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EFFECTS OF SLOPE AND SLEEVING ON THE BEHAVIOR OF LATERALLY LOADED PILES

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ABSTRACT

Pile sleeving is an annulus of compressible material between a laterally loaded pile and the adjacent ground and is a method adopted in Hong Kong for protecting the stability of sloping grounds and retaining walls. In practice, sloping grounds of various inclinations can be encountered and an appropriate sleeving thickness has to be selected for particular sites considering site-specific factors. To evaluate the effects of slope inclination and sleeving thickness on behavior of piles, a series of 3D analyses of the behavior of laterally loaded piles was conducted considering several sleeving thicknesses (0, 100, and 250 mm) and slope inclinations [level, 1(vertical):2(horizontal), and 3:4]. At a typical design lateral load, the effects of slope inclination on the pile response are found to be minor but the effects of sleeving thickness are significant. At large lateral loads, however, the horizontal displacements and bending moments of the pile will increase as the ground becomes steeper, especially when the ground is steeper than 1:2. Empirical relations between the displacements and bending moments of the pile in a sloping ground and those in the level ground are proposed. A criterion for selecting suitable sleeving thickness is also proposed considering both pile response and compressibility of the sleeving material.

Key words: finite difference, laterally loaded pile, load transfer, sleeving, slope stability (**IGC**: E4/K8)

INTRODUCTION

Pile sleeving is an annulus of relatively compressible material between a pile or a caisson and its adjacent ground, as shown in Fig. 1. It is installed on laterally loaded piles in Hong Kong (GCO, 1984; Siu, 1992; Ng and Zhang, 2001a; Ng et al., 2001b; Chung, 2003) as a mean to improve the stability of a sloping ground or a retaining wall by minimizing the transfer of lateral load from the piles to the ground or the retaining wall, particularly at shallow depths. A variation of pile sleeving in the form of a liner between a pile and the surrounding ground is also used sometimes as a reducer of negative skin friction on bored piles penetrating through marine deposits. Siu (1992) reported 13 cases involving the use of sleeved caissons on soil slopes near elevated roads or near retaining walls. Chung (2003) reported two cases of sleeved bored piles 2.7 m in diameter behind retaining walls. Completely decomposed granite (CDG) was encountered in most of these cases. Although the soil is typically classified as silty sand, it may contain some cementation and exhibit apparent cohesion when it is not fully saturated. Therefore, construction of the pile sleeving in CDG is feasible and the performance of sleeved piles has been satisfactory (Siu, 1992).

Poulos (1976, 1995), Chow (1996), Wakai et al. (1999), Cai and Ugai (2000, 2003), and other researchers have analyzed the behavior of laterally loaded piles in or near a slope. However, all the piles considered were not sleeved. Recently, Ng and Zhang (2001a) studied the performance of a laterally loaded sleeved pile in a sloping ground of different values of soil stiffness and Ng et al. (2001b) analyzed the influence of laterally loaded sleeved piles and pile groups on slope stability using a strength reduction technique. The two studies considered a 3 (vertical):4 (horizontal) slope and piles with a 250 mm-thick sleeving. The results from the two studies show that

1. The load transfer of a sleeved pile is primarily through a downward shear transfer mechanism in the vertical plane.
2. The pile sleeving is capable of significantly reducing the stresses caused by the laterally loaded piles in the slope in front of the sleeved pile segment.
3. The sleeving can improve the margin of safety against local failure but has little improvement on the global stability of the slope.
4. While the sleeving is beneficial to local stability of the slope in front of the pile, it will cause increases in lateral deflection and bending moment of the pile.

There are two key issues that have not been addressed in the previous studies. In practice, piles may be con-

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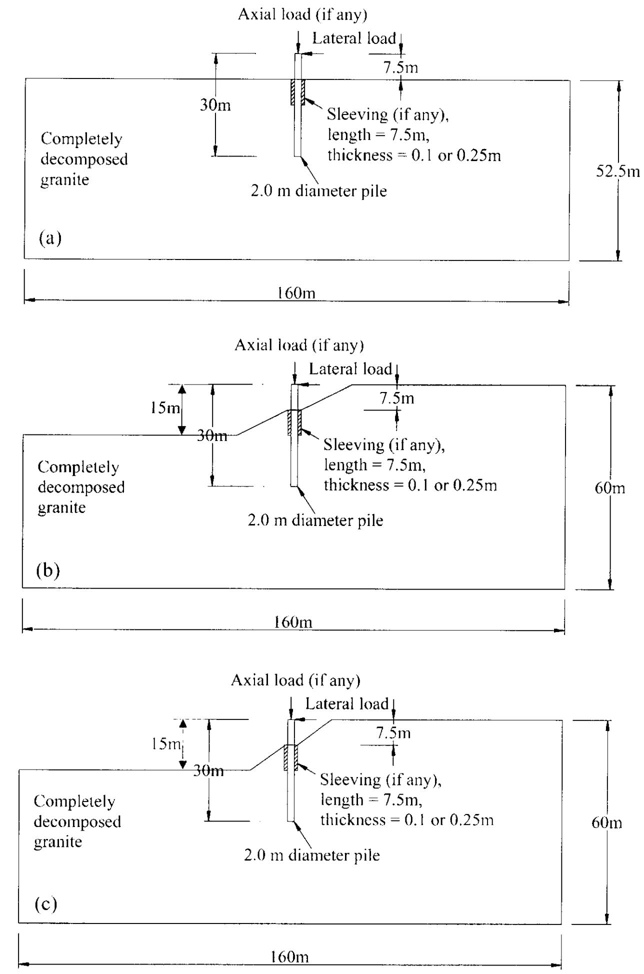

Fig. 1. Sleeved and unsleeved piles in (a) level ground, (b) 1:2 sloping ground and (c) 3:4 sloping ground

