Numerical Analysis of Sand Reinforced With Small Diameter Model Steel Piles

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ABSTRACT

The use of reinforcement steel bars and passive piles are the oldest method adopted in landslide prevention measure in which, their reinforcing mechanisms are designed to function independently. In practice, the combining effect of both lateral and vertical forces, especially in the case of an externally induced landslide may occur simultaneously. This research proposes new kind of piles, hereafter called small diameter steel piles (SDSP), which are able to resist both lateral and vertical forces in landslide countermeasure. The multirow arrangement of the installed SDSP was observed to accommodate higher loads and larger deflection in overall slope performance as opposed to the conventional passive piles and reinforcing bars. Failure mode in dense ground is apparently governed by soil's shearing resistance mobilized at a higher strain, while bending stiffness of the reinforcing material is more dominant in loose ground regardless of the piles arrangements. The reinforcing effect and failure mechanism in different ground densities of each arrangement were compared and examined through laboratory scale experiment (direct shear test) and 2D numerical model developed in PLAXIS 8.2 finite element analysis.

Keywords: Small diameter steel piles, direct shear test, finite element analysis, lateral soil movement, shear resistance, bending characteristics.

1 INTRODUCTION

Slopes stabilization using passive (preventive) piles, with minimum diameter of 300 mm (Taniguchi, 1967), is one of the oldest methods adopted in landslide prevention measures. Mechanism of such measure has been rigorously studied by various researchers (Ito and Matsui, 1975; Fukuoka, 1977; Poulos, 1995; Lee et al., 1995), from which the results have been integrated as design elements in actual practice. The amount of shearing resistance taken by the stabilizing piles in landslide prevention differs substantially based on pile toes condition, ground support by lower stratum and the anchorage length of pile embedment whereas, the rate of shear is significantly governed by soil properties and lateral movement mechanism. In recent years, a new type of pile called small diameter (90 mm-300 mm) steel pile otherwise known as micropile has been developed and is expected to function both as passive piles as well as reinforcing rods in slope stabilization technique (Hazarika et al. 2011; Watanabe et al. 2011).

2 MATERIALS AND METHODOLOGY

2.1 SDSP Model Piles

Two types of aluminum bars (square bar 10 mm x 10 mm and circular bar 3 mm in diameter) with equal length of 260 mm were utilized as the model steel piles to simulate the effect of different pile size i.e. large diameter piles and micropiles as countermeasures for slope instability. The testing schedule for reinforcements requires that the SDSP piles were arranged not only in single row but also taking into consideration the effect of multiple rows orientation in both loose and dense ground conditions.

2.2 Direct Shear Apparatus

Pile response due to loading condition is determined by the stress-strain relationship under shear deformation. It was expected that the reinforcing effects of small diameter steel piles could be verified by measuring the earth pressure and strain of either wall surface or piles thus, it is possible to equate the effect of shearing due to landslide with the mechanism of direct shear test appaparatus. The shear box apparatus with dimensions of 400 mm (length), 200 mm (width) and 300 mm (height) was employed for the simulation purposes. A standardize Toyoura sand (K7) was used as the soil model, compacted to relative densities of Dr_1=30% and Dr_2=80% in order to simulate different ground conditions. In all cases, pile toes were embedded into an aluminum fixing device located at the bottom part of the shear box to ensure identical simulation with pile toe end bearing condition. Silicon grease was also applied to the inner side of the shear box's wall and reinforcing rods' surface to prevent friction. The shear box was sheared at a constant strain rate of 1 mm/min under uniformly distributed overburden vertical pressure of 25 kPa.

2.3 FEA in PLAXIS 8.2 (2D) and Analytical apporach

Mohr-Coulomb's elastic-perfectly plastic soil model was employed in the study in which the mesh generation of the model was synchronized with experiment as shown in Figure 1. Likewise, the soil and material properties (model piles and wall) adopted in the model are shown in Table 1, Table 2 and Table 3 respectively. In addition, mathematical approach based on the uncoupled analysis of laterally loaded passive piles (Ito & Matsui, 1975 and Jeong et al., 2003) is adopted for results comparison. Pressure q, acting on the pile is evaluated based on Eqn. 1 while, pile deflection w, above and below the displacement interface are calculated based on Eqn. 2 and Eqn. 3 respectively.

