Bearing Capacity of Tapered and Step-tapered Piles Subjected to Axial Compressive Loading

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In this paper the bearing capacity of cylindrical, tapered and stepped piles under vertical static loads has been investigated using finite difference method based on the commercially available code, FLAC 3D (Fast Lagrangian Analysis of Continua). The pile is assumed to have linearly elastic. The main objective of the paper is to investigate whether a tapered pile can be idealized as some prismatic segments connected rigidly at nodes. The soil failure is assumed to obey Mohr-Coulomb criterion. The soil-pile interaction has been modeled using interface elements. Such elements allow the pile to slip from the soil when necessary. A cylindrical pile of the same volume and length has also been analyzed. This facilitates to compare load-carrying capacity of prismatic, uniformly tapered, and step-tapered piles of the same volume and length. To ensure the accuracy of the constructed numerical model of piles, the results obtained from numerical analysis have been compared with those obtained from experimental and theoretical approaches. This comparison indicates a very good agreement. It will be shown that a uniformly tapered pile cane be confidently idealized as a number of prismatic segments which are connected to each other. This is an interesting finding and enables users to apply simple one dimensional numerical analysis for determination of pile capacity.

Keywords: Finite difference method, pile foundations, tapered pile, bearing capacity, Mohr-coulomb criterion.

1. INTRODUCTION:

The bearing capacity of non-straight piles is of significant concern to design engineers in recent years. This is because it has been shown that the bearing capacity of a tapered pile is greater than a prismatic pile of the same volume and length (Ghazavi et al., 1997a; Ghazavi, 2000; Ghazavi and Etaati, 2001; Wei and El Naggar, 1998). Also it has been revealed that, in comparison with cylindrical piles of the same volume and length, such piles behave better in earthquake prone areas (Ghazavi, 2006), better in drivability (Ghazavi et al., 1996), and have better performance under axial harmonic vibrations (Ghazavi et al., 2003; Ghazavi et al., 1997b; Ghazavi and Ahmadi Bidgoli, 2002).

In most the above research work, for simplicity, a fully tapered pile has been idealized by a number of step prismatic segments connected rigidly to each other. The cross sectional areas of the segments decrease accordingly from the head to the toe along the pile shaft. Although this idealization was verified using numerical or experimental data, it is still necessary to evaluate it using sophisticated analyses. To this aim, in this paper, the behavior of three piles: cylindrical, fully tapered, and step tapered all with identical length, volume, mid-length radii are investigated using FLAC software.

2. ANALYSIS METHOD

As mentioned, three piles have been considered in this study. Two taper angles of 1 and 2^o are assumed for piles. The length of piles is 10 m with mid-length radius of 0.237 and 0.325 m. The pile is relatively compressible with slenderness ratio of L/r about 30~40. The details of piles are given in Table 1.

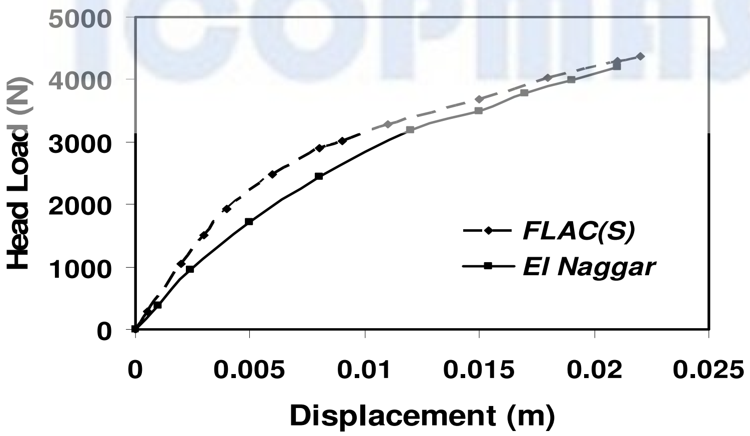
Table 1. Details of Piles

pile shape	*Taper Angle*	r_{top} , r_{bottom} *(m)*	*Test Series*
Fully Tapered	1 degree	0.325 , 0.15	FT1
	2degree	0.499 , 0.15	FT2
Step-Tapered	1 degree	0.325 , 0.15	ST1
	2degree	0.499 , 0.15	ST2
Cylindrical	0 degree	0.237	CYL1
		0.325	CYL2

