Extended Model of Cavity Expansion Theory for Evaluating Skin Friction of Tapered Piles in Sands

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The 7th Geo^3 T^2, NCDOT, Cary, USA

April 4-5, 2013

Outline of the Presentation

Phases

- Introduction
- Mobilized Mechanism
- Extended Model for Evaluating Skin Friction
- Results of the Model using Load Transfer Method
- Parametric Study and Validity of the Model
- Conclusions

Introduction

- Skin friction and radial stress are highly influenced by tapered piles with compared to conventional piles.

- A *small increase in the degree of tapering* can achieve *higher skin friction*.

- The mobilized mechanism demonstrates a good pressure effect when penetrated downward in a frictional mode for sands.

- The tapering and wedging effects are responsible for *increasing* the *normalised skin friction* and *normalized lateral stresses*.

- May be due to a lack of awareness of their basic existence together with a lack of modern and reliable analytical methods, very few researches have been carried out.
- A number of experts in geotech proposed theoretical methods using a cavity expansion theory.
- Vesic` (1972): Used to solve an infinite soil body by keeping volume change at the same soil at same density.

- Hughes et al. (1977): Assumed the small elastic deformation in the plastic zone when a limiting value of stress ratio reached after elastic deformation.

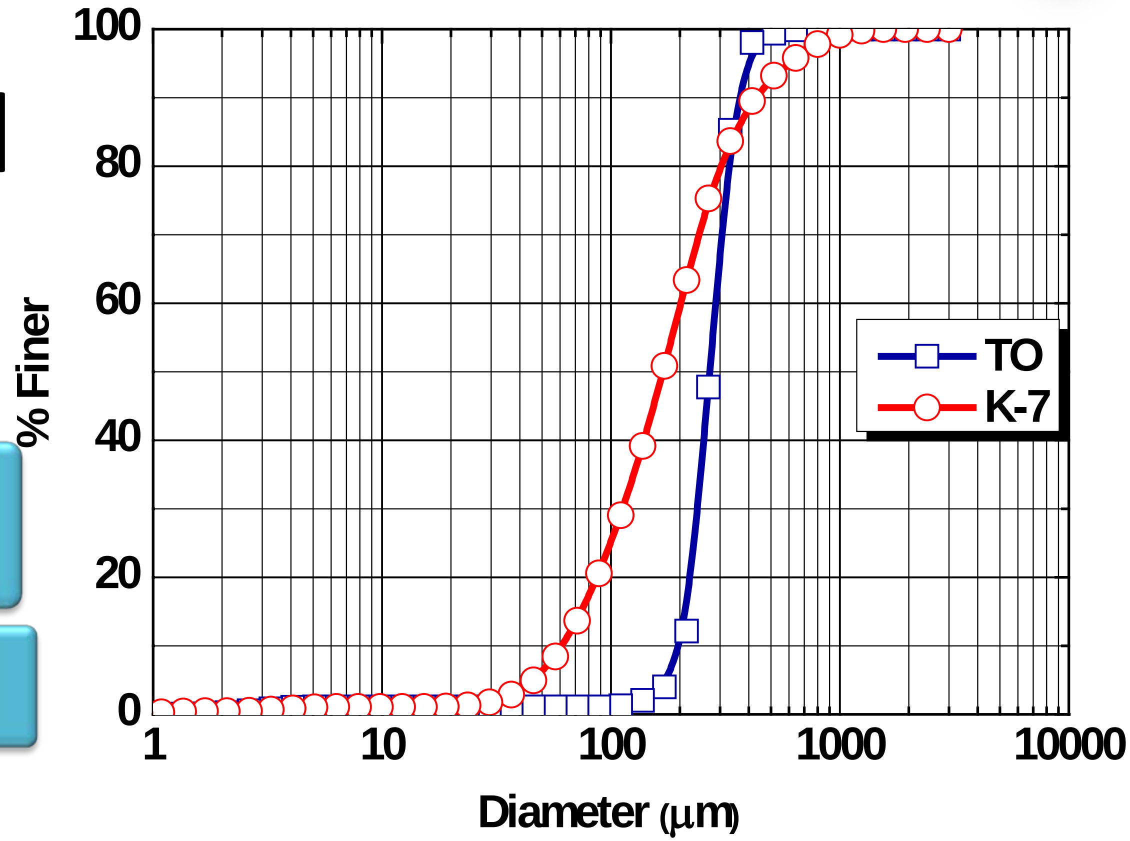
- Carter et al. (1986): Approximates a steady state deformation mode at *very large deformations* for small deformation problems.

- **Yu and Houlsby (1991):** The most closed form and complete solution for *large straining* condition for *cylindrical cavity expansion* in an ideal elastic-plastic model.

Mobilized Mechanism

Materials used

Soils → Toyoura (TO) sand; K-7 sand



Gradation curve of sands

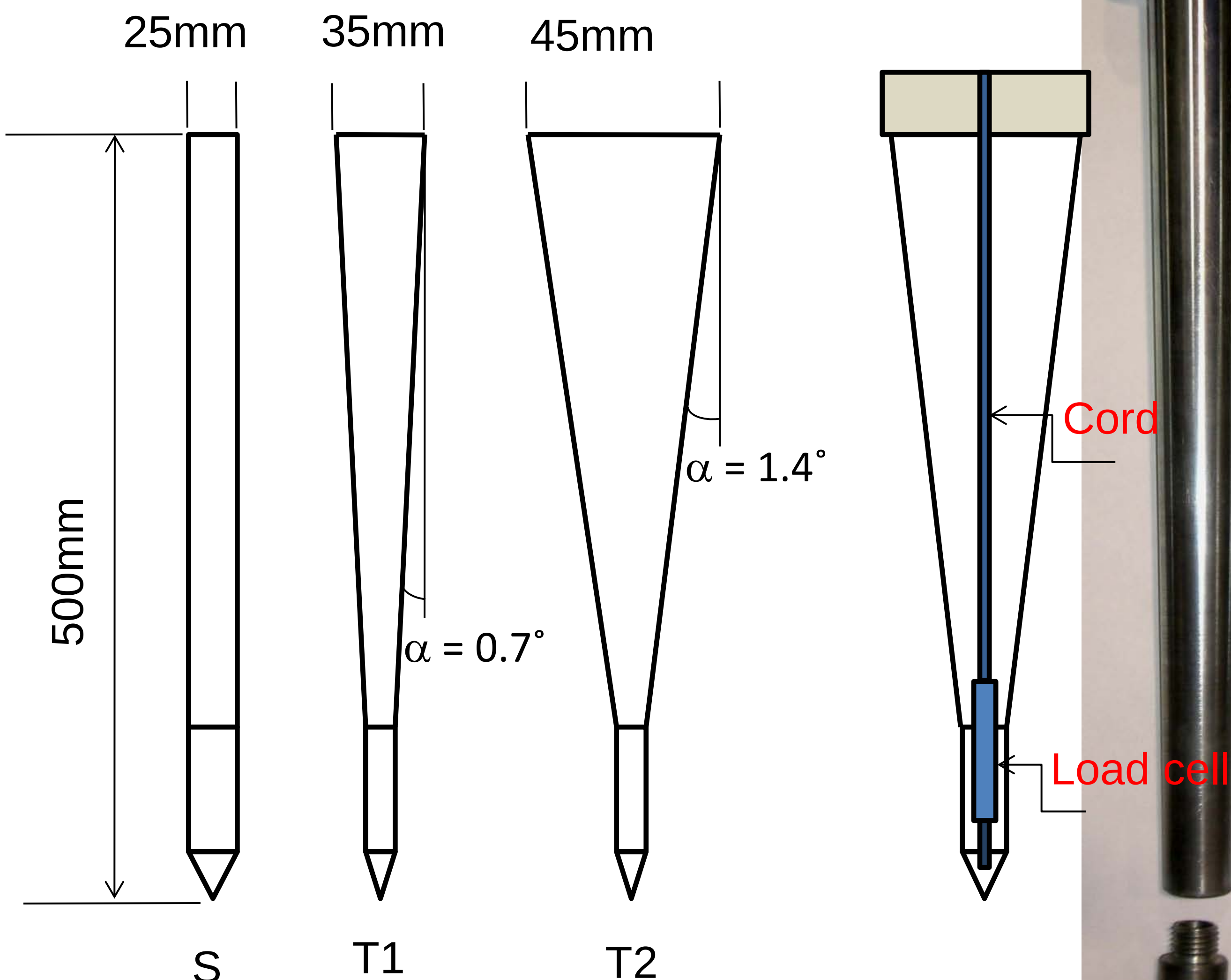
Relative Density (I_D) → TO(0.8); K-7 (0.6)