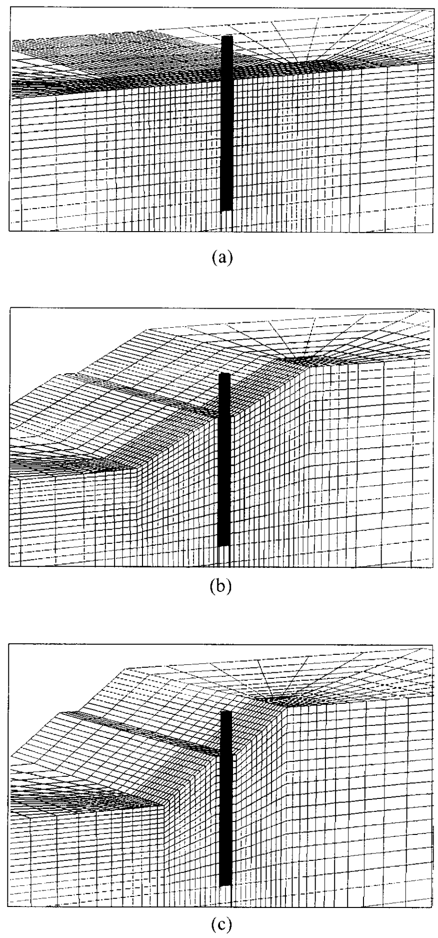

Fig. 2. Finite difference grids for piles in (a) level ground, (b) 1:2 sloping ground and (c) 3:4 sloping ground

structed in sloping grounds with inclination angles between 0 and 35°. It is necessary to study the behavior of piles in grounds of different inclinations and to compare the behavior with that of piles in a level ground of similar soil conditions. In addition, the selection of sleeving thickness for a specific site is critical for practical design. If the sleeving thickness is too small, the purpose of enhancing the slope stability may not be achieved. If the sleeving is too thick, however, the lateral deflection and bending moment of the pile will be excessive.

To address the two aforementioned key issues and to provide further basis for design of laterally loaded sleeved piles in sloping grounds, a series of 3D finite difference analyses considering three values of sleeving thickness and three slope inclinations is conducted and reported in this paper. Based on the analyses, the effects of the slope inclination and sleeving thickness on the behavior of laterally loaded piles are evaluated and a criterion for selecting the sleeving thickness is proposed.

3D NUMERICAL ANALYSIS PROCEDURES AND MODEL PARAMETERS

In this paper, large diameter piles with three sleeving thickness (0, 100 and 250 mm) in three grounds of different inclinations (level, 1:2, and 3:4) are investigated using the 3D finite difference program Flac3D (Itasca Consulting Group, 2002), which has been calibrated with many examples. The range of slope inclinations considered is common in Hong Kong. Figure 1 summarizes the three pile-soil systems considered. Figure 2 shows the 3D view of the finite difference grids for the three sloping ground cases. Only one half of each of the pile-slope systems is simulated taking advantage of symmetry. A space of 160 m long and 60 m wide is covered by each of the grids. The depth of the ground is 52.5 m for the case of the level ground but varies for the sloping grounds depending on the slope inclination. The bottom boundary is fixed while the side boundaries are allowed to move vertically, but not horizontally. The heights of the 1:2 slope and the 3:4 slope are 15 m. The cut slopes are formed by a series of excavation processes simulated numerically. Each step excavates 2.5 m of soil and the excavation continues until a slope 15 m high has been formed. The average slope angles of the three ground cases are 0°, 23.8° and 32.0°, respectively. As in previous analysis (Ng and Zhang, 2001a), the concrete pile is assumed to be 2 m in diameter, 30 m in length and 22.5 m in penetration in all cases. The 7.5-m free length above the ground represents approximately the location of

Table 1. Material parameters for finite difference analysis

Properties	Soil	Pile (concrete)	Sleeving material
Young's modulus (MPa)	50.0	26000.0	0.3
Poisson's ratio	0.3	0.2	0.3
Bulk modulus (MPa)	41.7	14400.0	0.25
Density (kg/m^3)	1800.0	2400.0	16.5
Internal friction angle ϕ' (degree)	35.0	—	—
Effective cohesion c' (kPa)	10.0	—	—
Earth pressure coefficient at rest	0.4	—	—

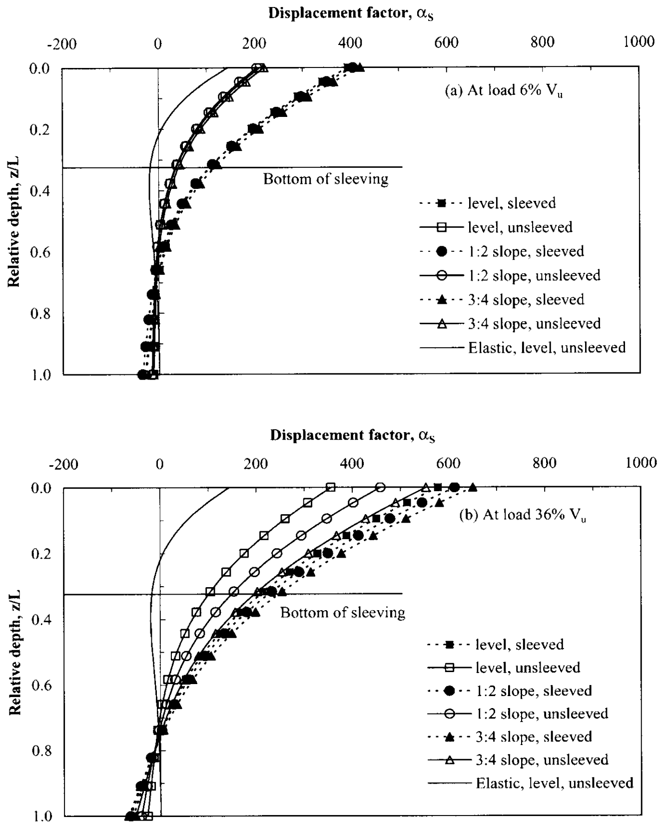

Fig. 3. Influence of slope inclination on the horizontal displacement factor α_S

resultant horizontal load such as the wind load on a bridge. In dense CDG, a 2-m diameter pile can still be considered flexible (Ng and Zhang, 2001a). Based on an elastic analysis proposed by Matlock and Reese (1960), the soil reaction on an unsleeved flexible pile is developed mostly at the upper one thirds of the pile. Therefore, the sleeving (if any) is installed at the upper 7.5 m of the pile to protect the stability of the ground in front of the pile. The sleeving material is assumed to connect with the pile and soil perfectly (i.e. no interface elements are used). The pile is assumed to be cast in-place with concrete in the middle of the cut slope. For simplicity, the ground water table is taken to be far below the pile tip in the analysis.