Table 1: Soil properties in FEM analysis input

Parameter	Name	Sand	Unit
Material model	Model	Mohr-Coulumb	–
Material behavior	Type	Drained	–
Soil behavior above phreatic level	γ_{dry}	16 – 17	kN/m^3
Horizontal permeability	Kx	1.0	m/day
Vertical permeability	Ky	1.0	m/day
Young's modulus	E	30000 – 80000	kPa
Poisson's ratio	ν	0.3	–
Cohesion	C	1.4	kPa
Friction angle	ϕ	30 – 34	°
Dilatancy angle	ψ	0.4	°
Interface strength ratio	R	0.6 – 1.0	–
Global coarseness	Coarseness	loose – dense	–

$$q = A_C \left[\frac{1}{N_\phi \tan\phi} \left\{ \exp\left(\frac{D_1 - D_2}{D_2} N_\phi \tan\phi \tan\left(\frac{\pi}{8} + \frac{\phi}{4}\right) \right) - 2N_\phi^{1/2} \tan\phi - 1 \right\} + \frac{2\tan\phi + 2N_\phi^{1/2} + N_\phi^{-(1/2)}}{N_\phi^{1/2} \tan\phi + N_\phi - 1} \right]$$
$$- c\left(D_1 \frac{2\tan\phi + 2N_\phi^{1/2} + N_\phi^{-(1/2)}}{N_\phi^{1/2} \tan\phi + N_\phi - 1} - 2D_2 N_\phi^{-(1/2)} \right) + \frac{\gamma \bar{z}}{N_\phi} \left\{ A \exp\left(\frac{D_1 - D_2}{D_2} N_\phi \tan\phi \tan\left(\frac{\pi}{8} + \frac{\phi}{4}\right) \right) - D_2 \right\} \quad (1)$$

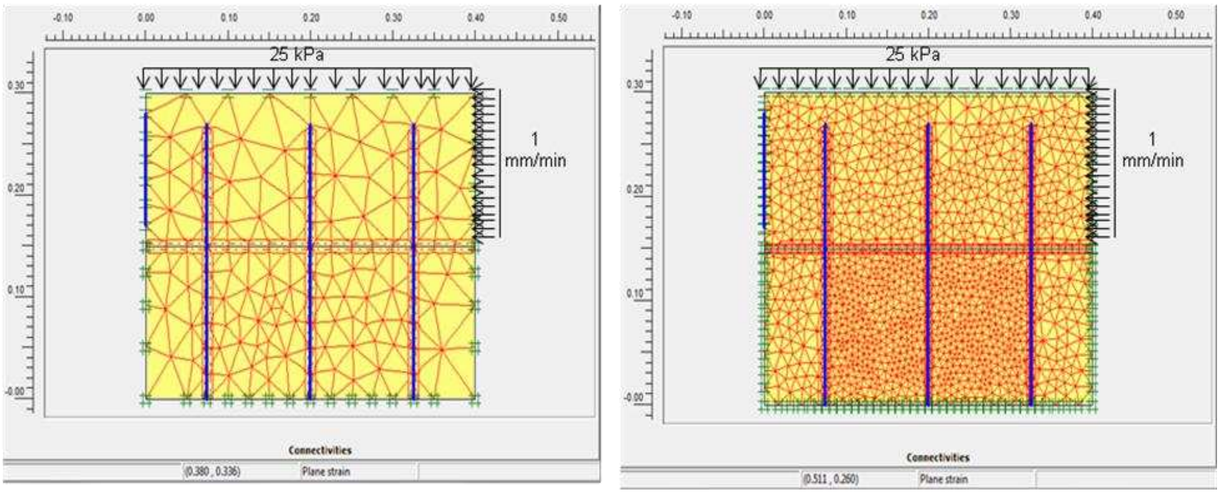
$$EI\left(\frac{d^4 w}{dz^4}\right)_i = p = K_i\left[(y_s)_i - w_i \right] = K_i \delta_i \quad (2) \qquad EI\left(\frac{d^4 w}{dz^4}\right)_i + K_i w_i = 0 \quad (3)$$