Pile geometry

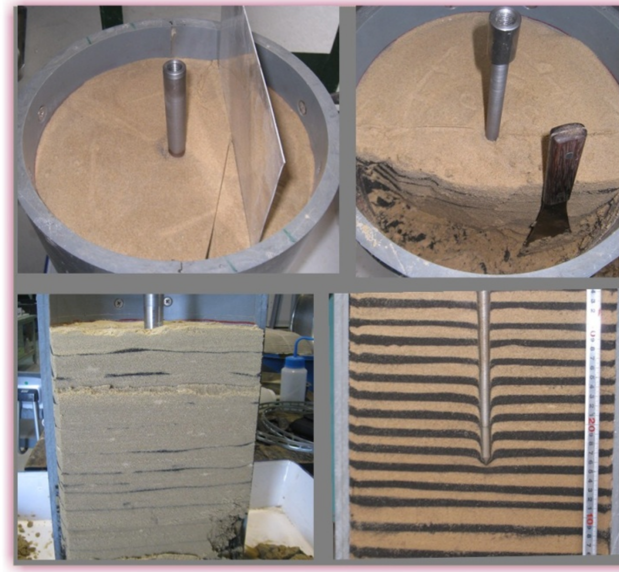
Types of Model Piles	Naming	L mm	D_t mm	d mm	α °	FRP reinforcement direction
Smallest model steel piles	S′	345	13	13	0.00	
	T_1'	45	20	13	0.70	
	T_2'	345	28	13	1.40	
Smaller model steel piles	S	500	25	25	0.00	na
	T-1	500	35	25	0.70	na
	T-2	500	45	25	1.40	na
Prototype FRP piles	FC	1524	168.3	168.3	0.00	na
	T-3	1524	170.0	198.0	0.53	0°
	T-4	1524	159.0	197.0	0.71	0°
	T-5	1524	155.0	215.0	1.13	0°

L: length of pile; D_t: diameter at the pile head; d: pile tip diameter; FRP: fiber-reinforced polymer; α: angle of tapering; na: not applicable

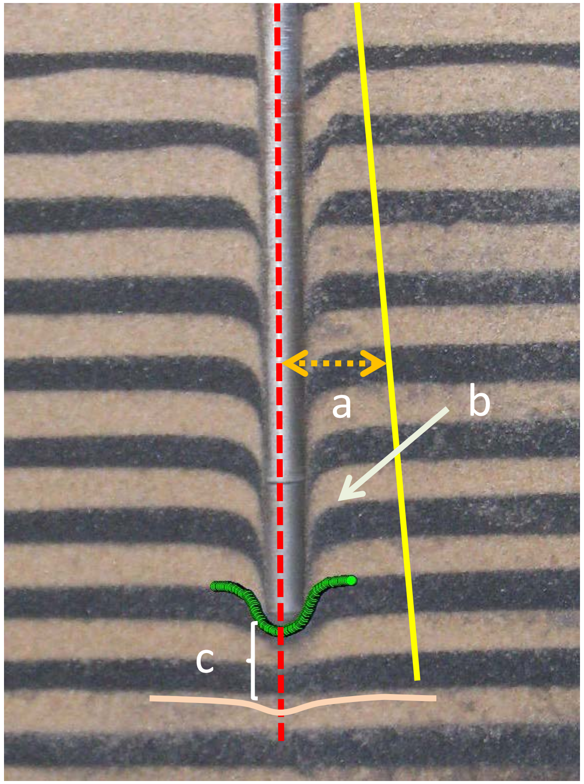
Steel Model Piles



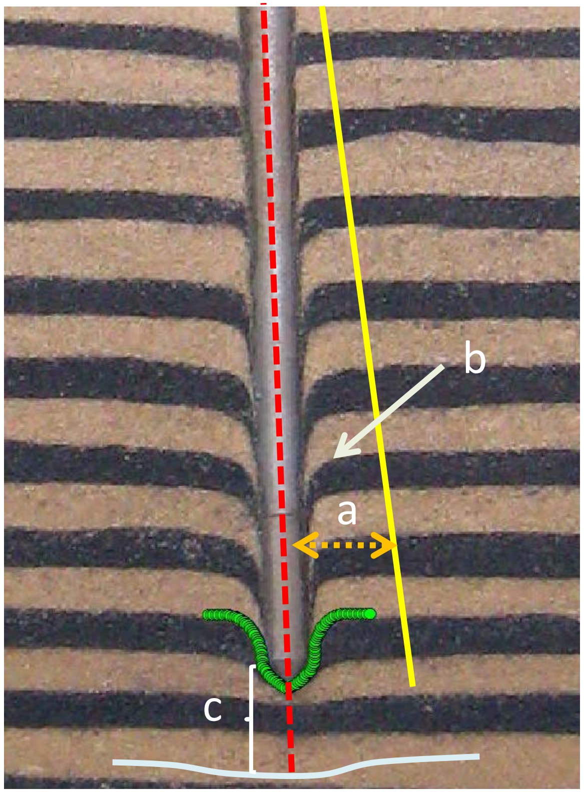
Outline of Pile Loading



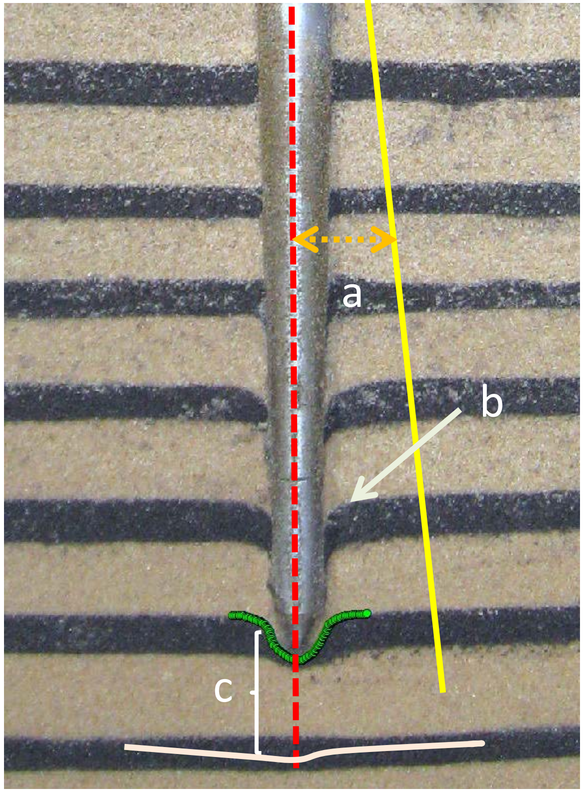
- Model test filled with colored TO (I_D=0.8) sand at *equal interval* and penetrated fully up to 10 cm; then put in water bath to prevent from failure of model ground when chamber was split up.
- Trimmed soil carefully to observe mobilized mechanism.



