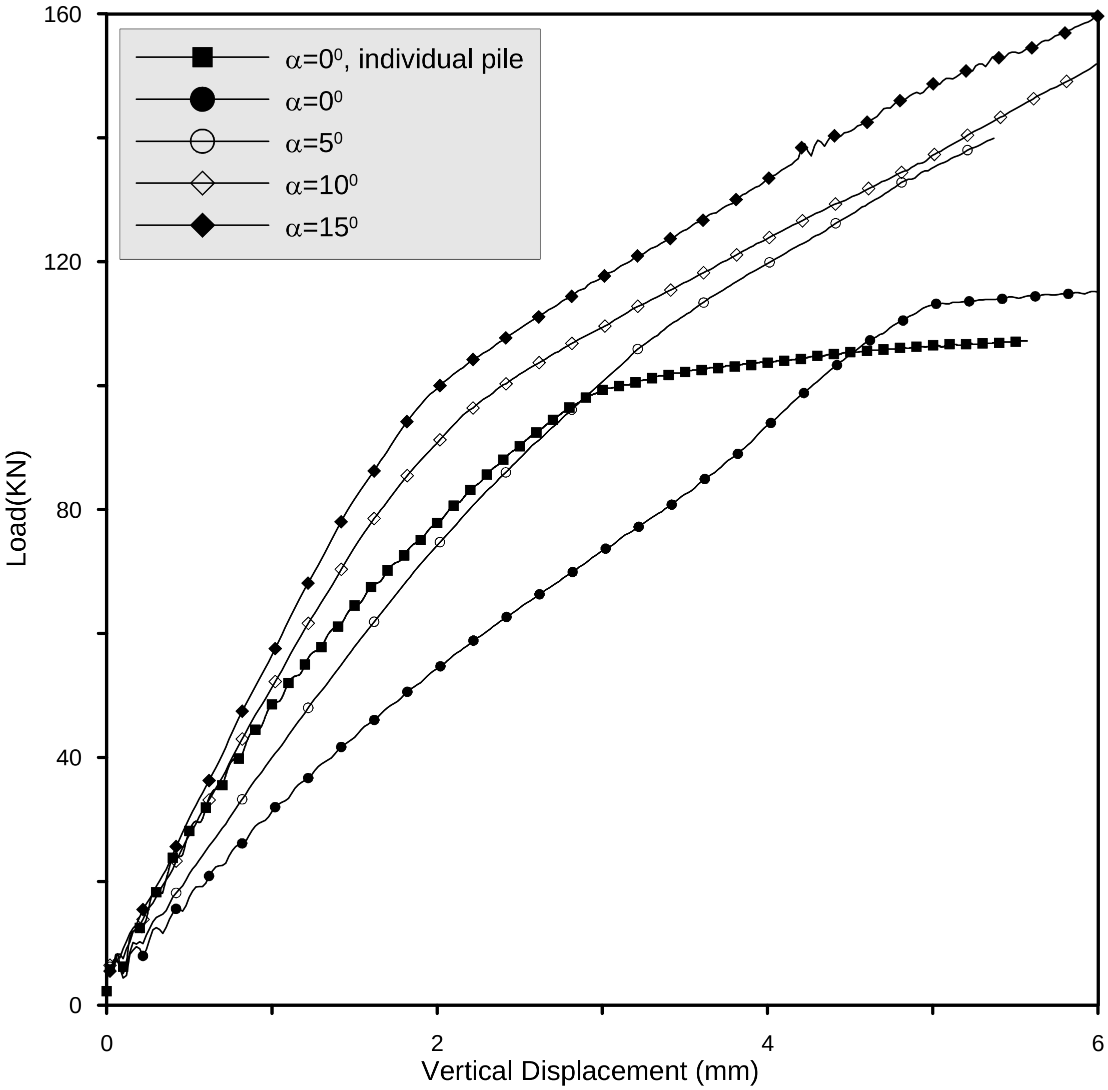

Figure 6c Total Resistance Variation with Network Pile Inward Inclination (ψ=-0.1)