Table 2: Model pile properties in FEM analysis input

Parameter	Name	Pile	Unit
Material model	Model	Plate	–
Material behavior	Type	Elastic	–
Normal stiffness	EA	1.85 x 10^9	kN/m
Flexural rigidity	EI	1.4 x 10^5	kNm^2/m
Equivalent thickness	d	0.03	m
Weight	w	0.35	kN/m/m
Poisson's ratio	v	0.15	–

Table 3: Model wall properties in FEM analysis input

Parameter	Name	Wall	Unit
Material model	Model	Plate	–
Material behavior	Type	Elastic	–
Normal stiffness	EA	1.96×10^9	kN/m
Flexural rigidity	EI	1.25×10^5	kNm^2/m
Equivalent thickness	d	0.03	m
Weight	w	0.25	kN/m/m
Poisson's ratio	**v**	0.15	–



(a) Mesh generation for Dr = 30% soil model (b) Mesh generation for Dr = 80% soil model

Figure 1. Sample of mesh generations for the FEM analysis

3 RESULTS AND DISCUSSION

3.1 Shear Stress-Strain Relationship

Shear deformation of the multiple rows arrangements of SDSP in different ground conditions (Dr_1=30% and Dr_2=80%) with consideration of different cross sectional shape of piles (i.e. square and circular piles) are depicted in Figure 2. The initial rate of increase in shear stresses for both circular and square piles is shown to be constant up to 3-5 mm strain. This is because in a loosely compacted ground, the applied shear stress is surmised to be exerted directly to the loose soil particles that contract upon shearing. As a result of soil contraction and gradual changes in soil volume, direct load transfer to the piles was limited. However, as the shear displacement increases and maximum soil volumetric strain is achieved, the shearing effect is clearly observed at higher strain (i.e. 5 mm onwards). Based on the results in loose ground condition, Case 3 was observed to exhibit the highest shearing stress value at 45 kPa while in dense ground; Case 2 dominates the others at 75 kPa critical shear stress regardless of piles cross section. It was predicted that Case 4 should provide the highest resistance because the piles are most densely arranged in which, soil's strength is assumed to be directly proportional to the number of piles arranged in the soil. The effect of reinforcing material's cross sectional area, which in turn affecting bending stiffness is observed to play a significant role in pile's overall strength as it implicitly altering the reinforced ground condition (Hayashi et al., 1992). In comparison, larger stress values generated at the same corresponding strain indicates that square piles, which possessed a comparatively bigger cross sectional area than the circular piles, are capable of resisting larger deflection regardless of their arrangements.