S′ (α =0 ˚)



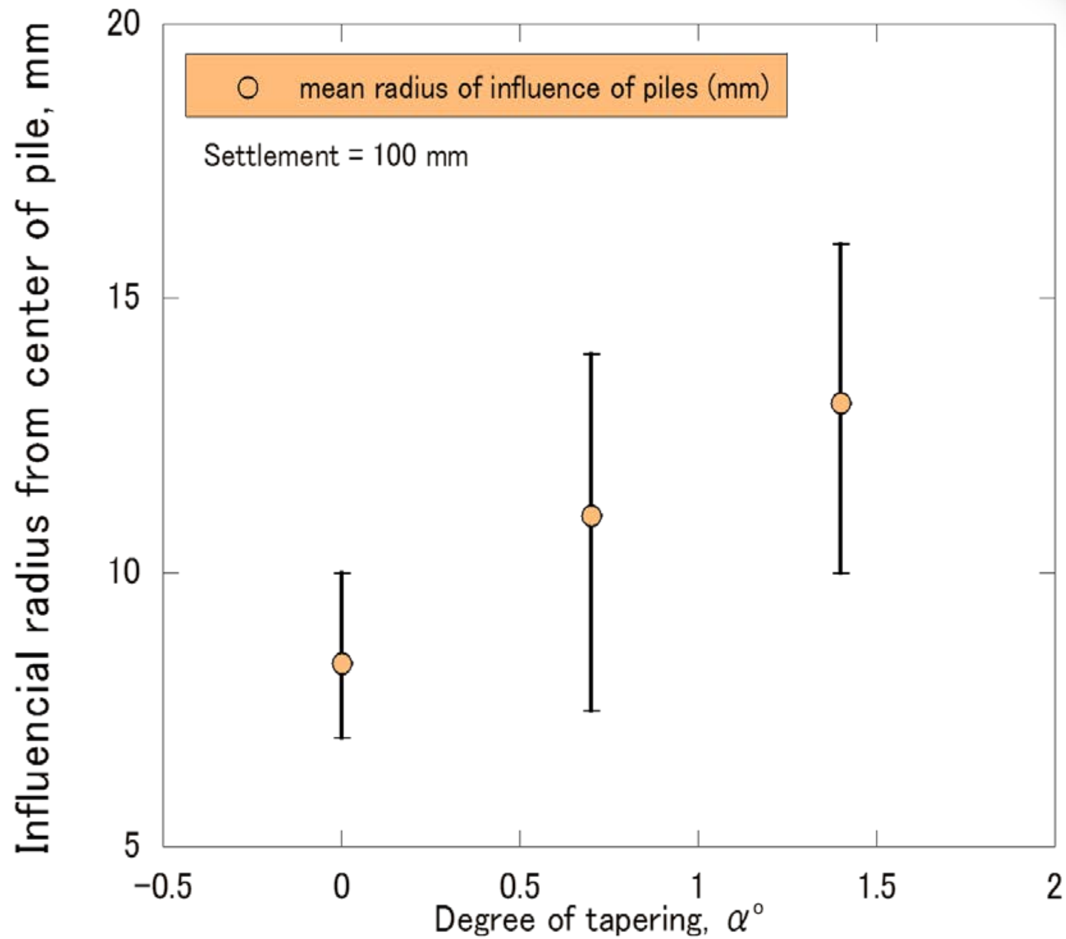
T_1′ (α =0.7 ˚)



T_2′ (α =1.4 ˚)

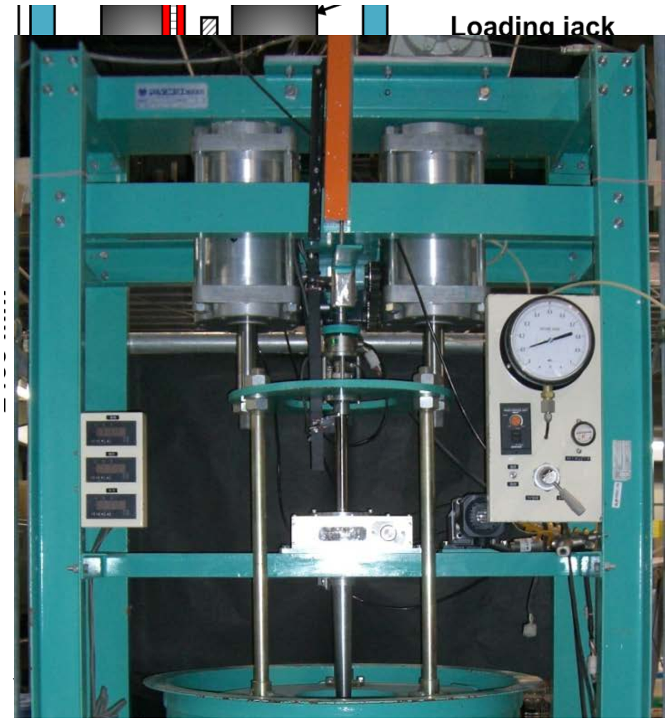
a = effective radius of influence, **increased** with tapering angle; b = **convex heave** due to effect of pile, **narrowed** with tapering angle; and c = failure tip influenced zone, **increased** with tapering angle

Visual Interpretation



The most tapered pile showed the highest radius of influence that gives a strong evidence of *increases* in *skin friction* and *lateral stress* with *minimizing* the *failure zone* effectively.

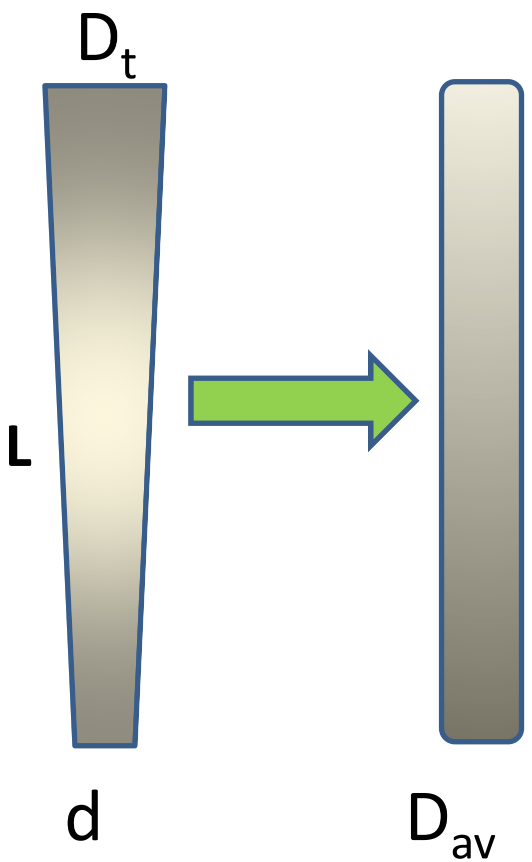
Merits of Laboratory scale Pile Loading Tests