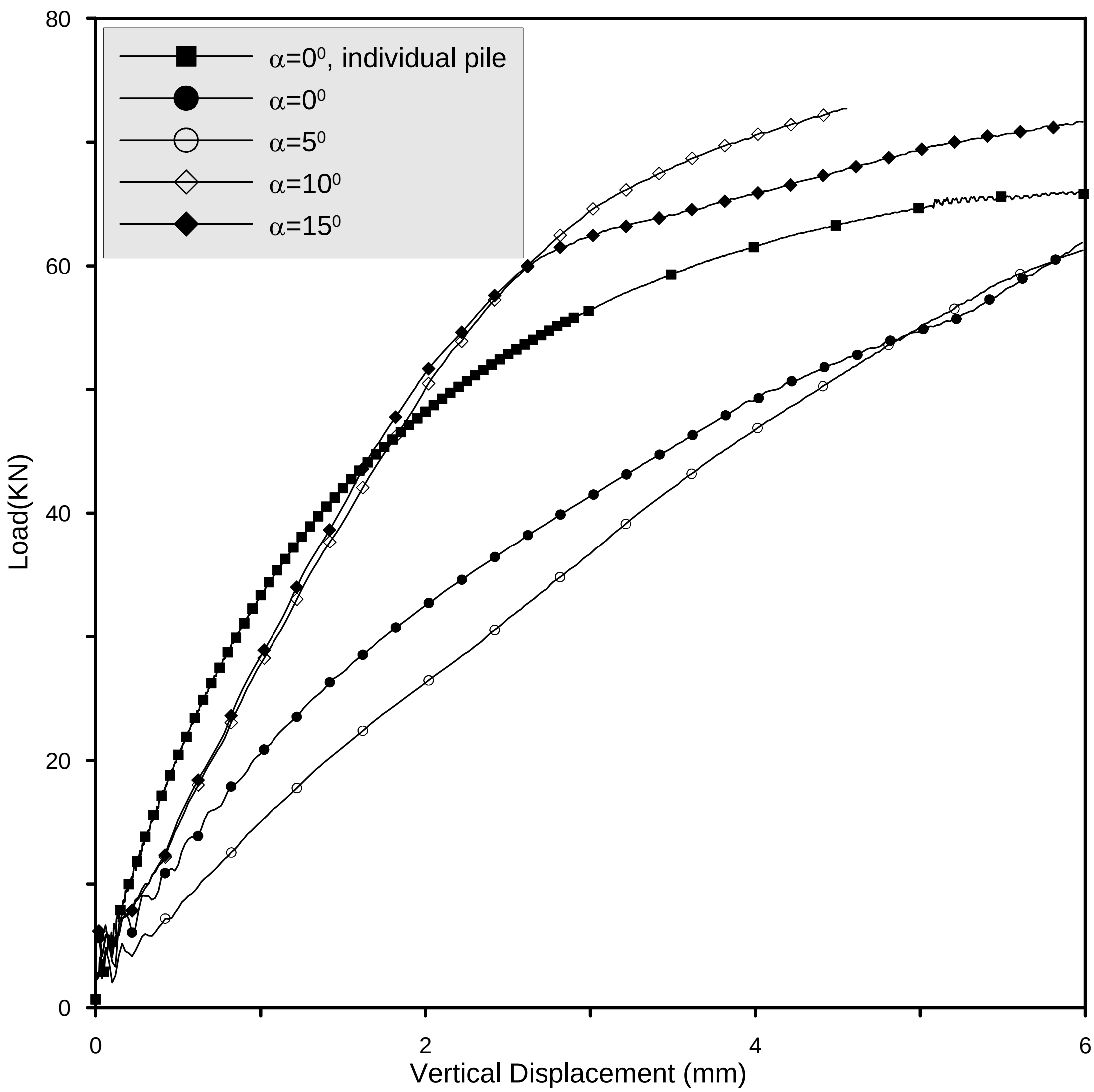

Figure 7a Side Resistance Variation with Network Pile Inward Inclination (ψ=0.0)