The soil is simulated with an elastic, perfectly plastic model. Failure is described by a Mohr-Coulomb criterion with a tension cut-off (Itasca Consulting Group, 2002). The tension cut-off is used because the CDG soil discussed in this paper typically exhibits some cohesion due to cementation. A Young's modulus E_s of 50 MPa is adopted, which represents a CDG soil with a typical standard penetration test blow count of about 50 (Chiang and Ho, 1980; Kulhawy and Mayne, 1990). The pile material is assumed to be linear-elastic. Polystyrene is assumed to be the compressible material for pile sleeving. This material has a density of 16.5 kg/m^3 and an average secant Young's modulus of 0.3 MPa based on results of odometer tests reported by Siu (1992). The parameters for the soil, the pile, and the sleeving material are summarized in Table 1. The piles are loaded incrementally to large displacements. For brevity, only the results at two representative load steps (i.e. 1000 and 6000 kN compared with a design load of approximately 2000 kN for an unsleeved pile and 1000 kN for an sleeved pile) are presented. As described by Ng and Zhang (2001a), the two loads correspond to approximately 6% and 36% of the shear capacity of the pile section V_u, respectively.

For general applications, the computed results are presented in various factors:

$$\alpha_S=\frac{EI}{F}S;\ \alpha_M=\frac{M}{F};\ \alpha_p=\frac{p}{F} \tag{1}$$

where F is applied load at the pile head; S is horizontal displacement; M and p are calculated bending moment and lateral subgrade reaction in unit length from numerical analyses, respectively; α_S, α_M and α_p are factors for S, M, and p, respectively; and EI is flexural stiffness of the pile. Although the pile diameter is as large as 2.0 m, the 30-m long pile in the assumed ground is still flexible based on the criterion of Matlock and Reese (1960). Ng and Zhang (2001a) have derived elastic solutions of α_S, α_M, and α_p for flexible piles on level ground. In this paper, these elastic solutions are also used for comparison with computed results.

INFLUENCE OF SLOPE INCLINATION

To investigate the effects of the inclination of slopes on the performance of sleeved and unsleeved piles, analyses with a level ground, a 1:2 sloping ground, and a 3:4 sloping ground are performed. The sleeving thickness considered in this section is 250 mm. The effects of slope inclination on the responses of lateral displacement, bending moment, and lateral subgrade reaction are examined. The effects of sleeving thickness will be discussed later in the paper.

Lateral Displacement

Serviceability considerations often dominate design of laterally loaded piles. Figure 3 shows the influence of slope inclination on the horizontal pile displacements caused by the applied lateral loads. In this figure, the relationships between the displacement factor α_S defined in Eq. (1) and the relative depth z/L of the pile at lateral loads of 6% V_u and 36% V_u are plotted, where z is the depth below the ground surface and L is the embedded depth of the pile. The elastic solution for the same

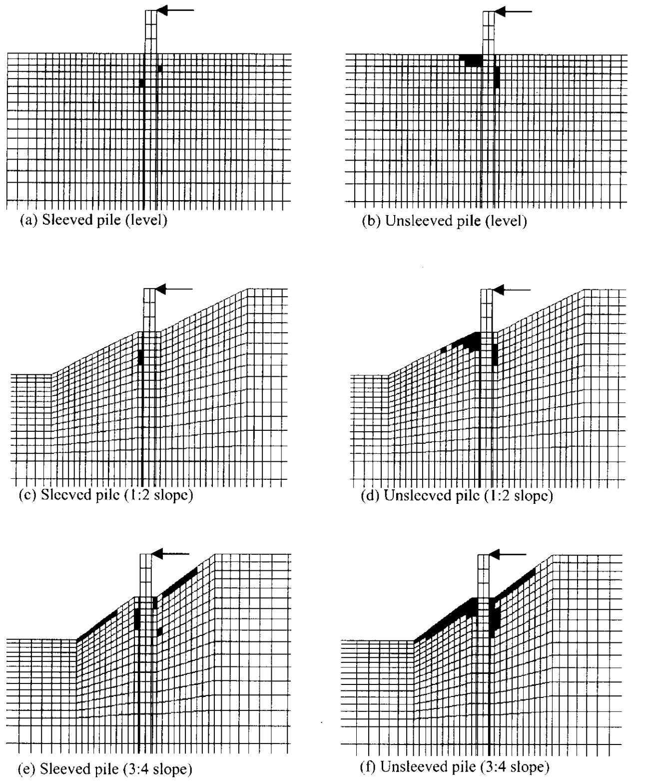

Fig. 4. Effects of slope inclination on the development of shear plastic zones around piles at load 6% V_u

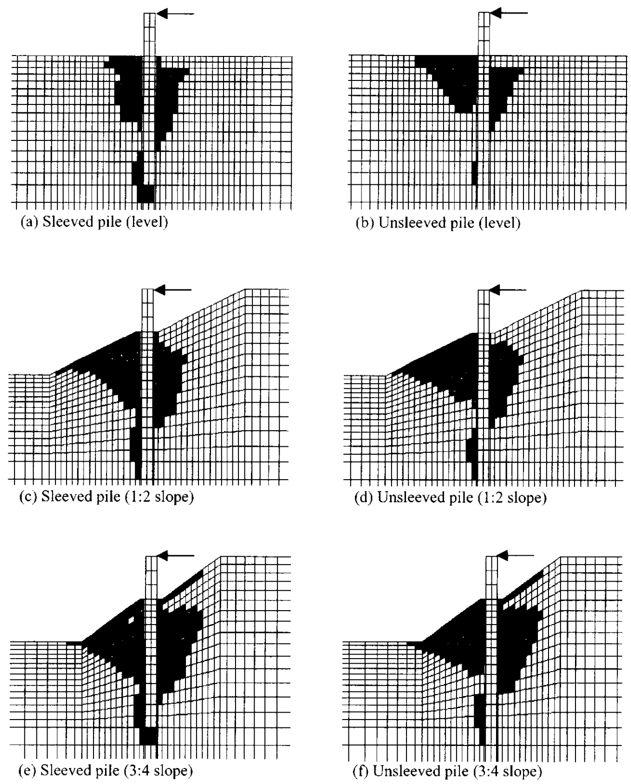

Fig. 5. Effects of slope inclination on the development of shear plastic zones around piles at load 36% V_u

