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Time-dependent behaviour of pile groups under combined axial and lateral loads

Comportement dépendant du temps des groupes de peux sous charges combinées axiales et latérales

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ABSTRACT: Time-dependent behavior of a single pile and pile groups (2×2 and 3×2) subjected to combined compressive and lateral loads have been carried out in this present study. For the analysis, finite element tool Plaxis 3D has been used. The behavior of soft soil surrounding the piles has been simulated by considering Soft Soil Creep Model (SSCM). The results obtained from the present study have been validated with the available results and shows good agreement. The effects of time on piles for different values of lateral loading have been investigated. The effects of load ratio and pile properties (slenderness ratio, spacing and group configurations) on time-dependent behavior of piles have been observed from the parametric studies. Time analysis has been carried out for understanding the effects of load ratio, slenderness ratio and pile group configuration on the pile displacements, excess pore water pressures, differential settlements and mobilized shear stresses. The lateral deflections in single isolated piles under combined loads are lower in comparison to pile groups. The total displacements observed at the pile head due to combined loads are about 9% to 15% higher than the pile head displacements due to compressive loads only.

RÉSUMÉ: Le comportement en fonction du temps de pieux simples et de groupes de pieux (2 × 2 et 3 × 2) soumis à des charges de compression et latérales combinées a été étudié dans la présente étude. Pour la présente analyse, l'outil éléments finis Plaxis 3D a été utilisé. Le comportement du sol mou entourant les pieux a été simulé en considérant le modèle de fluage du sol mou (SSCM). Les résultats obtenus à partir de la présente étude ont été validés avec les résultats publiés et montrent une bonne concordance. Les effets du temps sur les pieux pour différentes valeurs de chargement latéral ont été étudiés. Les effets du rapport de charge et des propriétés des pieux (élancement, espacement et configurations de groupe) sur le comportement des pieux en fonction du temps ont été observés à partir des études paramétriques. Une analyse temporelle a été réalisée dans cette étude pour comprendre les efforts du rapport de charge, du rapport d'élancement et de la configuration des groupes de pieux sur les déplacements des pieux, les pressions interstitielles excessives, les tassements différentiels et les contraintes de cisaillement mobilisées. Les déformations latérales des pieux isolés isolés sous charges combinées sont plus faibles que celles des groupes de pieux. Les déplacements totaux observés au niveau de la tête du pieu en raison des charges combinées sont d'environ 9% à 15% plus élevés que les déplacements de la tête du pieu dus uniquement aux charges de compression.

KEYWORDS: time-dependent, pile group, finite-element analysis, lateral loads, settlement.

1 INTRODUCTION

Soft soils are considered as one of the most difficult soils for construction because they are susceptible to large deformations owing to their high compressibility and low shear strength. Long-term monitoring of several structures such as bridges, roads, buildings, embankments etc. constructed in soft soils have suggested that the measured deformations show gradual increase over time (Danno & Kimura 2009, Huang et al. 2006, Feng et al. 2017 and Hoang & Matsumoto 2020). In adverse ground conditions, it may even take decades before the rate of time-dependent deformation becomes constant. Pile foundations have been extensively used for structures in soft soil because the bearing capacity is low and large settlements are anticipated. The total settlement of piles is a result of immediate settlement and time-dependent settlement; however, the time-dependent settlement component accounts for a major part of the overall settlement. The gradual development of time-dependent settlement at constant sustained loads is prevalent in all types of piles, irrespective of the type of loading (compressive or lateral or combination of both). Piles used as foundations systems in transmission towers, bridge piers and offshore structures such as loading platforms, deep-sea oil platforms, offshore wind turbines etc. experience lateral loads arising due to waves and heavy winds.

The experimental and analytical studies for time-dependent behavior of axially loaded piles in soft soils have been carried out by several researchers (Cheng et al. 2006, Huang et al. 2006, Danno & Kimura 2009, Luo & Chen 2014, Mishra & Patra 2018, Wu et al. 2019, Hoang & Matsumoto 2020 and Singh et al. 2020). A series of tests have been performed by Luo & Chen (2014) for investigating the creep characteristics of soil in marine and terrestrial deposits. Hoang & Matsumoto (2020) used a small scale physical model for studying the time effects on the behavior of two vertically loaded pile raft foundation models on saturated clay.