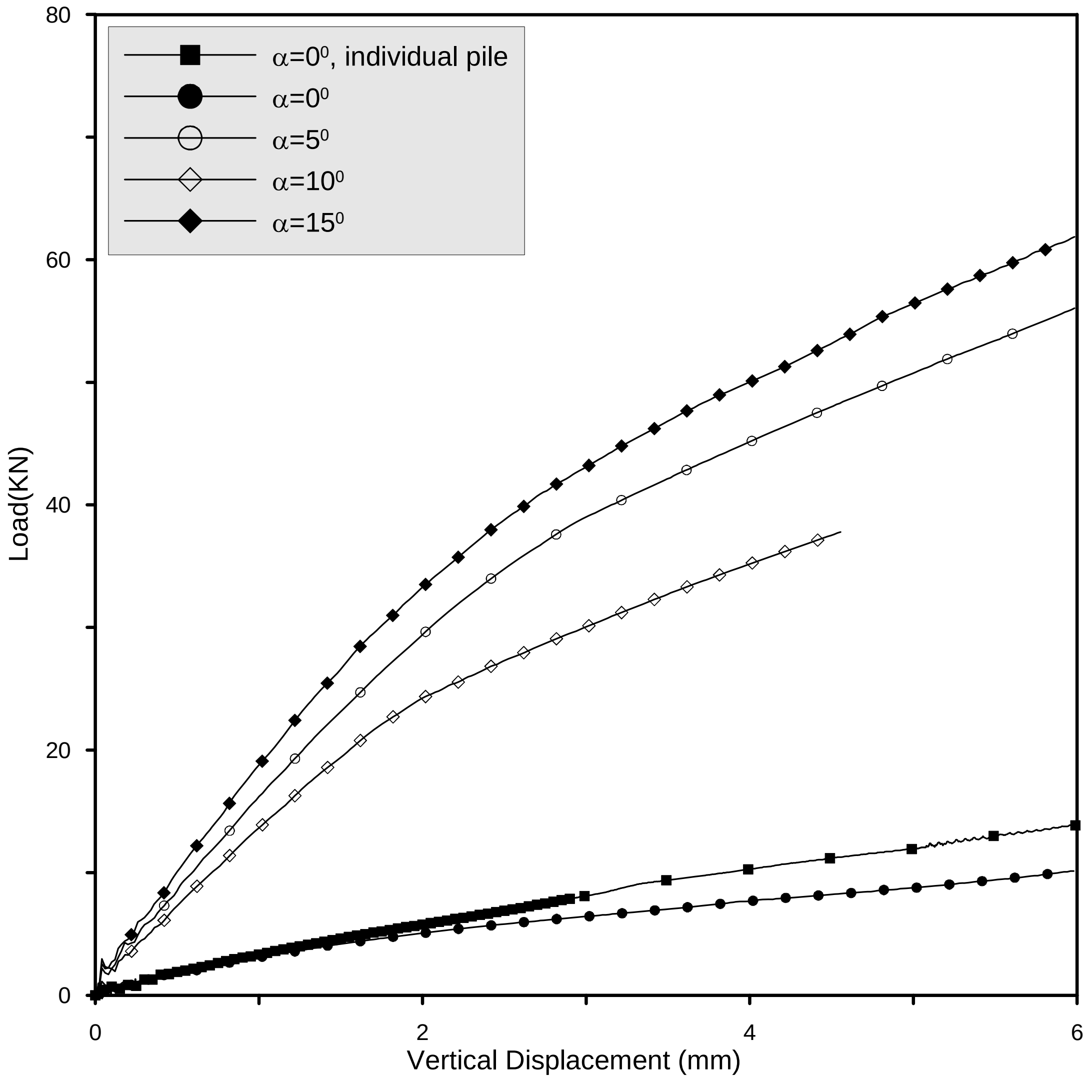

Figure 7b Tip Resistance Variation with Network Pile Inward Inclination (ψ=0.0)