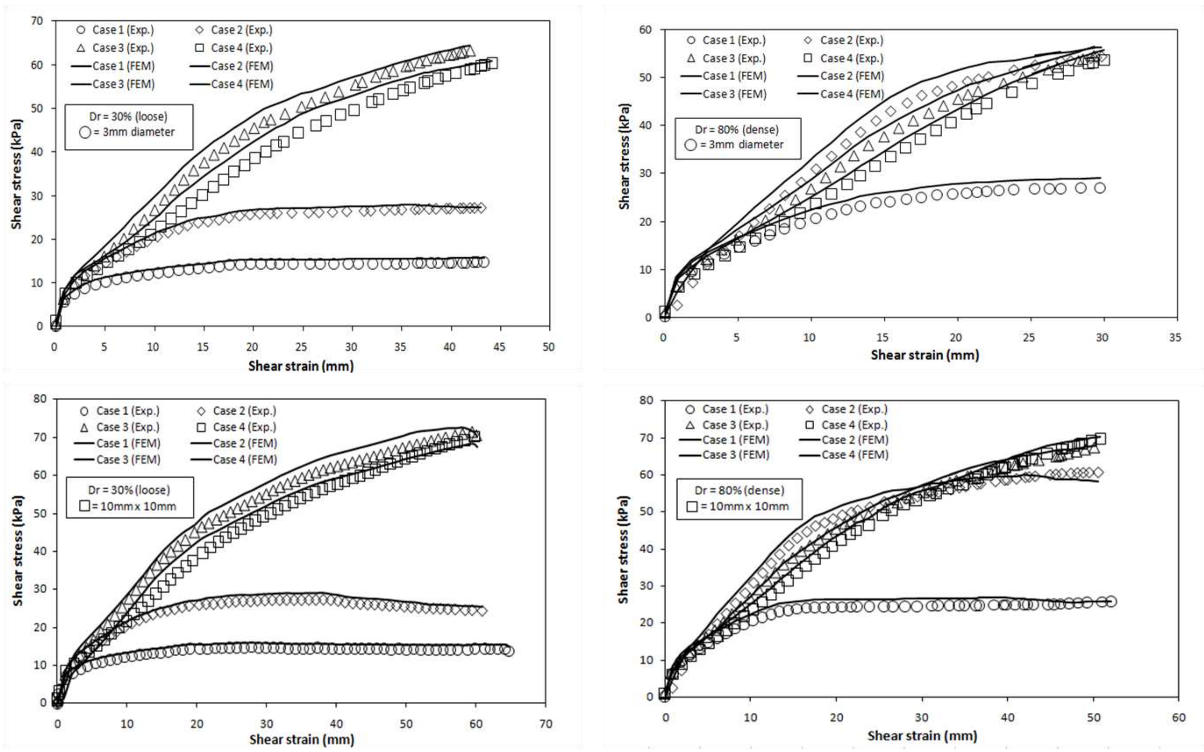


Figure 2. Shear stress-strain relationship for all the cases studied.

3.2 Pile Deflection and Vertical Soil Depth Relationship

Figure 3 portrays the deflection behaviors of SDSP under lateral loading. From the figure, it was observed that the deflection of both circular and square piles in loose ground was observed to be dependent on the EI of the reinforcing material. No apparent correlation between pile shape and ground condition was found in dense ground since all piles were displaced in the range of 0.2mm–3mm due to the confining effect of the densely compacted soil. It was also observed that the changes in ground densities had significantly influenced soil's dilatancy, in this case, Toyoura Sand.

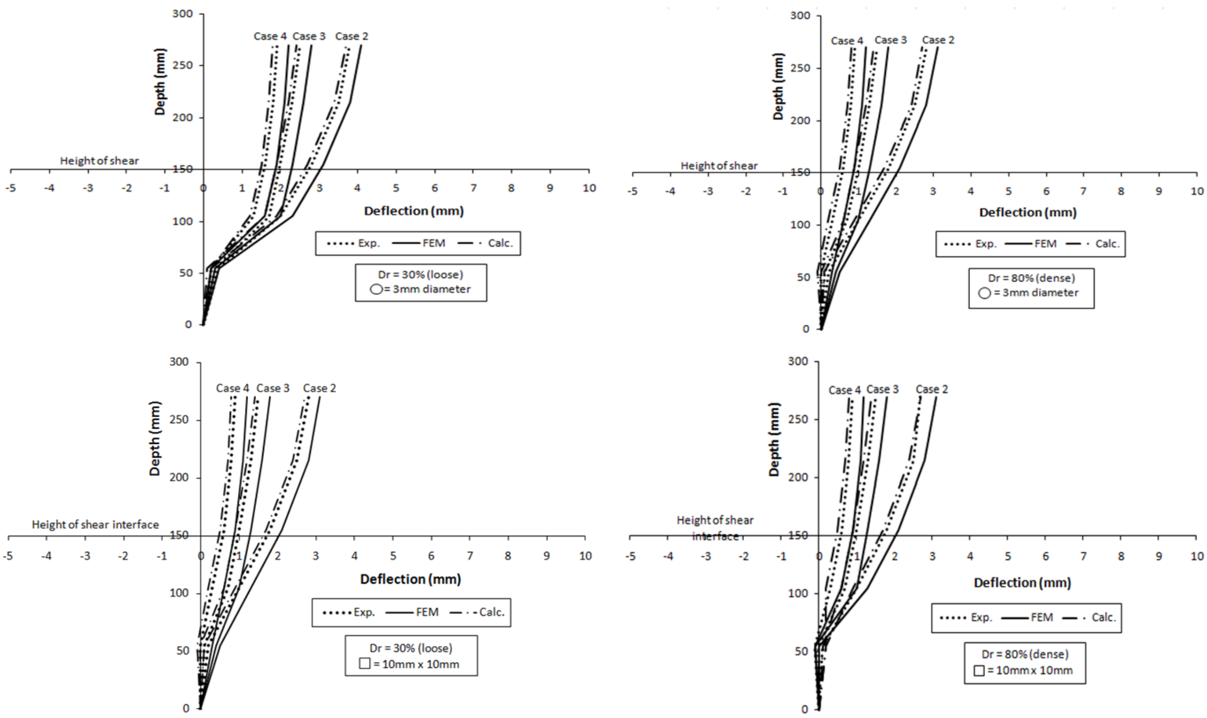


Figure 3. Variation of pile deflections with soil depth.