unsleeved pile in a horizontal ground is also plotted in the figure for comparison purposes. In both the sleeved pile and unsleeved pile cases subjected to the small load of 6% V_u (Fig. 3(a)), the differences among the α_S values of the three foundations of different inclinations are small. Therefore, the ground inclination has a minor effect on the pile displacement at the small load. At the large lateral load of 36% V_u (Fig. 3(b)), the effect of slope inclination becomes more significant. The α_S values at the ground surface in the level ground, 1:2 slope and 3:4 slope are approximately 2.5, 3.2, and 3.8 times the pile deflection from the elastic solution, respectively for the unsleeved pile and approximately 4.0, 4.3, and 4.5 times the pile deflection from the elastic solution, respectively for the sleeved pile.

The lateral displacements of both sleeved and unsleeved piles increase with the inclination of the sloping ground at the large load of 36% V_u. This is reasonable because the ultimate passive resistance of the wedge in front of a pile in a dipping ground is smaller than that in a level ground and a larger percentage of the lateral load is transferred to the deeper soils as the slope becomes steeper.

Figures 4 and 5 compare the stress states of the three grounds when the sleeved and unsleeved piles are subjected to the two lateral loads of 6% V_u and 36% V_u. At the small load (Fig. 4), some plastic zones develop in all three grounds, particularly behind the sleeved piles and in front of the unsleeved piles. Yet, most of the ground around the sleeved and unsleeved piles is still in an elastic state despite of slope inclination. Therefore, the piles would respond approximately as if they were in elastic media. The plastic zones in front of the sleeved piles are considerably smaller than those in front of the unsleeved piles, because the sleeving reduces shear stresses at shallow depths in front of the sleeved piles. At the large load of 36% V_u, extensive but similar plastic zones around the sleeved and unsleeved piles develop for each ground condition (Fig. 5). The plastic zone becomes more extensive as the ground slope becomes steeper. Therefore, the horizontal displacements of the piles will also increase as indicated in Fig. 3.

Experimental proof for the predicted effect of slope inclination on the horizontal displacements of unsleeved piles in this paper has been reported. Bhushan et al. (1979) conducted four field tests on 1.2 m diameter, cast-in-place drilled piers constructed in silty sand and sand clay grounds of different inclinations ranging from 20° to 55°. Uto et al. (1985) also conducted three field tests on piles 3.0–3.5 m in diameter, two in soft rock slopes and one in a sandy slope. Terashi et al. (1991), Bouafia and Bouguerra (1995), and Mezazigh and Levacher (1998) performed several centrifuge model tests and Schmidt (1977) performed conventional model tests on laterally loaded unsleeved piles in cohesionless soil slopes. These tests reveal that the difference in the horizontal displacements of a pile in a level ground and a pile in a sloping ground is small when the displacement is small (i.e. smaller than 20 mm) and that the difference increases with the displacement and becomes substantial at dis-

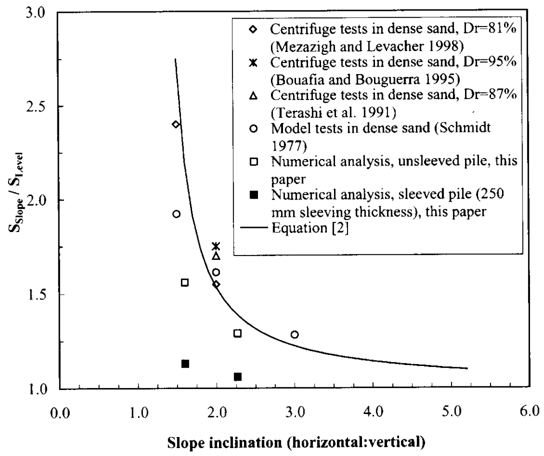

Fig. 6. Relationships between displacement ratio S_{Slope}/S_{Level} and average inclination of sloping ground. S_{Level} = displacement of pile in level ground, S_{Slope} = displacement of pile in sloping ground at the same load

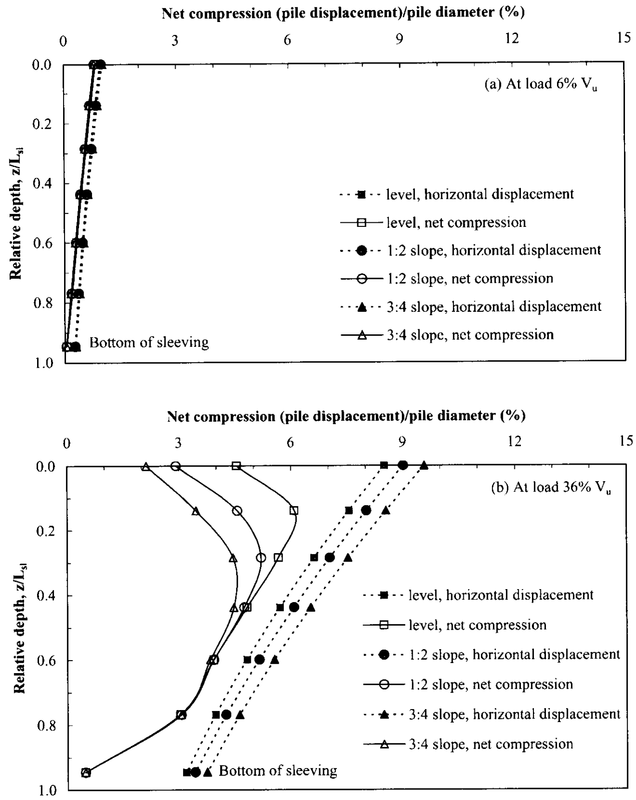

Fig. 7. Net compression of the sleeving and pile displacement along the sleeving

placements larger than 50 mm. The calculation results shown in Fig. 3 are consistent with the experimental observations. In Fig. 3, the displacement of the unsleeved pile at the ground surface elevation is only approximately 10 mm ($<$20 mm) under the small load of 6% V_u but reaches approximately 200 mm ($>$50 mm) under the large load of 36% V_u.