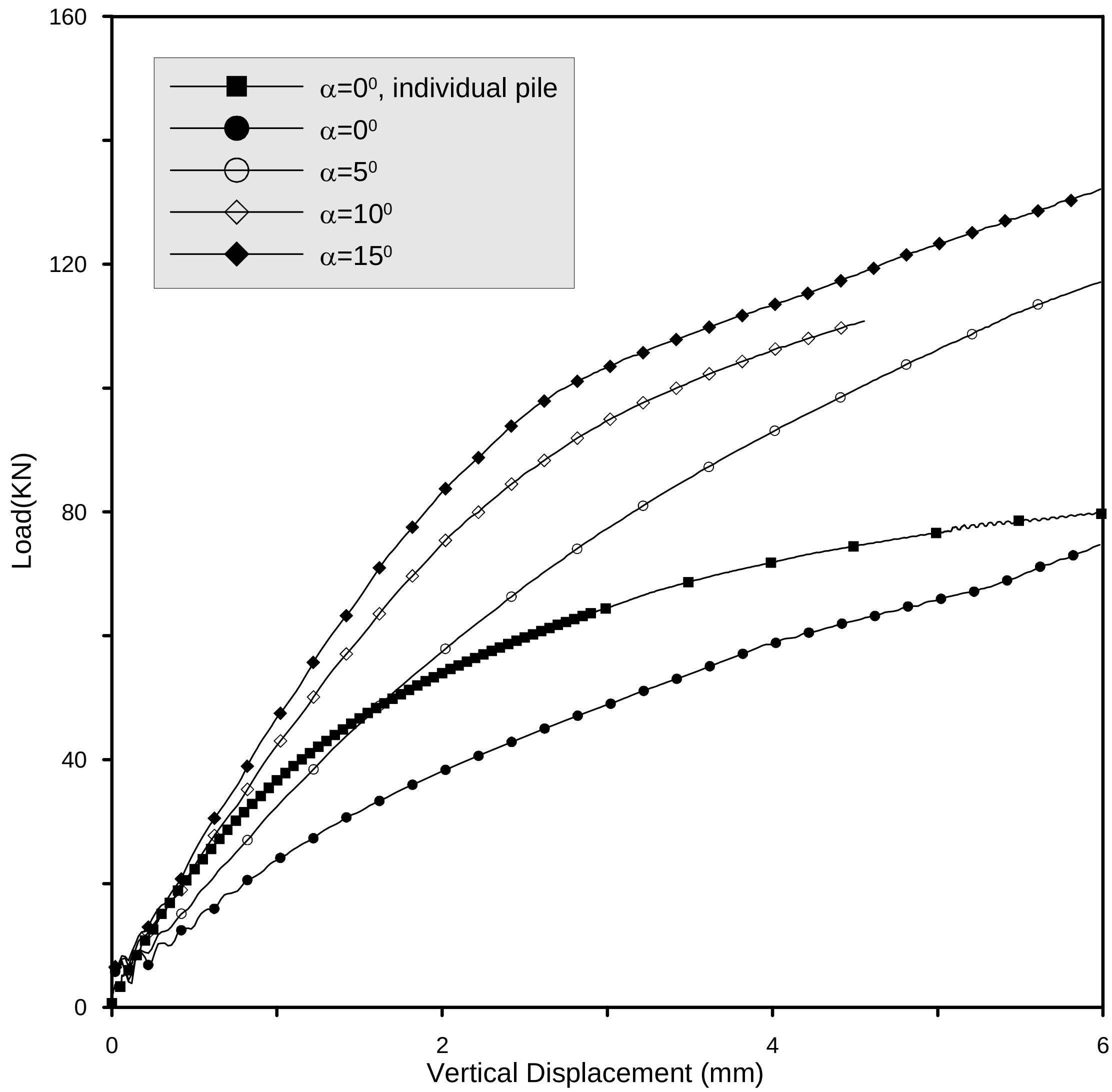

Figure 7c Total Resistance Variation with Network Pile Inward Inclination (ψ=0.0)