Skin friction and unit skin friction

$$P_S = P_T - P_B$$

P_S : Total skin friction
P_T : Total load bearing
P_B : Total end bearing



Unit skin friction, $f_s = \dfrac{P_S}{A_s}$

$$D_{av} = \frac{(D+d)}{2}$$

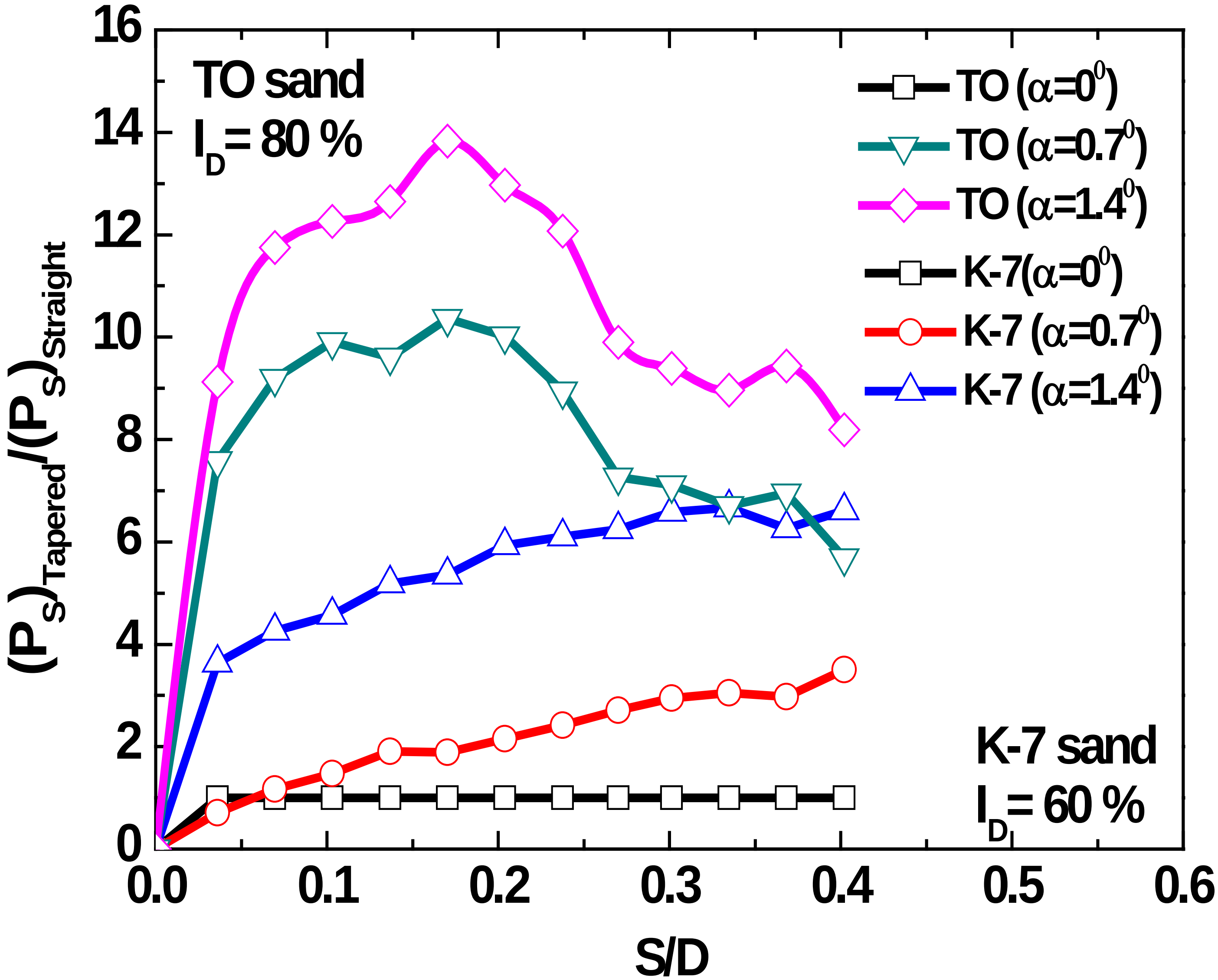
$$A_s = \pi D_{av}(L + \Delta L)$$

A_s : surface area

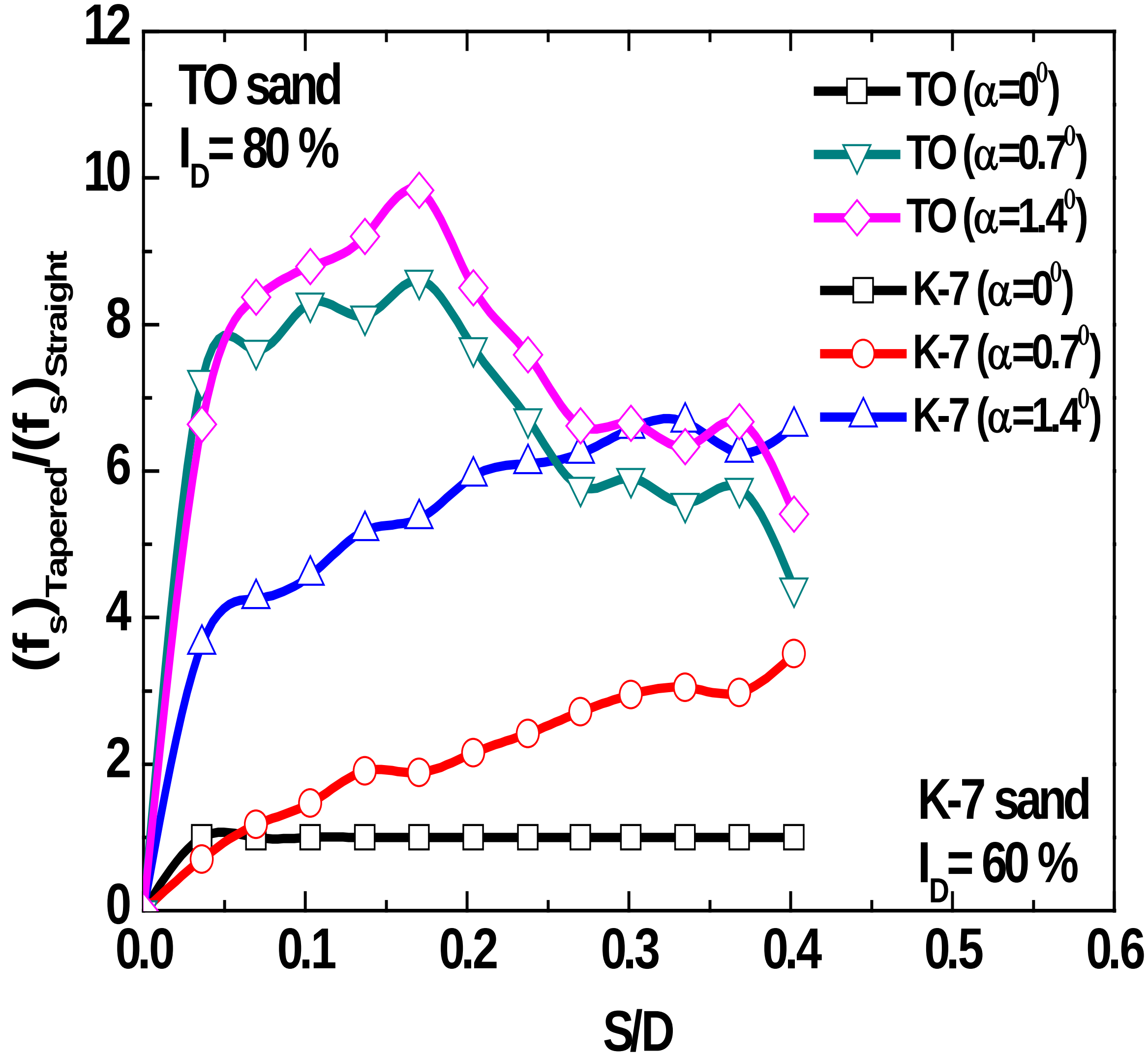
D_{av}: average diameter of pile head (D_t) and tip (d)