Figure 6 shows the relationship between slope inclination and the ratio of the displacements of the pile in sloping ground and of the reference pile in level ground measured from the reported tests at displacements larger than 50 mm. The displacement ratio increases rapidly when the slope is steeper than 1:2, but approaches 1.0 when the slope becomes flat. The computed results from this study at the large load of 36% V_u are also plotted in Fig. 6. At this load level, the pile displacements are sufficiently large ($>$50 mm). The computed displacement ratios of the unsleeved piles appear to be consistent with the test results although some cohesion is considered in the numerical analysis. For the sleeved piles, however, the displacement ratios are less sensitive to slope inclination and considerably smaller than the values for the unsleeved piles at corresponding slope inclinations, since the effect of slopes is much reduced because of the downward load transfer in the sleeved piles.

The relationship in Fig. 6 for unsleeved piles in cohesionless soil slopes can be approximated by the following empirical equation,

$$\frac{S_{Slope}}{S_{Level}} = 1 + \frac{k_S}{\dfrac{\tan\phi'}{\tan\alpha} - 1} \tag{2}$$

where α is the mean slope angle and $tan\alpha$ is the mean slope inclination; ϕ' is the friction angle of soil; and k_S is a curve fitting coefficient. In this study, a value of $\phi' = 38°$ as reported by Schmidt (1977) for dense sand and a k_S value of 0.3 are used. Equation (2) captures two effects of slope inclination. First, the displacement ratio will approach 1.0 when the slope angle α is very small. Second, a cohesionless soil slope will not be stable when the slope angle approaches the effective friction angle of the soil and the pile in the slope will fail with the slope. Note that there are a number of influence factors that are not considered explicitly in Eq. (2). Some of these factors are ground water effect in slopes, reinforcing effect of piles on slope stability, embedded pile length, relative stiffness between the ground and the pile and presence of pile groups. In particular, the patterns and effect of ground water flows in a level ground and in sloping grounds of different inclinations can differ significantly.

Net Compression of Sleeving Material

The functioning of the pile sleeving can be checked by its net compression, i.e. the change in the sleeving thickness, under lateral loading. The net compression at a particular elevation can be calculated by the difference in the horizontal displacements at the two end nodes of the sleeving at that elevation. In general, the compression of the sleeving is a function of applied load, relative stiffness between the soil and the pile and between the soil and the sleeving material, and strength parameters of soil used in analysis. Figure 7 shows the variations of the horizontal displacement of the pile and the net compression of the sleeving for the three grounds of different inclinations (i.e. level, 1:2 and 3:4 sloping grounds). The initial sleeving thickness considered is 250 mm. For the sleeved piles subject to the small load of 6% V_u (Fig. 7(a)), both

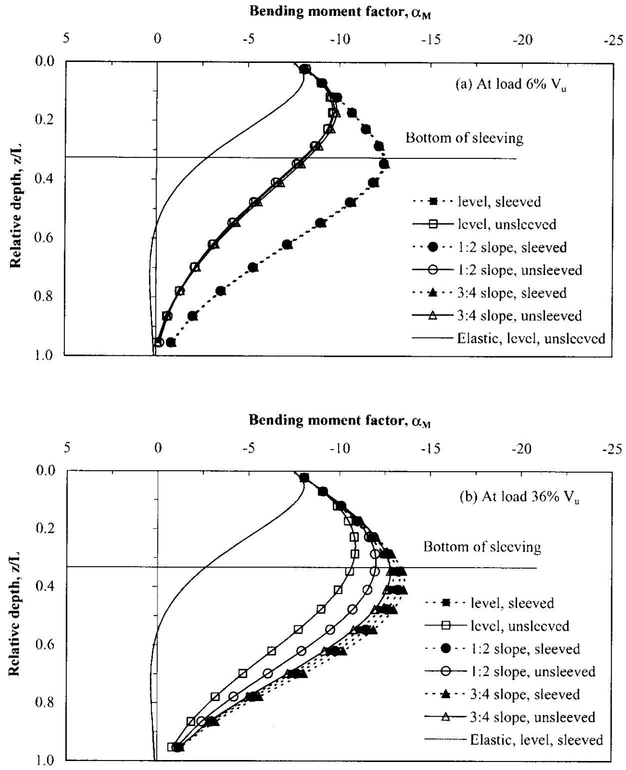

Fig. 8. Influence of slope inclination on the bending moment factor α_M

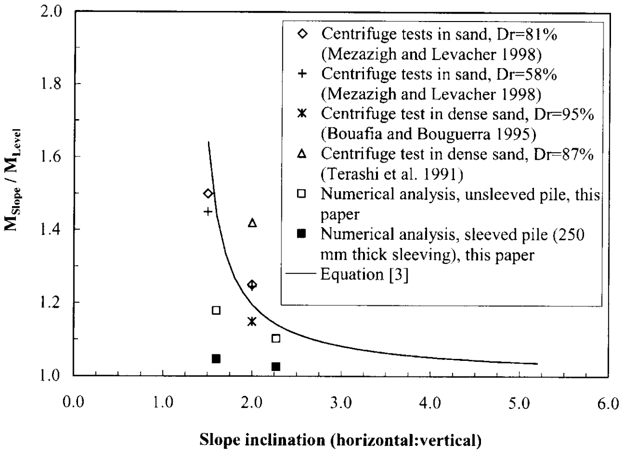

Fig. 9. Relationships between maximum bending moment ratio M_{Slope}/M_{Level} and average inclination of sloping ground. M_{Level} = maximum bending moment of pile in level ground, M_{Slope} = maximum bending moment in sloping ground at the same load

the pile deflection and the compression of the sleeving material increase from the toe to the top of the sleeving. The performances of the piles in the three grounds are similar. Approximately 60–90% of the pile deflection takes place by compression of the sleeving material in the upper 60% of the sleeving, with the percentage slightly decreasing with an increase in ground inclination.