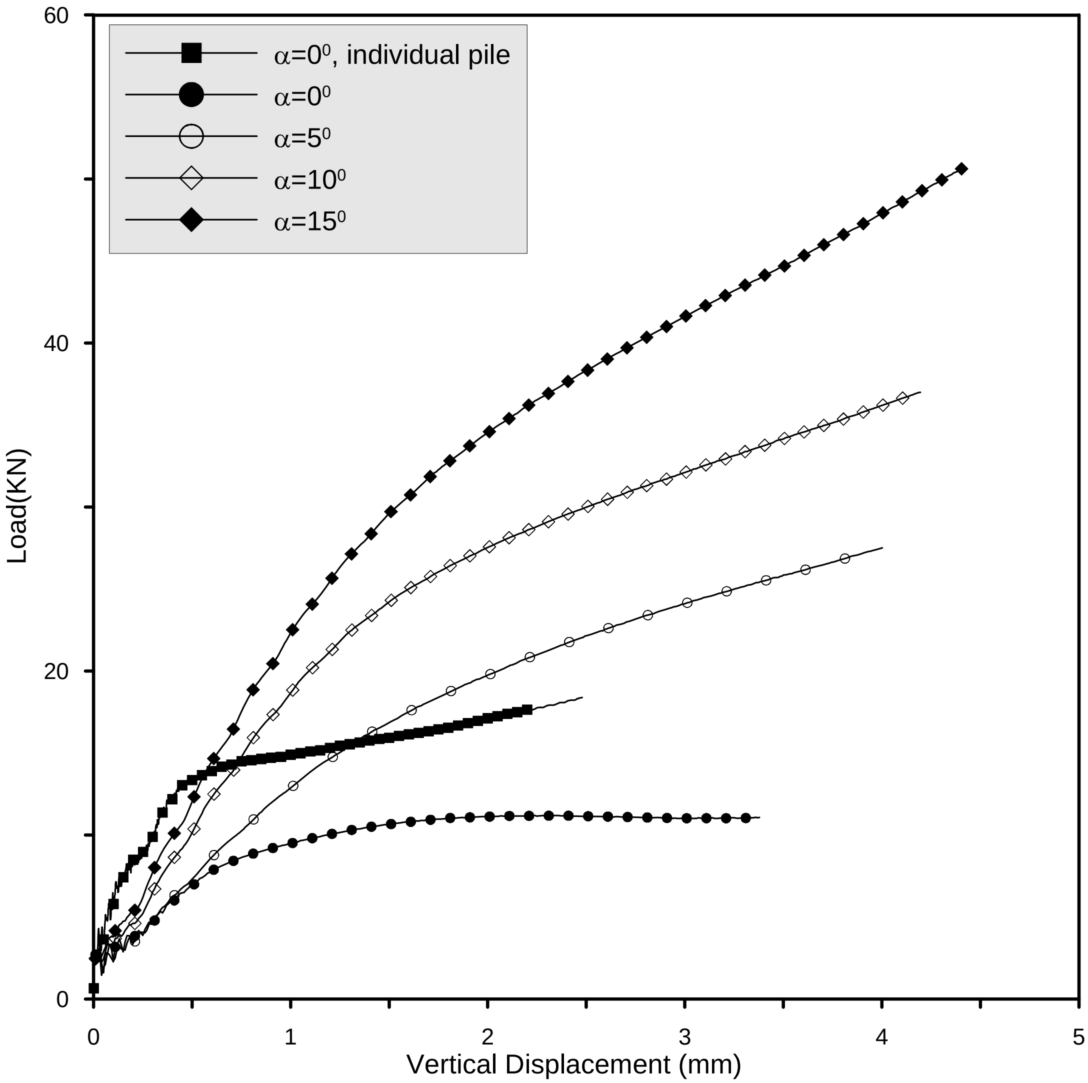

Figure 8a Side Resistance Variation with Network Pile Inward Inclination (ψ=0.1)