Few researchers (Small & Liu 2008, Feng et al. 2014, Hu et al. 2015, Tarenia & Patra 2019) reported numerical studies for time-dependent behavior of piles embedded in soft soils under compressive loads. Small & Liu (2008) combined the raft stiffness with the soil stiffness by using an 8-noded iso-parametric shell element and treated the piles as solid elements. Chen et al. (2020) performed a time dependent numerical stimulation for studying the creep settlement of high railway foundations. Numerical prediction on time dependent behavior of Ballina test embankment has been carried out by Jostad et al. (2018).

The immediate response of a laterally loaded single pile and pile groups have been reported by a few researchers (Katzennbach & Turek 2005, Li et al. 2010 and Luan et al. 2020). In addition to this, several researchers have investigated the immediate settlement of pile foundations subjected to both compressive and lateral loads (Small & Zhang 2002, Kartigeya et al. 2007, Choi et al. 2017, Palammal & Senthilkumar 2018, Tarenia & Patra 2020). Kartigeya et al. (2007) conducted a three-dimensional analysis and investigated the impact of vertical loads on laterally loaded piles. It has been observed that the behavior of laterally loaded piles is dependent on its slenderness ratio.

From the literature, it is evident that a majority of studies on long-term response of piles have been conducted for compressive loads only. The studies related to the behavior of single pile and pile groups subjected to combined loads with respect to time have been limited. The analytical studies have been limited because of the complexity in the development of a coupled model considering time-effects to analyze the pile response under combined loads. The present analyses focuses on the numerical investigation of long-term behavior of pile groups subjected to combined loads. In this study, time analysis has been done to understand how the load ratio, slenderness ratio, pile group configuration influences the pile displacements, excess pore water pressures, differential settlements and the mobilized stresses.

2 FINITE ELEMENT ANALYSES

The finite element tool Plaxis 3D has been employed to study the pile behavior subjected to combined axial and lateral loads over a period of time. The finite element model developed for the present assessment have been validated with previous study (Zhang et al. 1999) is shown in Figure 1.

2.1 *Soil geometry*

In this study, the boundaries of the soil geometry has been fixed by performing a sensitive analysis on the most complex condition (i.e. 3×2 pile group with pile cap resting on the soil). Based on this analysis, the soil geometry has been confined to $10d_g$, $10d_g$, $35d$ in x, y and z-directions respectively. It has been verified that the changes occurring in the soil volume due to loading are confined within the considered geometry.

Soft Soil Creep Model (SSCM) has been chosen to stimulate the behavior of the soft soil surrounding the piles. The water table exists at a depth of 0.5m from the ground surface. The soil properties and input parameters for SSCM model have been taken from Jostad et al. (2018).

Table 1. Input parameters considered for the present study

Parameter	Soil Properties	Pile	Pile Cap
Material Type	SSCM	LE	LE
γ_{unsat} (kN/m^3)	16	-	-
γ_{sat} (kN/m^3)	17	-	-
γ (kN/m^3)	-	25	25
e_{init}	0.5	-	-
$\lambda*$	0.1	-	-
$\kappa*$	0.018	-	-
$\mu*$	3E-3	-	-
Φ	30	-	-
ν_{ur}	0.15	-	-
ν	-	0.3	0.3
K_o^{nc}	0.4	-	-
k_x, k_y (m/day)	1E-3	-	-
k_z (m/day)	0.4E-3	-	-
POP (kPa)	24	-	-
E (GPa)	-	30	30

*SSCM- Soft Soil Creep Model, LE- Linear Elastic Model

2.2 *Pile and pile cap*

Concrete piles of 1.2m diameter and different slenderness ratio (5, 10, 15, 20, and 25) have been considered for the present analysis. The considered values of *L/d* have been adopted based on the characteristic length criteria as per IS 2911(Part 1/Sec 1). Based on this criteria, the behavior of piles can be classified as short rigid piles (*L/d*=5), intermediate between rigid and elastic piles (*L/d*=10), and long elastic piles (*L/d*=15, 20, 25).

The piles have been modelled by using polycurve option available in Plaxis 3D. The piles and pile cap are modelled using Linear Elastic Model and are assumed as non-porous material. Based on the recommendations of IS 2911 Part 1/Sec 1, the overhanging portion of pile cap beyond the outermost piles of the pile group is taken as 250mm and the pile embedded into the pile cap is taken as 100mm.