At the large load of 36% V_u (Fig. 7(b)), considerable differences can be found among the three grounds. In the level ground, the net compression takes up the largest portion (70–85%) of the deflection in the sleeved zone between $z/L_{sl}=0.3$ and 0.8, where L_{sl} is the length of the sleeving. In comparison, smaller percentages of the deflection are taken up by the net compression in the cases of the 1:2 slope and 3:4 slope, respectively. This indicates that the sleeving is the most effective in the level ground but becomes less effective with increasing slope inclination. At the bottom of the sleeving, deformation of the sleeving material is limited by end restraints.

Bending Moment and Subgrade Reaction

For flexural design of laterally loaded piles in a sloping ground, it is necessary to identify the differences between the maximum bending moment as well as its location in the piles in the sloping ground and those in the piles in a level ground. Figure 8 shows the relationship between the bending moment factor α_M and the relative depth z/L of the unsleeved and sleeved piles on foundations of different slopes. At the small load of 6% V_u (Fig. 8(a)), the α_M values for the unsleeved piles constructed in the three grounds of different inclinations are similar, so are those for the sleeved piles. Therefore, the ground inclination has little effect on the bending moments in the piles subject to the small load. Instead, the use of the sleeving has a significant effect on the bending moment, which will be discussed in detail later. At the large load of 36% V_u (Fig. 8(b)), the effect of slope inclination becomes noticeable. The maximum α_M values for the unsleeved piles in the 1:2 ground and the 3:4 ground are approximately 10% and 18% larger than that in the level ground. At the same time, their locations shift downward as the slope inclination increases. The bending moment in the 3:4 ground is the largest, which is consistent with the fact that the pile in the 3:4 slope develops the largest displacement among the three grounds (Fig. 3).

Figure 9 shows the variations of the maximum bending moment in the piles in sloping ground, M_{Slope}, with slope inclination at horizontal displacements larger than 50 mm, based on the results of the numerical analyses and those measured from the centrifuge tests conducted by Terashi et al. (1991), Bouafia and Bouguerra (1995), and Mezazigh and Levacher (1998). The bending moments are normalized with the corresponding maximum bending moments in the piles in the level ground, M_{Level}. In this figure, the maximum bending moment appears to increase significantly when the slope is steeper than 1:2. The computed values for the unsleeved piles fit the centrifuge test results reasonably well; but the computed values for the sleeved piles are lower than those for the unsleeved piles. Similar to Eq. (2) for horizontal displacements, the variations of the maximum bending moment with the slope inclination can be approximated by:

$$\frac{M_{Slope}}{M_{Level}}=1+\frac{k_M}{\dfrac{\tan\phi'}{\tan\alpha}-1} \tag{3}$$

where k_M is a curve fitting coefficient, which is 0.11 in Fig. 9. Once again, this equation is subject to similar limitations of Eq. (2) and does not consider explicitly the effects of several factors mentioned earlier.

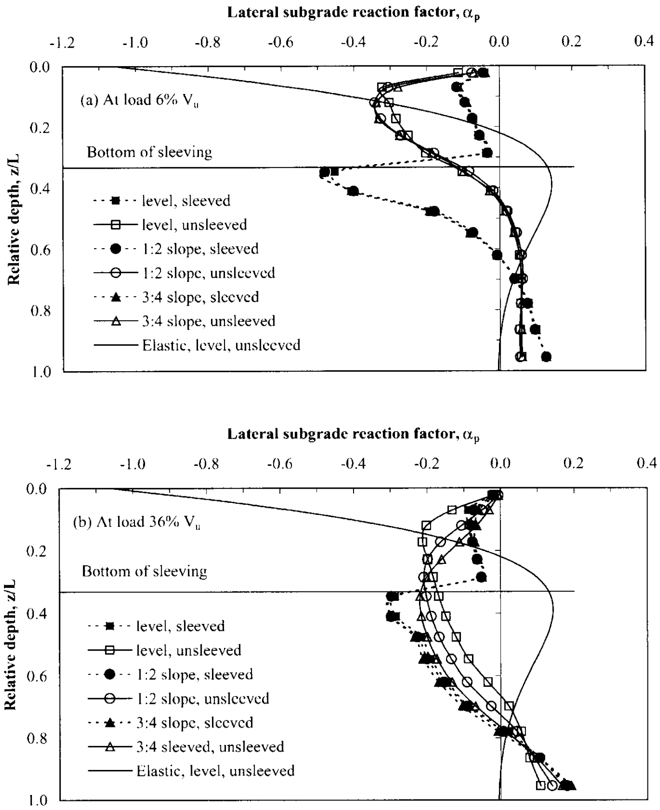

Fig. 10. Influence of slope inclination on the lateral subgrade reaction factor α_P