3.3 Bending Moment and Vertical Soil Depth Relationship

Bending moments that appeared in the vicinity of the pile toes at the lower part of the shear interface as shown in Figure 4 are expected because no rotation in both X and Y planes is allowed (fixed boundary condition). The occurrence of the large bending moments generated at pile toes can be minimized by considering appropriate piles spacing and designated embedded length into the potential slip surface. Though FEA results were overestimated particularly in circular piles because of the assumed 2D plane strain simplification in PLAXIS 8.2 (2D) FEM analysis, SDSP arrangement that combines both the linear (installed vertically on slope surface) and planar (installed normal to the slope surface) countermeasures provide better resistance for both axial and lateral forces that may affect slope instability during landslide due to the effect of the arranged multirow arrangements of the piles.

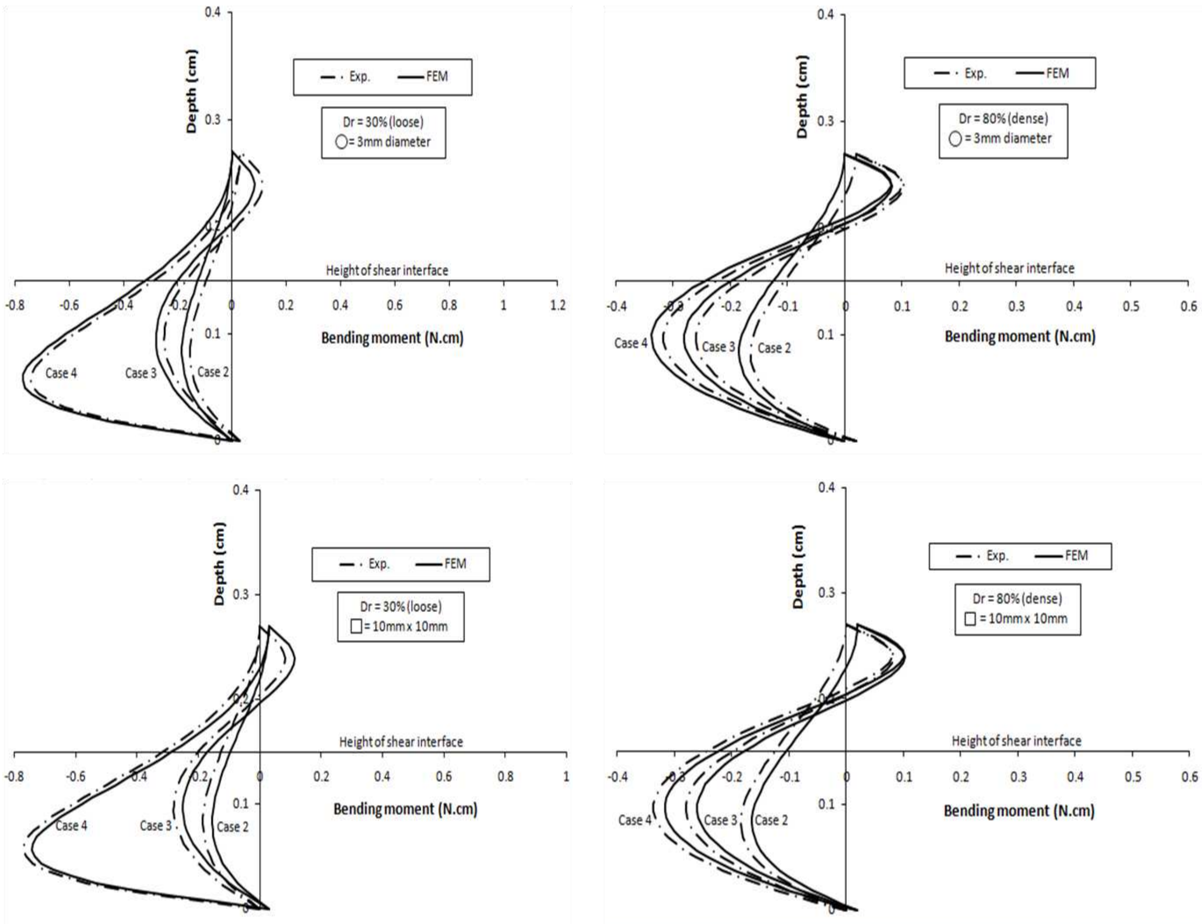


Figure 4. Variation of bending moments with soil depth.

4 CONCLUSIONS

In this research, the deformation characteristics in terms of the shearing stresses (both lateral and axial directions) of the small diameter model steel piles (SDSP) was studied in which the effectiveness of the reinforcing effect of SDSP is validated by their long term ability in resisting larger deflection through the experimental, theoretical and analytical analysis. From the findings, the following conclusions could be made:

1) Resistance to both lateral and axial forces is significantly enhanced with multirows arrangement of small diameter steel piles in landslide prevention.
2) In loose ground, the reinforcing effect is generated mainly through the bending stiffness (EI) of the reinforcing materials while in a densely compacted ground, shearing resistance is mobilized at a considerably higher strain, denoting the increased of the reinforced soil's strength.

3) Failure mode in dense ground is governed by the shearing resistance of the reinforced soil while material's EI becomes a dominant factor in loose ground condition regardless of the piles arrangement.