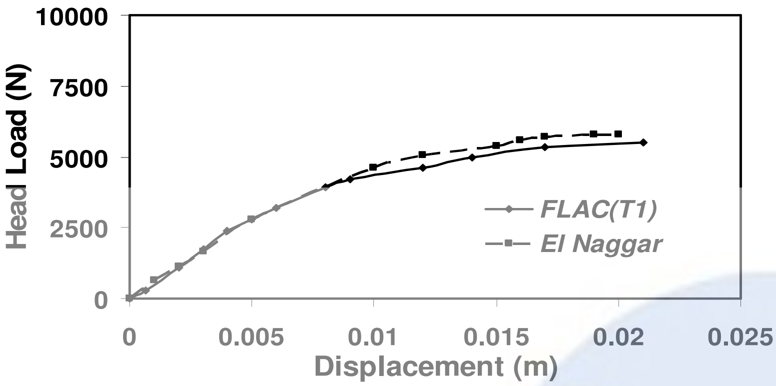
The stepped pile is divided into 5 segments, each of which has a constant radius. In the numerical modeling, to facilitate the slip between the pile and the soil interface element is used. The concrete pile material is assumed to be elastic. The soil failure is simulated according to the Mohr-Coulomb failure criterion with associated flow rule.

3. VERIFICATION

To ensure the accuracy of the numerical modeling, verification has been made using experimental data reported by Wei and El Naggar (1998). Fig. 1 shows this comparison. As seen in Fig 1, the numerical modeling has acceptable ability to predict the accurate results for load distribution in straight-sided and tapered pile.



a) cylindrical steel pile verification (S series in El-Naggar)



b) Tapered steel pile verification (T1 series in El-Naggar)

Fig 1. Comparison for load-displacement variation

4. PARAMETRIC STUDY

For this section, the soil and pile properties are shown in Table 2. The soil is saturated undrained clay the friction angle of ϕ=0. The pile is made of concrete with properties given in Table 2.

Table 2. Soil and concrete properties

	γ (kN/m^3)	K (MPa)	G (MPa)	c (kPa)	ν (Poisson)
soil (Clay)	15.5	83.33	38.46	30	0.30
Concrete	25	13.9E3	10.4E3	–	0.20

The details of interface element are shown in Table 3. Here, K_n and K_s represent normal and shear stiffness of interface element, respectively.

Table 3. Interface parameters

`K_n (MPa)	K_s (MPa)	φ_{int}	c (kPa)
100	100	20	30

To reduce the analysis time, only one square of system is modeled. The lateral boundaries of soil-pile grid are 20 $r_{mid\text{-}length}$ in x and y directions. The bottom boundary is about $2L_{pile}$.

5. ANALYSIS RESULTS

The results of numerical analysis are shown in Figs 3 and 4. Fig. 3a and b represents the variation of stress and load with settlement of pile head for three piles in test series of FT1, ST1 and CYL1, respectively. Fig. 4 shows the load-settlement variations pile the heads in test series of FT2, ST2 and CYL2.

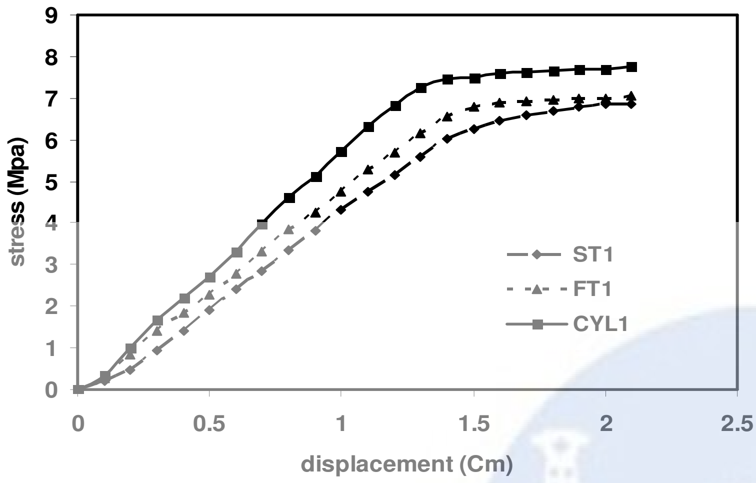


Fig. 3.a) stress-displacement curve at pile head (ST1, FT1 and CYL1)