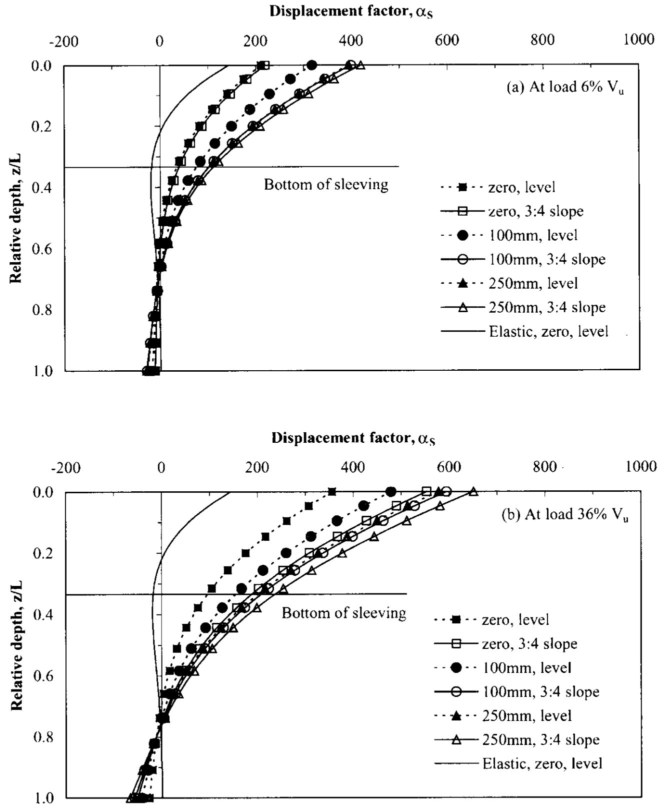

Fig. 11. Influence of sleeving thickness on the displacement factor α_S

The mechanism of lateral load transfer from the pile to the ground can be shown from distributions of lateral subgrade reaction along the pile. Figure 10 shows the influence of slope inclination on the lateral subgrade reaction factor α_P. Figure 10(a) reveals two distinct patterns of lateral load transfer at the lateral load of 6% V_u for the sleeved and unsleeved piles. For the unsleeved piles, the load transfer is primarily through the subgrade reaction at the upper part of the pile. For the sleeved piles, the subgrade reaction in the sleeved zone is small and the majority of lateral load is transferred to the soil beneath the sleeving. Nevertheless, there is no considerable difference among the α_P values with the three ground inclinations for both unsleeved and sleeved cases. Therefore, the influence of ground inclination on the subgrade reaction is minor at a small load. At the lateral load of 36% V_u (Fig. 10(b)), there is a tendency for the soil in greater depths being mobilized to resist the lateral load on the unsleeved pile with an increase in the ground inclination. The subgrade reaction at shallow depths decreases due to plastic yielding; hence, the sleeving is less effective at the large lateral load. The load transfer to greater depths will result in a larger horizontal displacement as shown in Fig. 3.

According to Fig. 10, use of sleeving, load level and slope inclination are three major factors affecting the load transfer from the pile to the ground. At a small load level at which the soil around the pile is primarily elastic, the use of sleeving is a dominant factor for load transfer. At a very large load, a widespread plastic zone develops around the pile (Fig. 5) and the plastic flow of soil becomes a dominant factor. An increase in slope inclination only causes some further downward load transfer.

INFLUENCE OF SLEEVING THICKNESS

Lateral Displacement

Figure 11 shows the effects of sleeving thickness on the horizontal displacement factor α_S, plotted against the relative depth z/L of the pile for the level ground and the 3:4 sloping ground. For the piles subjected to the 6% V_u load in the level ground (Fig. 11(a)), the use of a 100 mm-thick sleeving leads to a significant increase in the displacement at the ground surface by approximately 50% over that of the unsleeved pile. However, a further increase of sleeving thickness to 250 mm causes only an additional 24% increase over that with the 100 mm-thick sleeving. At the 36% V_u load (Fig. 11(b)), the effects of the sleeving thickness become less significant. The displacement of the pile with 100 mm sleeving thickness is 35% larger than that of the unsleeved pile and the displacement of the pile with a 250 mm-thick sleeving is 21% larger than that of the pile with the 100 mm-thick sleeving, which are smaller than the differences at the load of 6% V_u. This is because the plastic zones around the three piles installed with sleeves of different thickness are similar at the large load. For the piles in the 3:4 slope, the sleeving effect is also significant at the small lateral load similar to that in the level ground, but is much reduced at

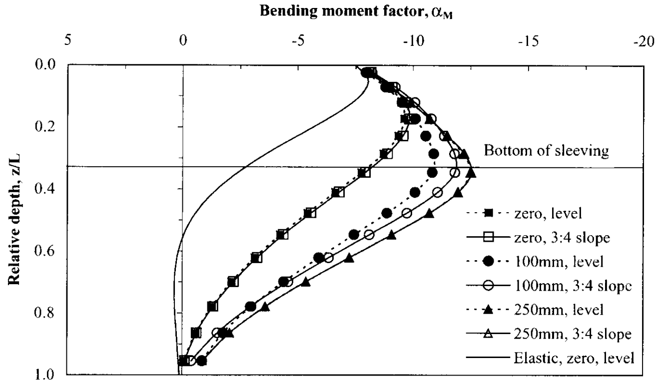

Fig. 12. Influence of sleeving thickness on the bending moment factor α_M at the lateral load 6% V_u

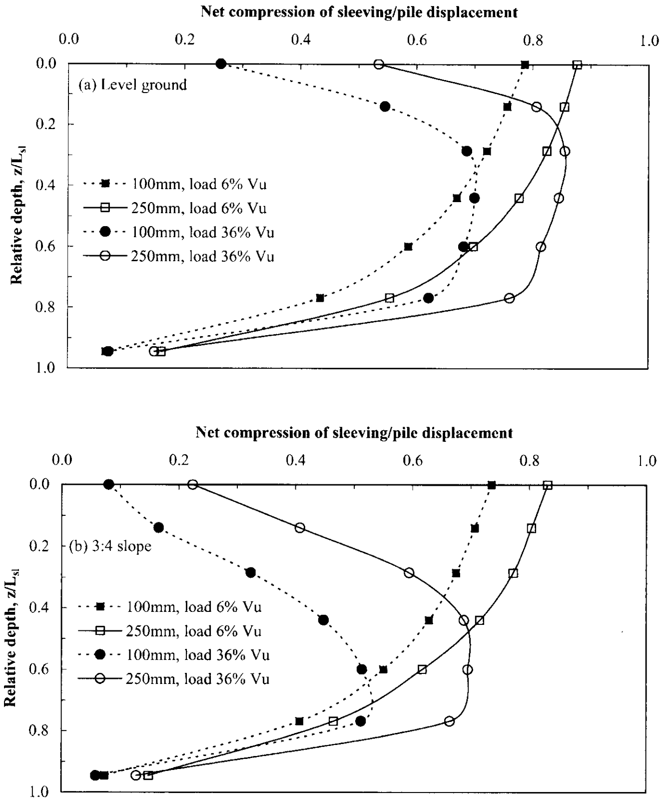

Fig. 13. Variation of the ratio of net compression to pile displacement with depth

the large load because of more widespread development of plastic zones in the sloping ground.