4) Regardless of pile sizes (○3mm or □10mm) material's bending stiffness plays a significant role in ensuring the overall reinforcing capacity of the piles. In case when more than 2 rows of piles are arranged, the coupled effect of reinforcement and countermeasure should be carried out simultaneously.

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REFERENCES

Fukuoka, M. (1977). "The effects of horizontal loads on piles due to landslides." *Proceedings of the Specialty Session 10, the 9th International Conference on Soil Mechanics and Foundation Engineering*, Tokyo. The Japanese Society of Soil Mechanics and Foundation Engineering, 27–42.

Hayashi, S., Ochiai, H., Otani, J., Umezaki, T., Jiang, Z. and Shackel, B. (1992). "Function and Evaluation of Steel Bars in Earth Reinforcement." *Earth Reinforcement Practice*, Ochiai, Hayashi & Otani, eds.: Balkema, Rotterdam. ISBN 90 5410 093 1, 481–486.

Hazarika, H., Mujah, D., Watanabe, N., Ahmad, F., Yasafuku, N. and Omine, K. (2011). "Fundamental Study on Earth Reinforcing Effect using Small Diameter Model Steel Pile." *Proceedings of the 13th International Summer Symposium, Japan Society of Civil Engineers (JSCE)*, Kyoto, Japan, 207-210.

Ito, T. and Matsui, T. (1975). "Methods to Estimate Lateral Force Acting on Stabilizing Piles." *Soils and Foundations*, 15 (4) 43–59.

Jeong, S., Kim, B., Won, J. and Lee, J. (2003). "Uncoupled Analysis of Stabilizing Piles in Weathered Slopes." *Computers and Geotechnics*. (30) 671–682.

Lee, C. Y., Hull T. S. and Poulous, H. G. (1995). "Simplified Pile Slope Stability Analysis." *Computers and Geotechnics*. (17) 1–16.

Poulos, H. G. (1995). "Design of Reinforcing Piles to Increase Slope Stability." *Canadian Geotechnical Journal*. (32) 808–818.

Taniguchi, T. (1967). "Landslides in Reservoir." *3rd Proceedings of Asian Regional Conference on Soil Mechanics and Foundations Engineering*, Bangkok, Thailand. (1) 258–261.

Watanabe, N., Hazarika, H., Okuno, M., Inoue, T., and Kato, T. (2011). "Bearing Capacity Characteristics of Grouted Screw Piles." *13th International Conference of the International Association of Computer Methods and Advances in Geomechanics*, Melbourne, Australia. (2) 916–922.