2.3 *Finite element model*

Numerical modelling have been performed in step-by-step construction. In the initial step, soil volume is created by using borehole option and the corresponding properties listed in Table 1 have been assigned. In the next step, piles and pile cap have been created by using polycurve and surface options, respectively. Staged construction has been selected for studying the creep behavior of the surrounding soil. Consolidation analysis have been considered and the long-term behavior of pile group has been simulated for a time period of 200years.

Table 2. Input parameters considered for validation

Parameter	Properties
Unit Weight γ (kN/m^3)	14.05
Friction angle Φ (°)	34.5
Relative Density D_r (%)	36
Shear Modulus G (MN/m^2)	8.23
Poisson's Ratio ν	0.3
Elastic Modulus E (MN/m^2)	21.4
Skin friction τ_f (kN/m^2)	48.3
Ultimate Tip Capacity Q_f (kN)	800

3 RESULTS

3.1 *Comparison of present model results with the existing model results*

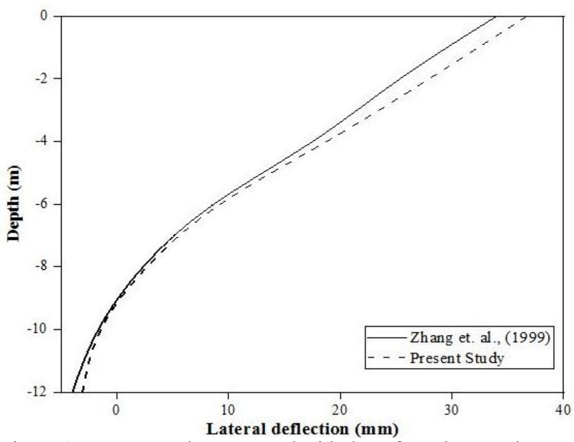


Figure 1. Present results compared with that of previous study

The results obtained from the present study have been validated with the results by Zhang et al. (1999) for a 4×3 pile group embedded in sand. The diameter and length of the piles is 0.43m and 13.7m, respectively, and a free head of 2.3m has been provided. The input parameters which have been considered for validation are presented in Table 2.

As per the comparison shown in Figure 1, it can be inferred that the present study is in good concurrence with the reported outcomes and shows a maximum deviation of 8%.

3.2 *Parametric studies*

3.2.1 *Load ratio*

The coastal and offshore structures experience lateral loads in addition to compressive loads, due to winds, wave action and tidal variations. In case of onshore structures, the lateral loads experienced by the structures are about 10-15% of vertical loads

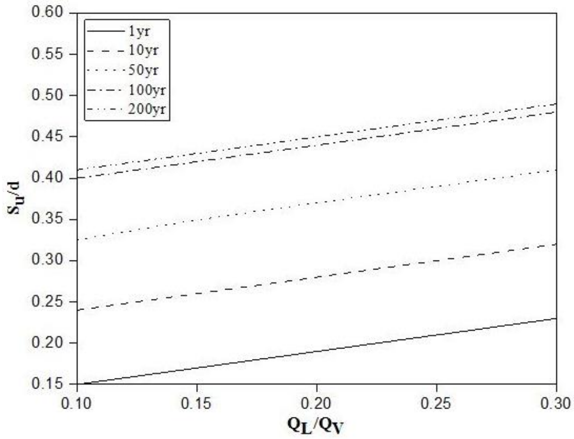


Figure 2. Time dependent variation of single pile for L/d = 20 and different load ratios

and about 25-30% in coastal and offshore structures. The influence of load ratio (ratio of lateral to vertical load) on the time dependent behavior of piles in clays has been investigated and shown in Figure 2. With increasing load ratio, a linear increment in settlement ratio (S_u/d) has been observed over a period of 50 years, after which it becomes almost constant.

