# Mechanical Behavior of Tapered Piles in Sand

Suman Manandhar, Noriyuki Yasufuku, Kiyoshi Omine, and Taizo Kobayashi
Department of Civil and Structural Engineering, Kyushu University, Fukuoka, Japan

## 1 INTRODUCTION

Yasufuku and Ohiai (2006) revised the model of soil-pile interaction mechanism based on direct shear mode at critical state friction angle to check the skin friction of non-displacement of piles. In this paper, direct shear failure mode of fully mobilized skin friction of straight pile at the critical state friction angle has been utilized to see the effects on tapered piles. Manandhar et al. (2009) explained that the mechanism of tapered piles has good pressing effects towards the depth of penetration. The main theme of this paper is to observe the mechanical behavior of piles based on the simple mathematical techniques. In order to fulfill the target, silica sand (Toyoura sand) was used to make the model ground by pouring at high relative density of 80 % through multiple sieving. Then three different piles, one straight (S) and two tapered (T1 and T2) with degree of tapering 2.5 % and 5.0 %, were installed to sculpt the cast-in-place condition, furnishing 50 kPa overburden pressure. The chromium plated steel model piles with equal lengths of 500 mm and same tip diameters of 25 mm were used for pile penetration.

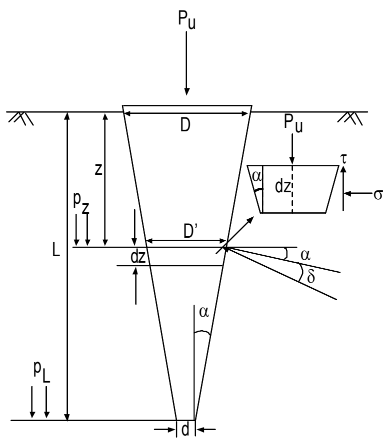


**Fig. 1**. Geometry of pile penetration

## 2 SHEAR FAILURE MODE ASSUMPTION

In general, the shaft resistance used for the evaluation of skin friction at requires depth can be expressed as:

$$f_s = \int_0^L K_\delta \, p_z \sin(\alpha + \delta) \sec\alpha \, C_z \, dz \tag{1}$$

Where, $f_s$ is belonged to skin friction of the pile at the require depth, $p_z$, effective overburden pressure, L, depth from ground surface to pile point, z, depth below ground surface, $K_\delta$, a dimensionless factor defined as the ratio of the resultant of the effective normal and shear stresses at the incipient failure plane passing through a point and the effective overburden pressure at that point, α, the tapering angle of the pile, δ, the friction angle on the surface of sliding including the pile shaft, and $C_z$, the minimum perimeter encircling the pile (Fig. 1).

For simplicity, skin friction at the require depth can be estimated as the sum of pile to soil adhesion and friction factors by the following equation:

$$f_s = c'_\delta + \sigma'_h \tan\phi'_\delta \tag{2}$$

Where $c'_\delta$ and $\phi'_\delta$ are adhesion and friction parameters between pile and soil, and $\sigma'_h$ is the horizontal effective stress acting on the pile. In the case of practical design the settlement criterion for the drifting of the maximum $f_s$ is exceeded. Hence, it is practicable to use the strength parameters at the critical state corresponding to large displacements, such that:

$$c'_\delta = 0; \quad \phi'_\delta = \phi'_{cv} \tag{3}$$

Where, $\phi'_{cv}$ is a friction angle at the critical state independent on density, overburden pressure and values of minimum strength, applicable for design purpose.

The horizontal effective stress $\sigma'_h$ depends on overburden pressure $\sigma'_v$ such that:

$$\sigma'_h = K\sigma'_v \tag{4}$$

Where, K is the coefficient of horizontal effective stress which depends on horizontal effective stress.

The mechanical behavior of skin friction of tapered pile is based on direct shear mode similar to the cylindrical straight pile. Fig. 2 illustrates that $\sigma'_{vf}$ and $\sigma'_{hf}$ is the vertical and horizontal effective stresses respectively on direct shear mode when piles are fully mobilized. At the critical state in the simple shear test, the strain increment in the vertical direction is zero, so that the inclination angle of the maximum principal strain increment axis to the vertical direction is equal to π/4 with the internal friction angle $\phi'_{cv}$ and the relation becomes:

$$\sigma'_{hf} = \sigma'_{vf} \tag{5}$$

This is an averaged stress condition of the ground surrounding the pile, and then based on the definition of $\overline{K_{df}}$ $(= \sigma'_{hf}/\sigma'_{vf})$ as unity assuming $\sigma'_{vf} = \sigma'_v$. Proceeding, Fig. 2 can be expressed in terms of principal shear stress is a function of effective horizontal stress at critical state such that:

$$\tau_f = \sigma'_h \tan\phi'_{cv} \tag{6}$$

In tapered pile, $\tau_f$ is obtained by multiplying by $\cos\alpha$ as below:

$$\tau_{fm} = \tau_f \cos\alpha \tag{7}$$

Where $\tau_{fm}$ is the mobilized shear stress of pile. Regarding to the experimental model pile load tests, the function of $\tau_f$ is altered to $\tau_{fo}$ affecting the taper angle α and can be expressed by simple formula as:

$$\tau_{fo} = \frac{\tau_{fm}}{\cos\alpha} \tag{8}$$

In which $\tau_{fo}$ is obtained from the experiment during pile penetration named as obtainable shear stress. When this mechanism is transferred to the theoretical definition as function of shearing, Eq. (6) be changed into the form:

$$\tau_f = \sigma'_{hf} \tan \phi'_{cv} = \tau_{fo} \quad (9)$$

Therefore, $$\sigma_{hf} = \frac{\tau_{fo}}{\tan \phi'_{cv}} = \frac{\tau_{fm}}{\cos\alpha \quad \tan \phi'_{cv}} \quad (10)$$

Eq. (10) is utilized in this paper to see the effects of skin friction of tapered piles to understand the mechanism properly.

Based on Eq. (10), the normalized unit skin friction $f_s$ in the experiment can be equated to see the mechanism of piles as below:

$$\tau_{fm} = f_s \quad (11)$$

Hence, Eq. (11) can be equated as shown below:

$$\sigma_{hf} = \frac{f_s}{\cos\alpha \tan \phi'_{cv}} \quad (12)$$

## 3 RESULTS AND DISCUSSIONS

The average diameters of tapered piles were taken for normalized unit skin friction ($f_s$) and checked the effects accordingly. Fig. 3 depicts horizontal shear stresses of straight (S) and tapered piles with different angle of tapering. To satisfy Eq. (5), the horizontal shearing component during pile penetration increases with the penetration depth. After the yield point, with satisfying critical state of angle of friction, property of skin friction has fit linearly with the depth. The skin frictions of tapered piles have increased considerably showing the shearing effect with compared to straight pile. Afterwards, these obtained results are normalized by dividing constant overburden pressure of 50 kPa and plotted against degree of tapering at settlement ratios at 0.1, 0.5, 1.0, 2.0, and 4.0 respectively (Fig. 4). However, the effect of normalized skin friction is slightly increased in straight pile, tapered piles show linear and higher.

## 4 CONCLUSIONS

The mechanical behavior of tapered piles shows horizontal stresses increase after yield point with increasing normalized settlement ratio. The effects of skin frictions governed by tapered piles are increased considerably as shown by the normalized horizontal stresses of tapered piles. These results could be the phenomena to evaluate the skin friction of tapered piles.

## 5 ACKNOWLEDGMENTS

The authors are pleased to Mr M. Nakashima, Mr Y. Fujiwara and Mr Y. Ishikawa for help during experiment.

## REFERENCES

Manandhar, S. et al., (2009): Skin friction of taper-shaped piles in sands, *Proc. ASME 2009 28th OMAE 2009,* Honolulu, Hawaii, USA.

Yasufuku, N. and Ochiai, H., (2006): Skin friction of non-displacement piles related to simple shear mode with large strain state friction angle, *Soils and foundations,* **46** (4), 537-544.

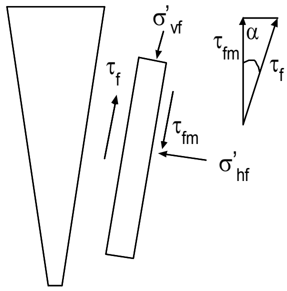


**Fig. 2.** Shear failure mode of tapered pile

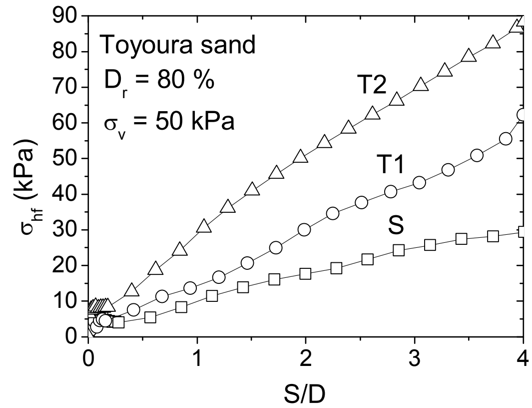


**Fig. 3.** Increment of horizontal stress along with S/D ratio

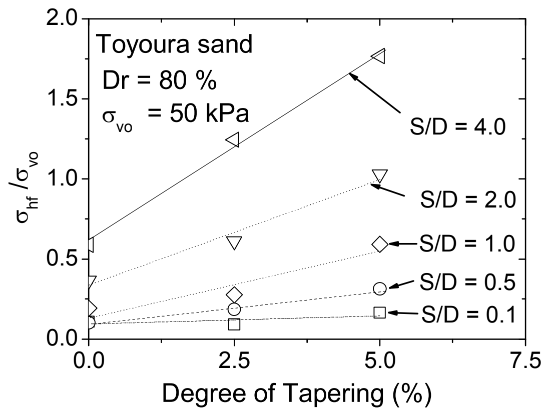


**Fig. 4.** Normalized horizontal stress against tapered angle