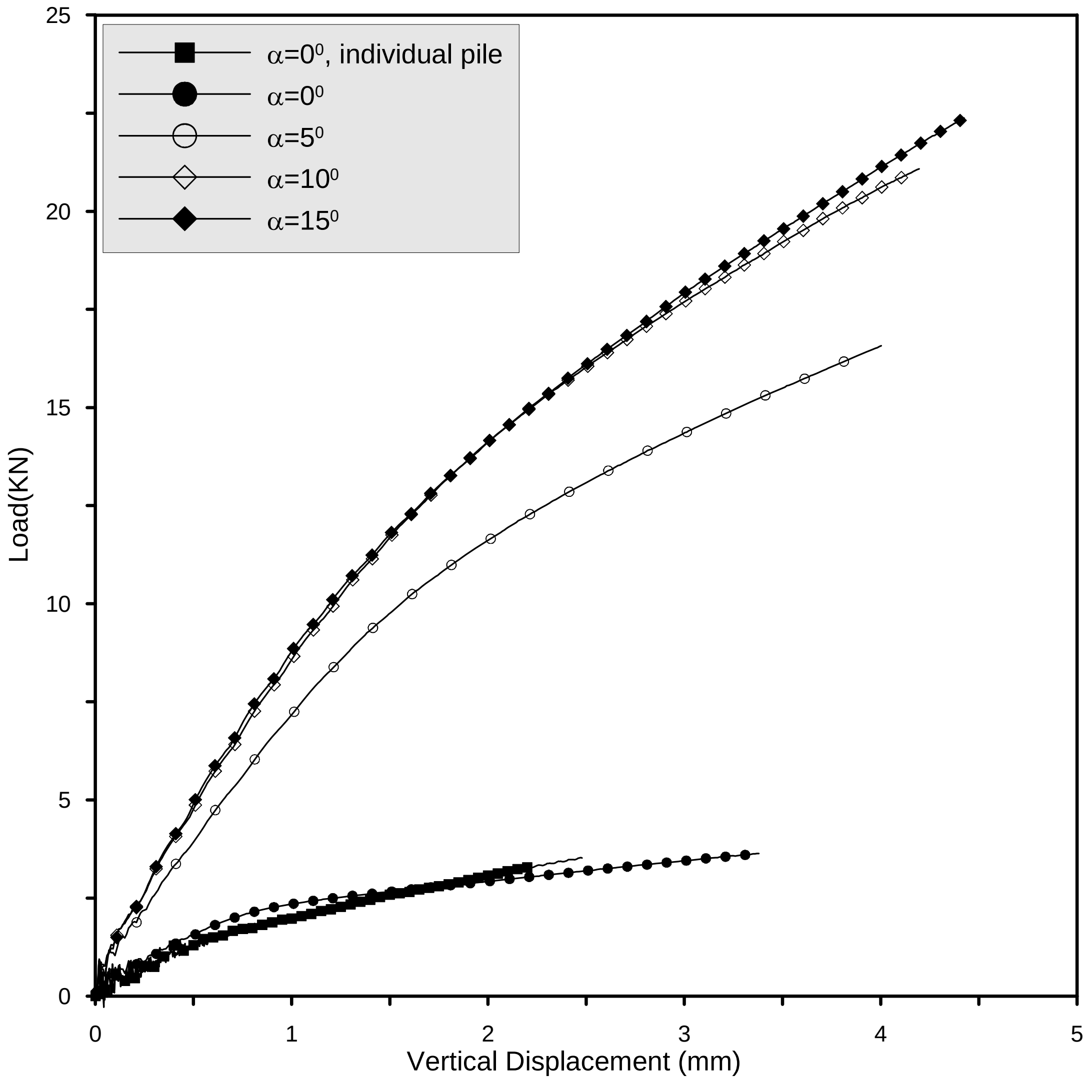

Figure 8b Tip Resistance Variation with Network Pile Inward Inclination (ψ=0.1)