3.2.2 *Time dependent behavior of a piles*

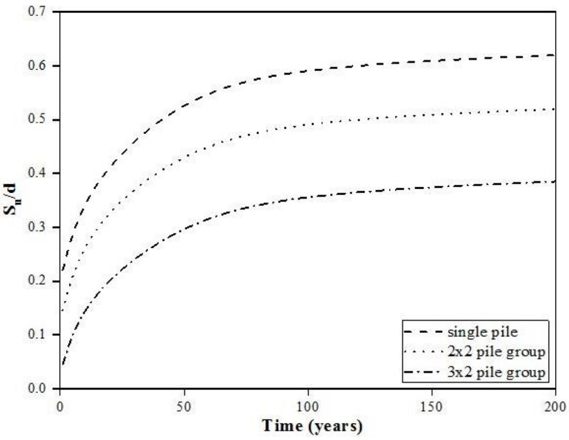
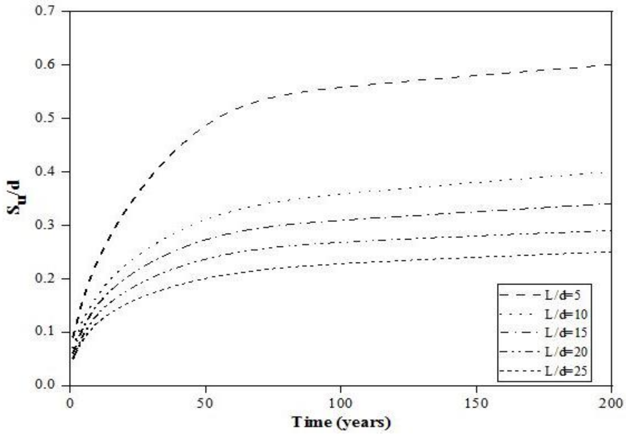


Figure 3. Time dependent variation of various configuration of pile groups

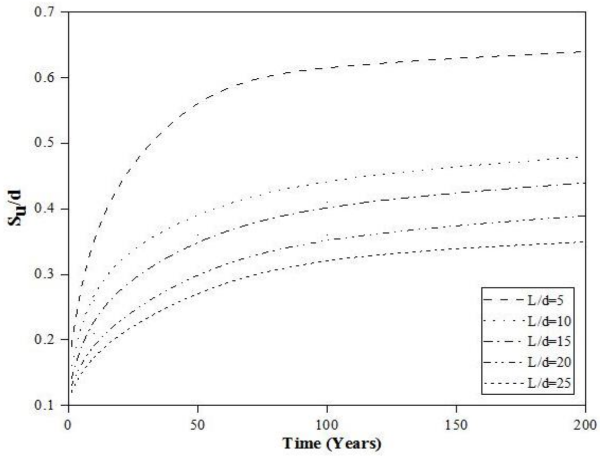
The total displacements of a single pile and pile groups (2×2 and 3×2) has been observed over a period of time, as shown in Figure 3. Based on this study, the settlements of a single pile are higher than the settlements of pile groups, due to the block effect of pile groups. The settlements of 2×2 and 3×2 pile groups are about 17% and 45% lower than the settlement of single piles, respectively. The block effect mainly depends on the number of piles in the pile group. Due to this, settlements of larger pile group configurations (3×2) are lower than the settlements of smaller pile group configurations (2×2). In this study, the settlements of 3×2 pile group are about 17.5% lower than the settlements of 2×2 pile group.

3.2.3 *Slenderness ratio*

The effect of slenderness ratio on time-dependent behavior of 2×2 and 3×2 pile groups are shown in Figure 4a and 4b respectively. In general, short piles embedded in clay exhibits large settlements due to lack of sufficient length available for mobilization of skin friction, in comparison to long piles. It has been observed that the settlement ratio (S_u/d) for short piles are 50% and 140% higher than the settlement ratio for intermediate and long piles respectively.



(a)



(b)

Figure 4. Time dependent variation of (a) 2×2 (b) 3×2 pile group for Q_L/Q_V=15%, s/d=3 and for different L/d ratios

3.2.4 *Effect of load ratio and pile spacing on lateral displacements*

When piles are subjected to lateral loads or combined loads (both compressive and lateral), maximum lateral movement occurs at the pile head and becomes almost insignificant beyond z/L=0.5. The behavior due to lateral loads is different for rigid and elastic piles. Rigid piles when unrestrained at top fails by rotation, whereas restrained at top fails by translation. Elastic piles of both