Bending Moment

Previous discussions have shown that sleeving thickness has a reduced effect on the horizontal displacements of piles in sloping grounds at the large load of 36% V_u. Hence, only the effects of sleeving thickness on the bending moment in the piles under the small load of 6% V_u are discussed here. Figure 12 shows the relationship between the bending moment factor α_M and the relative depth z/L for the piles with three different sleeving thicknesses. The sleeving thickness has considerable effects on the distributions of α_M. If a pile were sleeved, the maximum α_M value would increase and its location shift downward over those of the unsleeved pile. The changes in the maximum bending moment value and its location depend on the thickness of sleeving. For the pile with a 100 mm-thick sleeving in the level ground, the maximum α_M increases by approximately 13% over that of the unsleeved pile and its location shifts downward to about $z/L=0.34$ (from about $z/L=0.17$). This indicates that the load on the pile is transferred to deeper soils through a downward load transfer mechanism (Ng and Zhang, 2001a). For the pile with a 250 mm-thick sleeving, the maximum α_M further increases by approximately 15% over that with a 100 mm-thick sleeving. Similar sleeving effect is observed for the case of the 3:4 sloping ground.

Selection of Sleeving Thickness

At around the design load level, use of sleeving has been shown to be able to effectively decrease the horizontal movements of soil in front of the pile and improve the local stability of the sloping ground (Ng et al., 2001b). Yet, the previous sections have shown that these favorable functions are achieved in the expense of greatly increased horizontal displacements of the pile and increased bending moments in the pile. The conditions at very large loads (the ultimate state) may not govern the design of laterally loaded piles and the selection of sleeving thickness, because the influences of sleeving on the pile response (Figs. 3, 8, and 10–12) are relatively small at large loads. Instead, serviceability concerns often control the selection of sleeving thickness. It is also expected that the sleeving should remain readily compressible under the design load. Considering both pile response and compressibility of the sleeving material, a suitable criterion for selecting sleeving thickness would be to use a minimum thickness to accommodate a tolerable horizontal pile displacement. In other words, the net compression of the sleeving at a horizontal pile displacement equal to the tolerable displacement should not be greater than the permissible compression of the sleeving material,

$$RS_{\mathrm{tol}} \leq \varepsilon_{\mathrm{per}} t \tag{4}$$

where R is the ratio of net sleeving compression to horizontal pile displacement at the ground surface; S_{tol} is the tolerable horizontal pile displacement; t is sleeving thickness; and $\varepsilon_{\mathrm{per}}$ is the permissible strain of the sleeving material. The minimum sleeving thickness is therefore,

$$t=\frac{RS_{\mathrm{tol}}}{\varepsilon_{\mathrm{per}}} \tag{5}$$

The tolerable horizontal displacement of a structure depends on the type and size of the structure, properties of the structure and soils, and other factors (Wahls, 1981). For buildings in Hong Kong, an allowable horizontal displacement of 20–25 mm is usually considered (Chu et al., 2001).

The ratio of net compression to the pile displacement depends on several factors such as slope inclination, relative sleeving-ground stiffness, sleeving thickness, and load level. Figure 13 shows the variations of the R-ratio with the relative depth z/L_{sl} in the level ground and the 3:4 sloping ground. At the 6% V_u load, the R-values are approximately between 0.6 and 0.9 in the upper 60% of the sleeving for the 250 mm thick sleeving case, and between 0.6 and 0.8 for the 100 mm thick sleeving case. Hence, a R value of 0.8 should suffice if the sleeving thickness is smaller than 100 mm. The R-value tends to decrease as the slope becomes steeper and may vary with the pile diameter. However, the R-value is obviously limited to an upper bound of 1.0. Note that, at the 6% V_u load, the computed horizontal pile displacements at the ground surface are 18.7 and 19.4 mm respectively for sleeves of 100 and 250 mm thick in the 3:4 sloping ground, which are not greater than the tolerable displacement. In addition, the maximum compressive strains of the sleeving material are only approximately 13% and 7% for sleeves of 100 and 250 mm thick, respectively in the level ground; and 15% and 7% respectively in the 3:4 slope. These strain values are within the permissible strain range of the simulated material. At the very large load of 36% V_u, the R-values decrease considerably, especially at the top of the sleeving. Therefore, the sleeving thickness calculated using the ratio at the design load would be sufficient for larger loads.

The permissible strain of the sleeving, ε_{per}, depends on materials used. In Hong Kong, polystyrene has been a frequently used material. Siu (1992) reported results from confined odometer tests for investigating the behavior of polystyrene for pile sleeving purpose. At strains smaller than 50%, the polystyrene samples are highly compressible. Beyond 50%, however, the cell structure of the material is gradually destroyed and the material becomes less compressible. Therefore, the ε_{per} value of the material can be taken to be 50%. Assuming a R-value of 0.8 and a S_{tol} value of 25 mm, a minimum sleeving thickness of 40 mm can be calculated from Eq. (5). If the upper bound R-value of 1.0 were used, the calculated minimum sleeving thickness would be 50 mm. In practice, the GCO (1984) recommended a sleeving-thickness range from 25 mm to 100 mm.

CONCLUSIONS

The following conclusions can be drawn based on the present study:

(1) The effects of slope inclination in the range from level ground to 3:4 slope on the pile performance are generally minor at a small lateral load of 6% V_u. At a very large load, however, a pile in a steeper sloping ground will develop larger horizontal displacements and bending moments. This is because the shear strength of deeper soil layers has to be mobilized in a steeper sloping ground and the ultimate lateral resistance of the soil wedge in front of the pile decreases as the slope becomes steeper. Empirical relations for estimating the horizontal displacement and the maximum bending moment of a pile in a sloping ground are proposed. The horizontal displacement and the maximum bending moment appear to increase significantly when the slope is steeper than 1:2.

(2) At a small load level close to the design load, the soil around the pile is primarily elastic and the use of sleeving is a dominant factor for load transfer. As the sleeving thickness increases from 0 to 250 mm, the downward load transfer mechanism of sleeving causes considerably increased horizontal displacements of the pile and considerably increased bending moments in the pile. However, the effect of sleeving does not change significantly when the sleeving is thicker than 100 mm.

(3) A criterion for selecting suitable sleeving thickness is proposed considering both pile response and compressibility of the sleeving material, which suggests the use of a minimum sleeving thickness to accommodate a tolerable horizontal pile displacement. That is, the net compression of the sleeving at a horizontal pile displacement equal to the tolerable displacement should not be greater than the permissible compression of the sleeving material. For the CDG soil and polystyrene sleeving material studied in this paper, the recommended minimum sleeving thickness is from 40 mm to 50 mm.

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