L: Effective length of pile

ΔL: Incremental depth of pile penetration



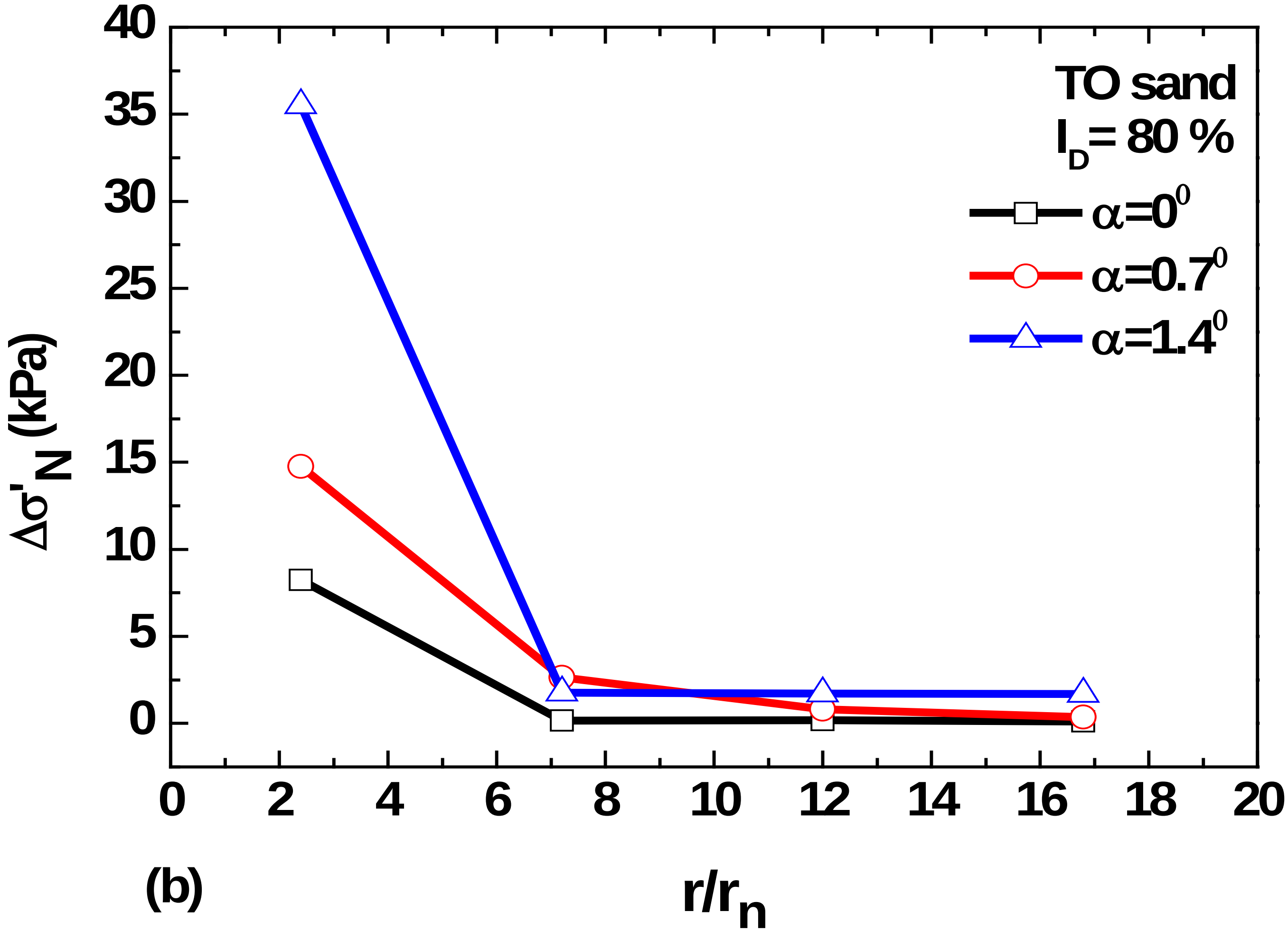
Skin friction increases with increasing tapering angle.



Unit skin friction also maintains the same trend.

Effects of lateral earth pressure

Radial distance from the center of the pile normalized by dividing distance of transducers to the pile tip radius (r/r_n)



Tapering effects are *higher* in the most tapered piles adjacent to pile-ground interface

Extended model for Evaluating Skin Friction

- The proposed model was extended after Kodikara and Moore (1993); the model was incorporated for determination of skin friction using *cylindrical cavity expansion theory* by Yu and Houlsby (1991).

- Generally, one of the soil parameters, either angle of internal friction or dilatancy angle is assumed to be constant.

- However, the stress-dilatancy relationship is interdependent on the confining pressure, relative density and angle of internal friction.

Concept of Determination of Skin Friction

After Kodikara & Moore (1993)

the vertical pile movement u_p *at any point X* on the pile-ground interface > the vertical ground movement u_g at the *corresponding point Y*. While the pile is displaced from point X to X′, the ground moves from point Y to Y′, obtaining the lateral movement **v**.

Pile ground slips but exhibits elastic deformation

$$\tau_x = \frac{K_e \tan\alpha \tan(\phi_i + \alpha) u_p + \sigma_0 \tan(\phi_i + \alpha) + c_i'}{1 + \frac{K_e r_m}{G} \tan\alpha \tan(\phi_i + \alpha)}$$

when ($u_p > (u_p)_Y$) or $\sigma > \sigma_Y$, the plastic zone is developed *along with slippage* to obtain an elastic perfectly plastic pile-ground interface and plastic zones extends more. In this case, the radial stress (σ) will be changed into the form:

$$\sigma = \sigma_Y + \int_{vY}^{v} K_p \, dv$$

Where, v_Y can be computed using $(u_p)_Y$ and $(\tau_{x,})_Y$ which is the vertical shear stress when $u_p = (u_p)_Y$. Then, the corresponding vertical shear stress, τ_x can be expressed as:

$$\tau_x = \left(\sigma_Y + \int_{vY}^{v} K_p \, dv \right) \tan(\phi_i + \alpha) + c_i'$$

Improved Skin Friction

Stress-Dilatancy Relationship

- Generally, the dilatancy angle is considered to be zero for evaluating large strain analyses.
- But the real ground behaves the angle of internal friction and the rate of dilatancy at the critical state are as interdependent functions of *density* and *effective stress*.
- The *density and confining pressure* change significantly when a tapered pile penetrates with settlement ratios.
- The confining pressure increases with *increasing* relative density together with the angle of internal friction and dilatancy.
- Therefore the stress-dilatancy property is inserted in the cavity expansion theory (Yu and Houslby, 1991) and proposed model for determination of the ***skin friction*** by Kodikara and Moore (1993).