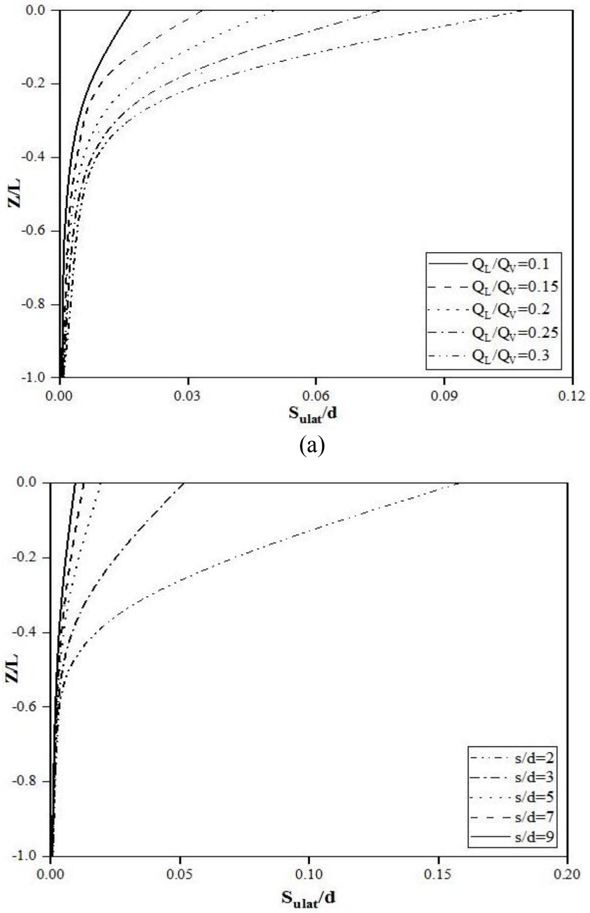


Figure 5. Variation of lateral deflection with depth for 3×2 pile group (a) *L/d*=20, *s/d*=5 (b) *L/d*=15, Q_L/Q_V=10

unrestrained and restrained at top fails by fracture at a point where the maximum moment is developed.

The effect of load ratio and pile spacing on lateral pile head displacements are shown in Figure 5a and 5b. It has been noticed that the lateral pile head displacement increases with the increasing load ratio. From Figure 5a, it is clear that the lateral movement of piles are observed upto a depth of 0.35*L*, after which it becomes negligible. In general, the lateral movement of pile groups with larger pile spacing are restricted in comparison to pile groups with smaller spacing. From Figure 5b, it is evident that the lateral movement of piles is insignificant beyond a pile spacing of 5*d* and depth of 0.4*L*.

It has been observed that the total pile head displacements due to combined loads are about 9% to 15% higher than the pile head displacements due to compressive loads only. The variation of lateral displacements of piles and mobilized shear stresses are observed to be significant upto a critical depth of 7m, irrespective of pile slenderness ratio, spacing between piles and load ratio.

3.2.5 *Variation of differential settlement ratio with respect to spacing*

The ratio of maximum differential settlement to the maximum settlement is termed as differential settlement ratio (S_{diff} ratio). For calculating differential settlement, the settlements have been estimated at the center and corner of the pile cap. From Figure 6, it can be concluded that S_{diff} ratio is almost zero at the top and bottom of the pile and maximum at 0.4*L* from the surface. For lesser values of *s/d*, S_{diff} ratio have been observed to be maximum up to a spacing of 5*d*.

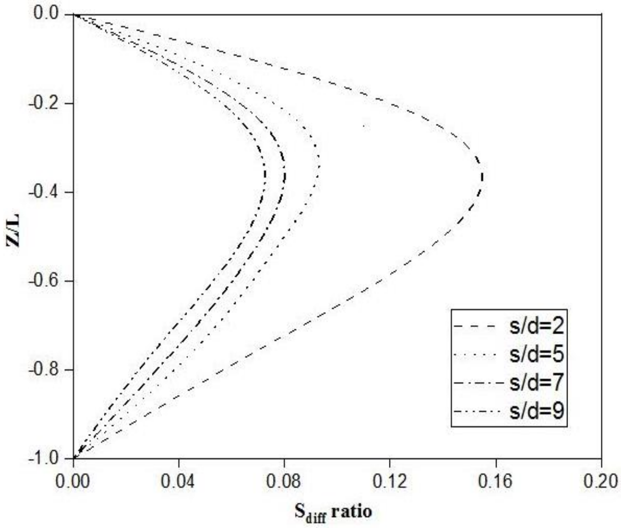
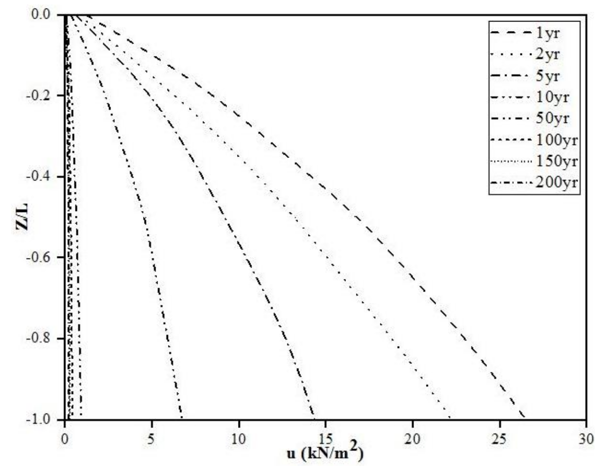