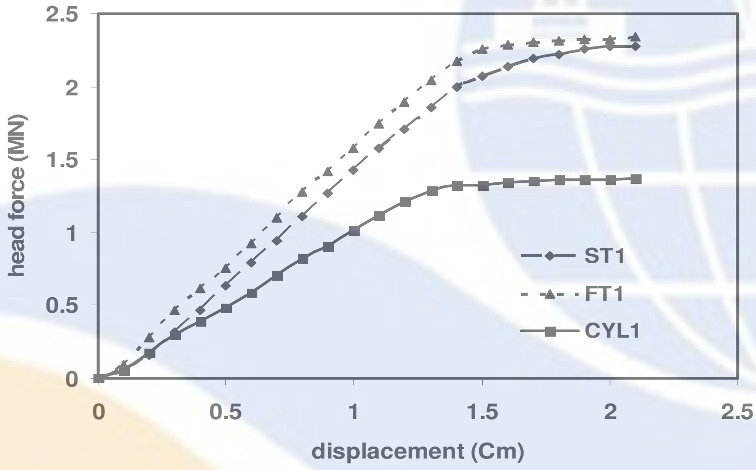


Fig. 3.b) Load-displacement curve at pile head (ST1, FT1 and CYL1)

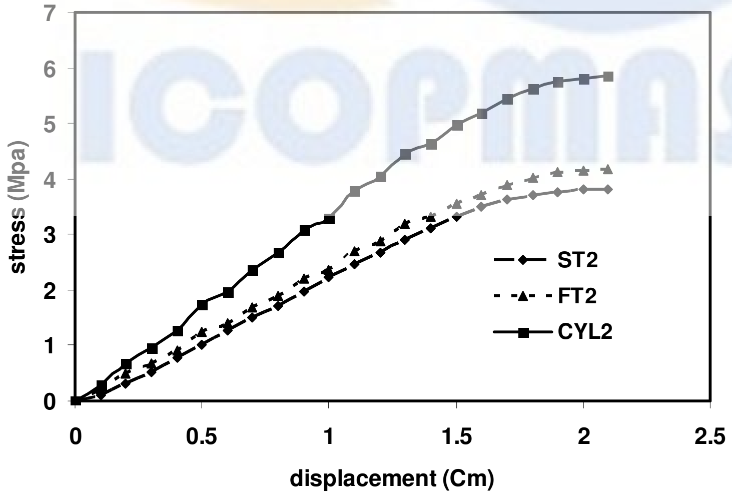


Fig. 4.a) stress-displacement curve at pile head (ST2, FT2 and CYL2)

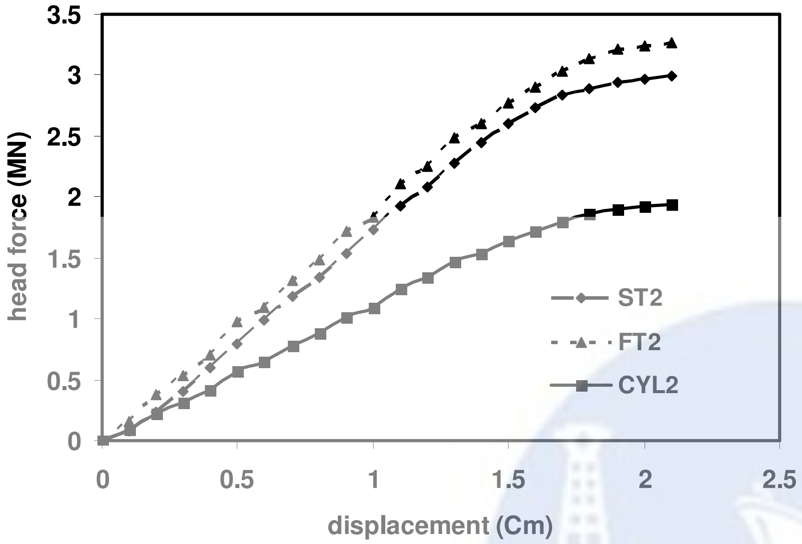


Fig. 4.b) Load-displacement curve at pile head (ST2, FT2 and CYL2)

As seen in Figs. 3 and 4, the use of tapered or stepped piles causes a decrease in normal stress at the pile head. Also the load carried by the pile heads increase. The bearing capacity of stepped piles is about 10% less than that of fully tapered piles.

6. CONCLUSIONS

A comparison has been made between three shapes of concrete piles with equal volume and length using finite difference analyses based on FLAC 3D. The main objective was to ensure if a fully tapered pile may be replaced with some step cylindrical segments. The results have showed that:

1. Greater stress is developed in cylindrical piles at a given equal pile head settlement, compared with a tapered pile.
2. The difference between the bearing capacity of stepped and fully tapered piles is less than 10%. This demonstrates that simplifying a tapered pie to some prismatic segments is justified. As a result, in bearing capacity collation, the simple idealization may be used confidently and conveniently.

7. REFERENCES

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