Stress-Dilatancy Relationship (Bolton, 1986,1987)

$$\phi'_{max} - \phi'_{cv} = \mathbf{0.8}\psi_{max} = \mathbf{5}\ I_R^o \quad \text{and,} \quad I_R = I_D(\mathbf{10} - \ln p') - \mathbf{1}$$

- Where, ϕ'_{max}, ϕ'_{cv}, ψ_{max}, and I^o_R are the maximum angle of friction, the angle of friction at critical states, maximum dilation angle and the relative dilatancy index at plane strain.
- The relative dilatancy index I_R is a function of relative density I_D and mean effective stress p'.
- A plastic zone will be obtained at the cavity wall within the region $a \le r \le b$, with an *increment of cavity pressure* p. By *partitioning elastic and plastic regions*, the stress component at the plastic region that satisfies the equilibrium condition as:

$$p' = -p_0 b^{\frac{(\alpha'-1)}{\alpha'}} r^{-\frac{(\alpha'-1)}{\alpha'}}$$

At the *boundary of plastic region* where $r \le a$, the effective mean stress can be modified to:

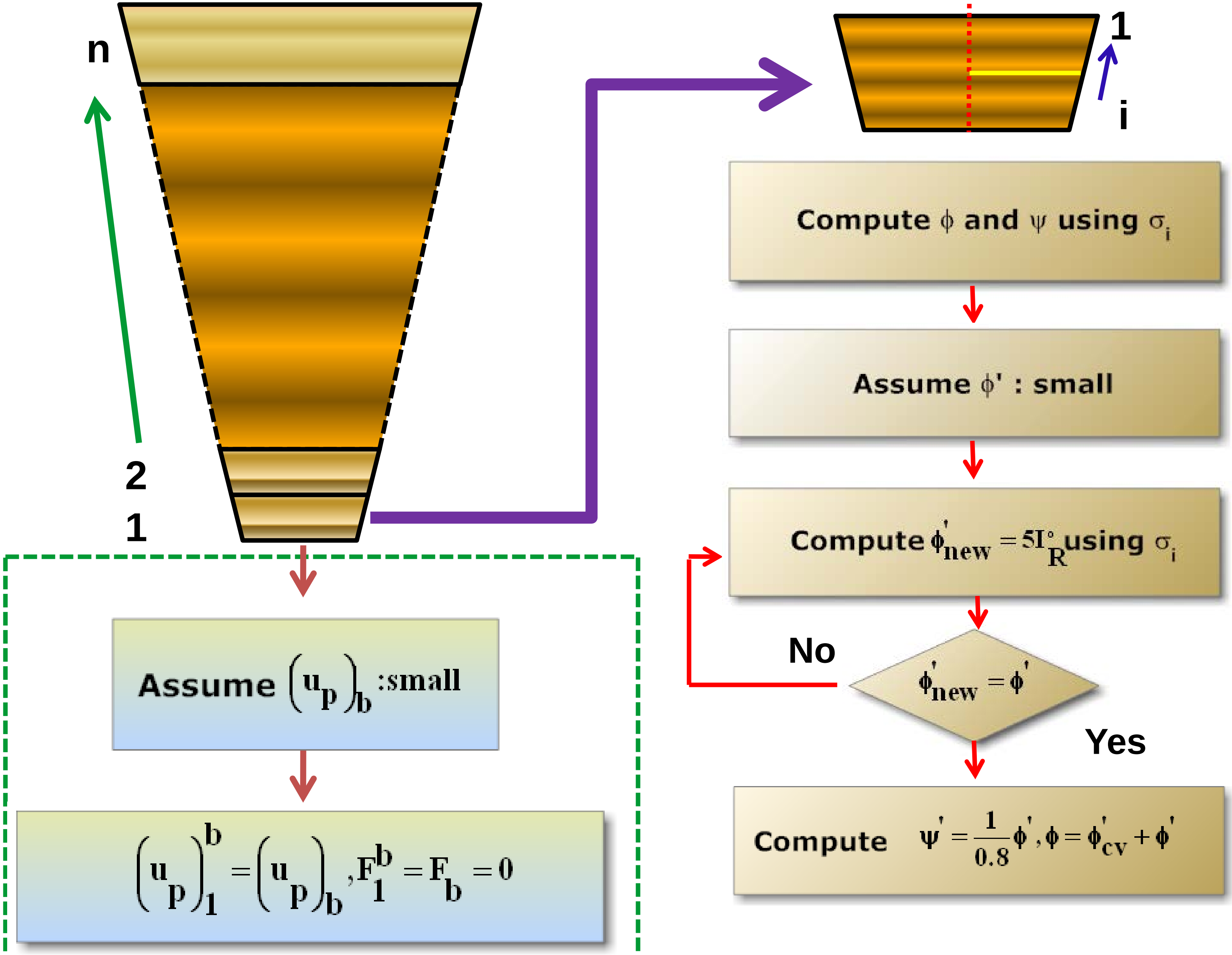
$$p' = -p_0 R$$

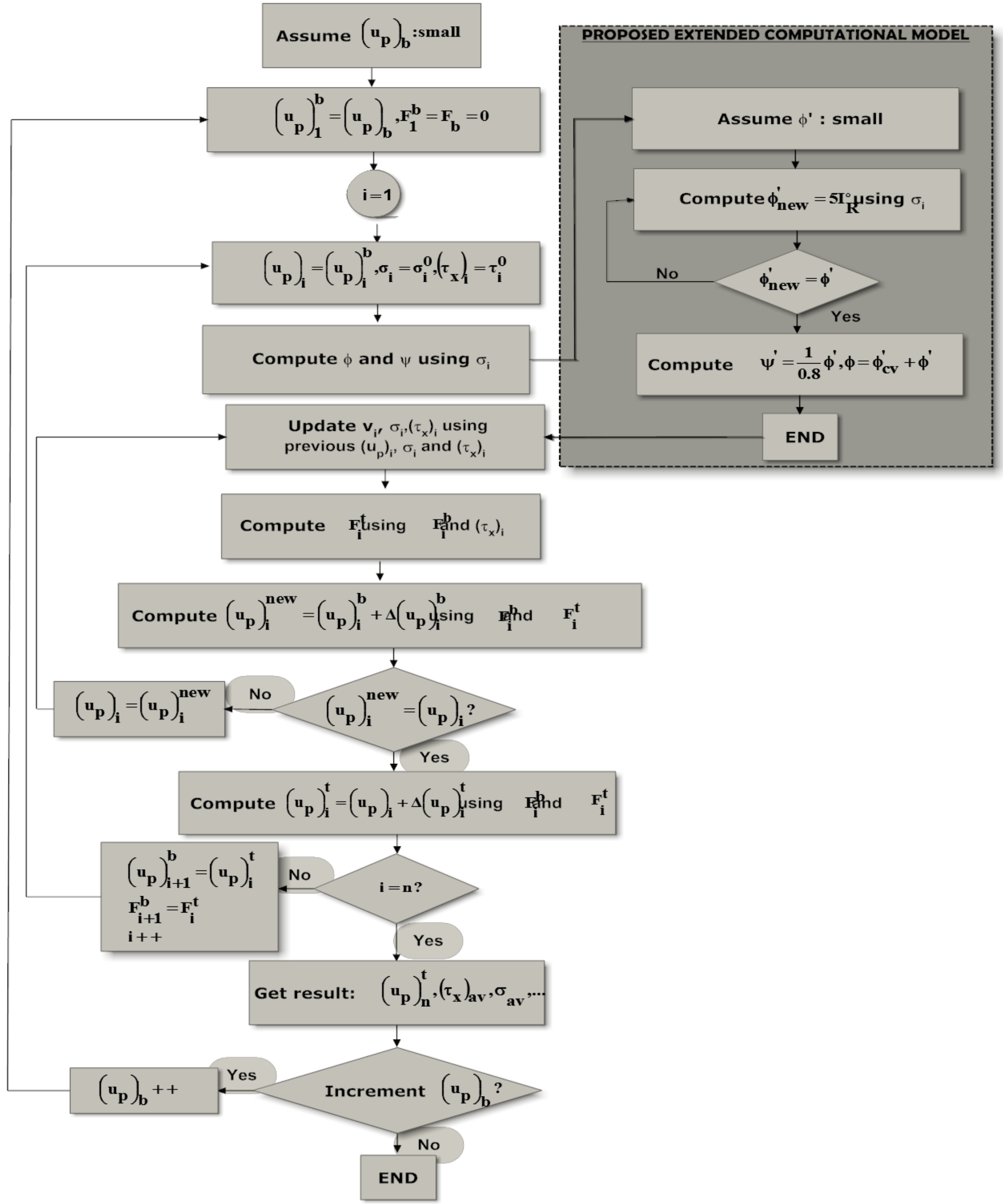
Results of the Model using Load Transfer Method