Figure 6. Variation of differential settlement ratio with respect to depth for 3×2 pile group, L/d=10, Q_L/Q_V=20

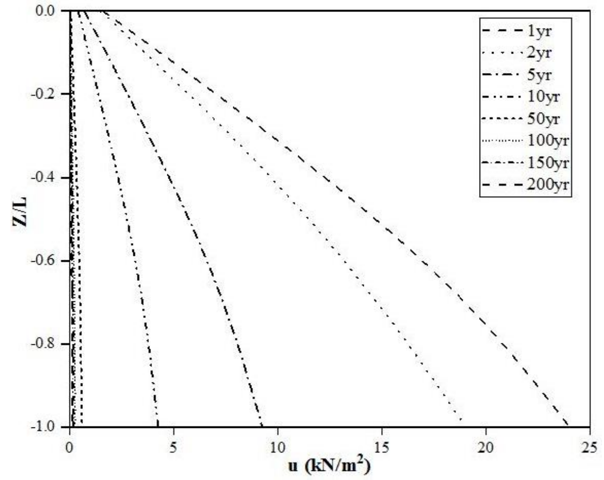
3.2.6 *Effect of pore water pressure with respect to depth*

During the pile driving process, soil volume surrounding the pile experiences a maximum disturbance and the pore water pressures developed are generally high in this region. In clays, the dissipation of excess pore water pressure developed during pile installation may take several months or years to complete. After the application of load on these piles, soil in the vicinity of piles experiences a large amount of excess pore water pressures. The effect of developed pore water pressures due to loading and installation process are limited upto a critical radius from the pile shaft.

In this study, excess pore water pressures have been computed at 0.5*d*, 5*d*, 7*d* and 10*d* distances from the centre-line of the pile and observed to be higher at a distance of 0.5*d*. The variation in excess pore pressures are observed up to a distance of 5*d* beyond which the increasing percentage of excess pore water pressures is less than 5%. Figure 7a and 7b shows the variation of excess pore water pressures with respect to depth, calculated at 0.5*d* and 5*d* from the center line of pile. From the present analysis, it is evident that the excess pore water pressures shows about 95% dissipation within the time period of 50 years.



(a)



(b)

Figure 7. Variation of excess pore water pressure of a single pile with respect to depth, Q_L/Q_V=10% and L/d=25 (a) at 0.5d (b) 5d away from the centre line of the pile

4 CONCLUSIONS

Finite element method has been used to study the time dependent variation of a single pile and pile groups under combined axial and lateral loads. The predicted results from the present study are in good concurrence with the published results. The effects of load ratio and pile properties on the differential settlements, total pile head displacements, lateral displacements and pore water pressures around the periphery of the pile have been observed from the parametric studies. Following are the conclusions derived from this study:

- The total pile head displacements due to combined loads are about 9% to 15% higher than the pile head displacements due to compressive loads only.
- The settlement ratio (S_u/d) for short piles are 50% and 140% higher than the settlement ratio for intermediate and long piles, respectively.
- The differential settlement ratio increases gradually over time, and is typically in the range of 0.001 to 0.025 over a period of 200 years.
- The differential settlement ratio is about 35% to 45% higher for pile groups subjected to combined loads, in comparison to pile groups under pure compressive loads.
- The variation of lateral displacements of piles and mobilized shear stresses with depth is almost insignificant beyond a critical depth of 7m, irrespective of the slenderness ratio, spacing between piles and load ratio.

List of notations

L	Pile length
d	Pile diameter
d_g	Diameter of pile group
Q_V	Vertical load
Q_L	Lateral load
Q_L/Q_V	Load ratio
z/L	Depth ratio
S_u	Ultimate settlement
S_u/d	Settlement ratio
S_{diff} ratio	Differential settlement ratio
E	Young's modulus
Φ	Friction angle
v	Poisson's ratio
LE	Linear elastic model
SSCM	Soft soil creep model
e_{init}	Initial void ratio
λ^*, κ^*, μ^*	Basic stiffness parameters in SSCM
v_{ur}	Poisson's ratio for both unloading-reloading
K_o^{nc}	Stress ratio
k_x, k_y, k_z	Permeability in x, y, z-directions respectively
POP	Pre-overburden pressure

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