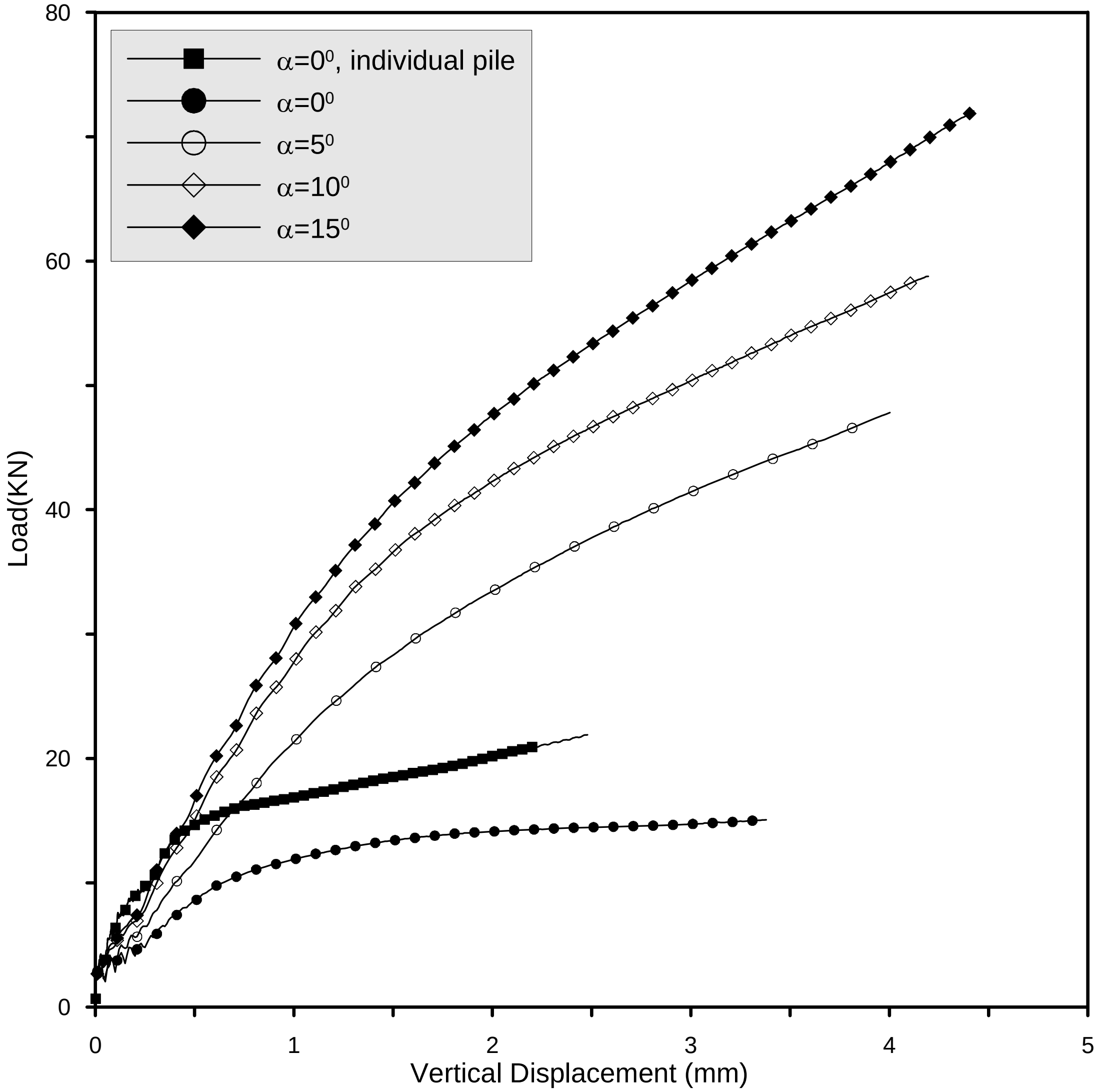

Figure 8c Total Resistance Variation with Network Pile Inward Inclination (ψ=0.1)