- The load transfer method proposed by Coyle and Reese (1966) [based on Seed and Reese (1957)] is used to estimate the skin friction by *inserting* a stress-dilatancy property as the ***extended model***.

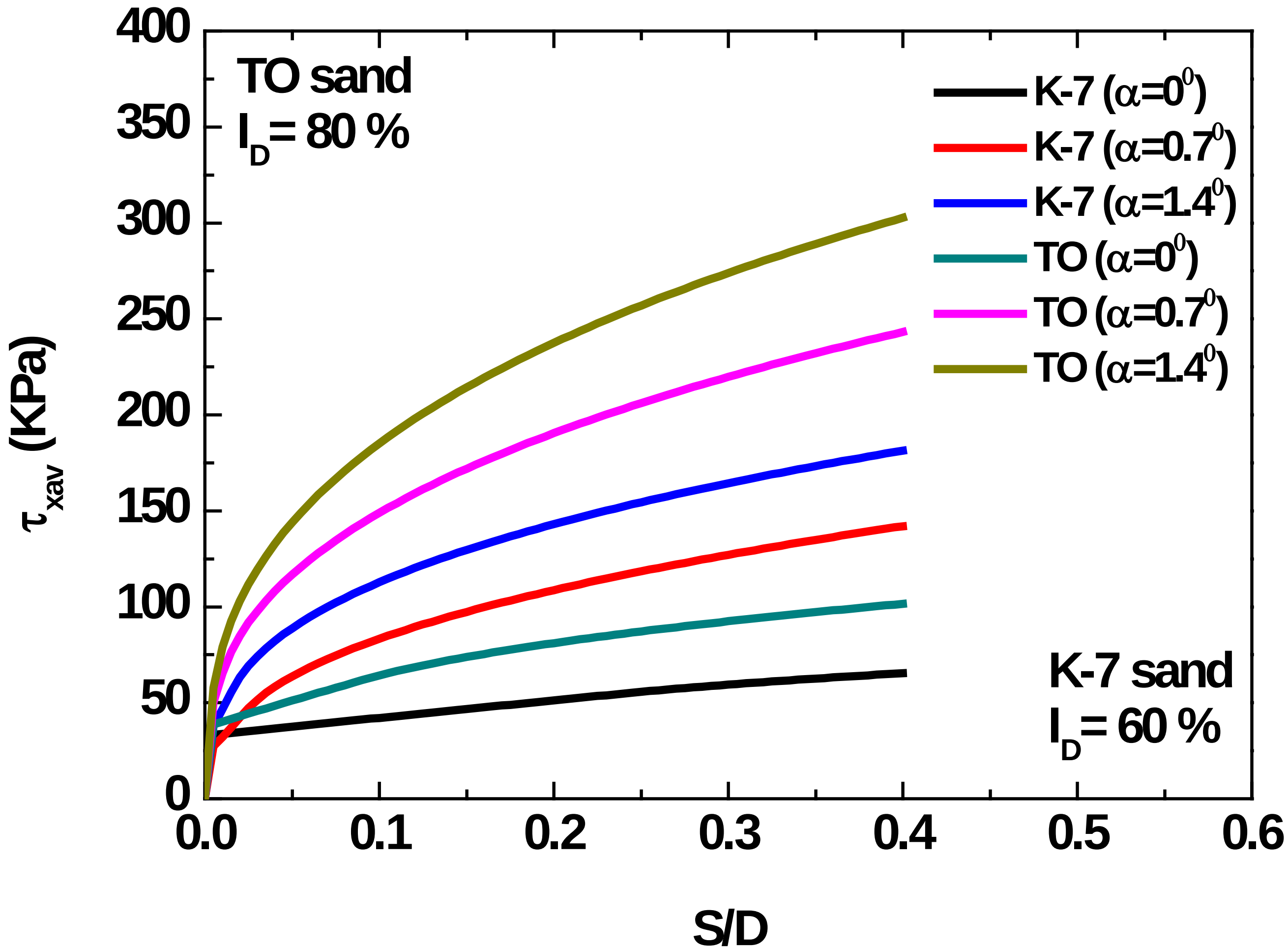
- A small settlement at the pile base is ***specified*** and the axial load at the ***top of*** this ***segment*** is iteratively ***synchronized*** to *satisfy* the ***equilibrium condition,*** and the process undergoes to *next segment* to calculate the ***settlement.***

Proposed Extended Model

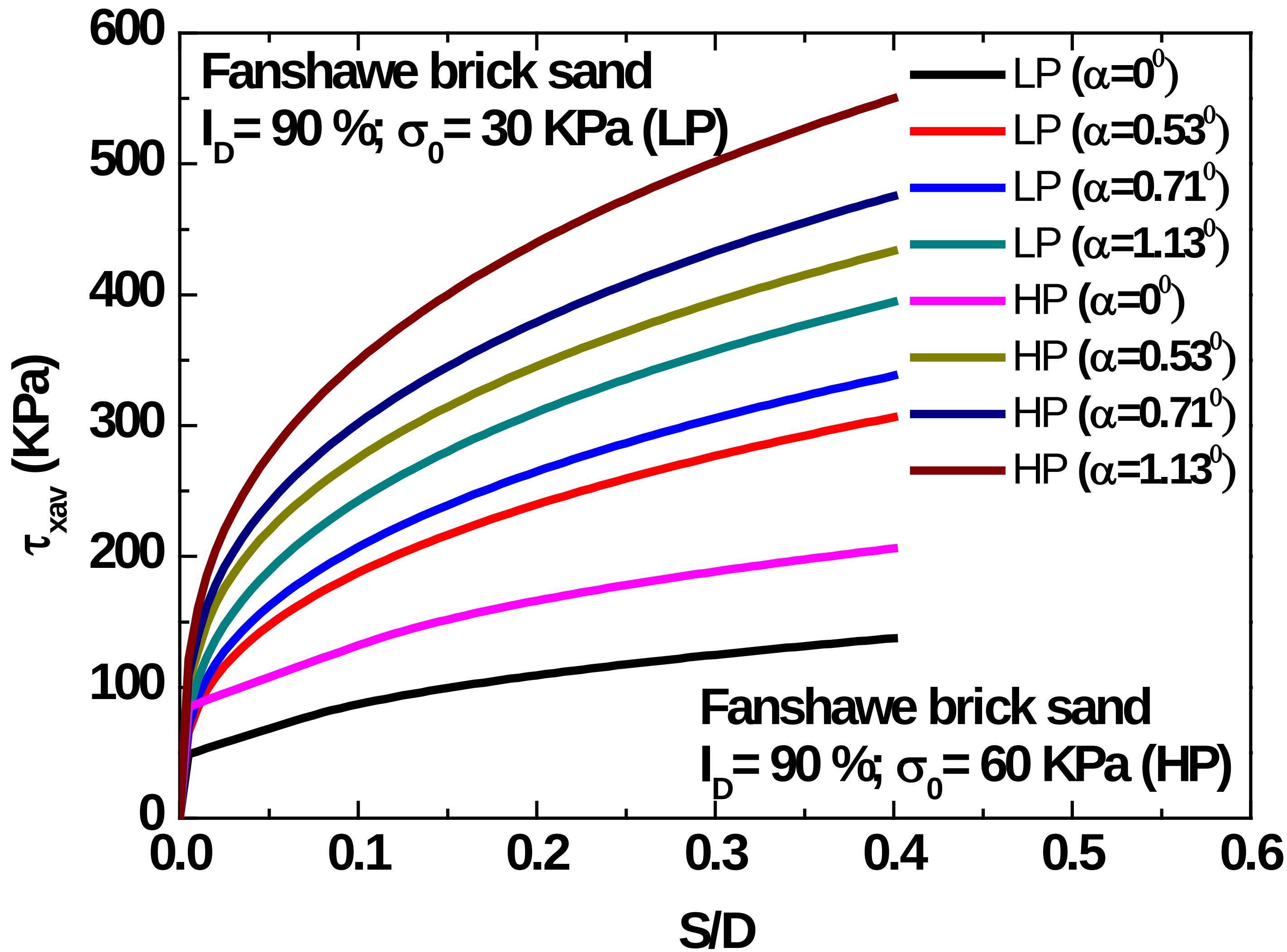



Assume (up)b :small
(up)1b = (up)b , F1b = Fb = 0
i=1
(up)i = (up)ib ,σi = σi0,(τx)i = τi0
Compute ϕ and ψ using σi
PROPOSED EXTENDED COMPUTATIONAL MODEL
Assume ϕ' : small
Compute ϕ'new = 5IR using σi
No
ϕ'new = ϕ'
Yes
Compute ψ' = 1/0.8 ϕ', ϕ = ϕ'cv + ϕ'
END
Update vi, σi,(τx)i using
previous (up)i, σi and (τx)i
Compute Fit using Fib and (τx)i
Compute (up)inew = (up)ib + Δ(up)ib using Fib and Fit
(up)i = (up)inew
No
(up)inew = (up)i ?
Yes
Compute (up)it = (up)i + Δ(up)it using Fib and Fit
(up)i+1b = (up)it
Fi+1b = Fit
i++
No
i=n?
Yes
Get result: (up)nt, (τx)av, σav, ...
(up)b ++
Yes
Increment (up)b ?
No
END

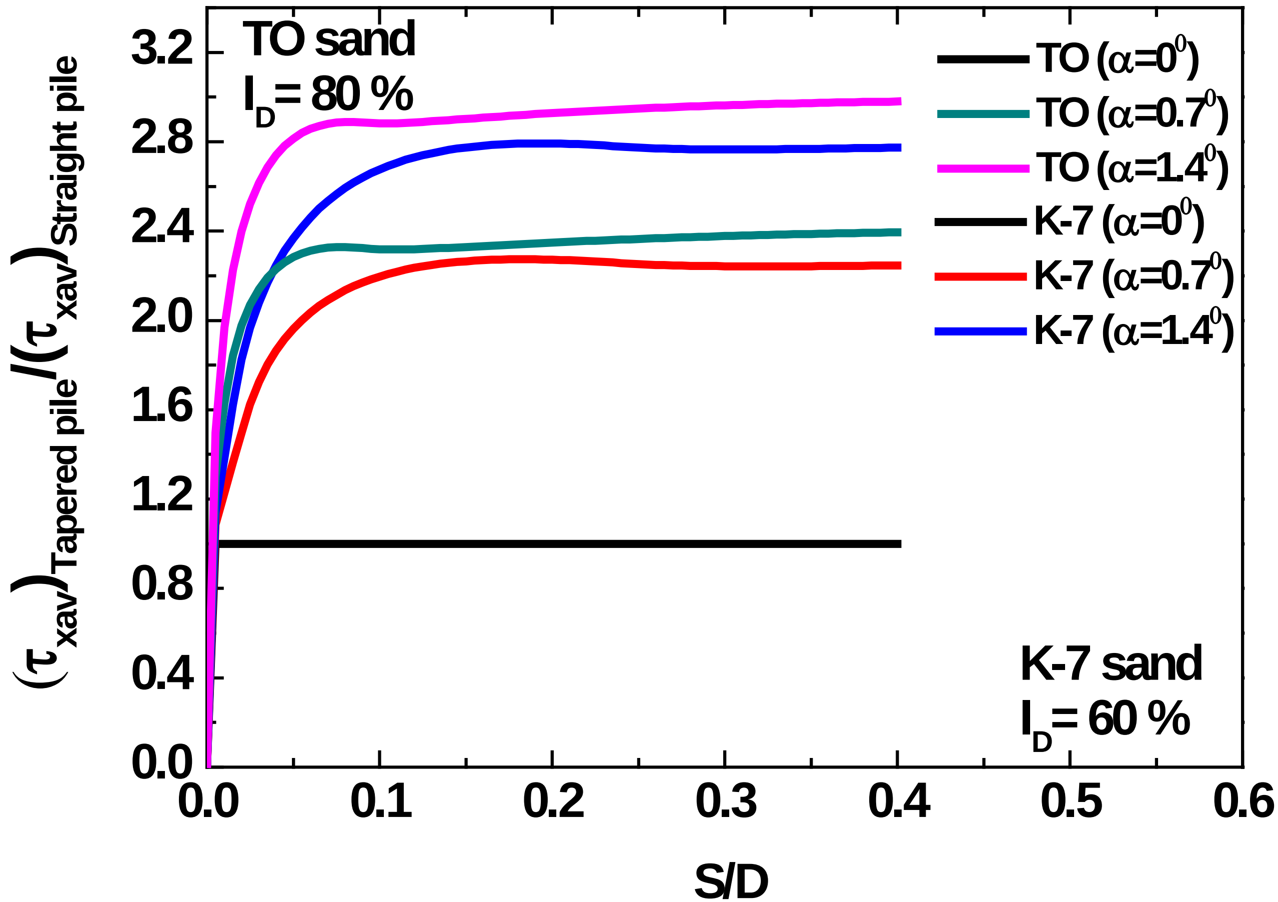
Results



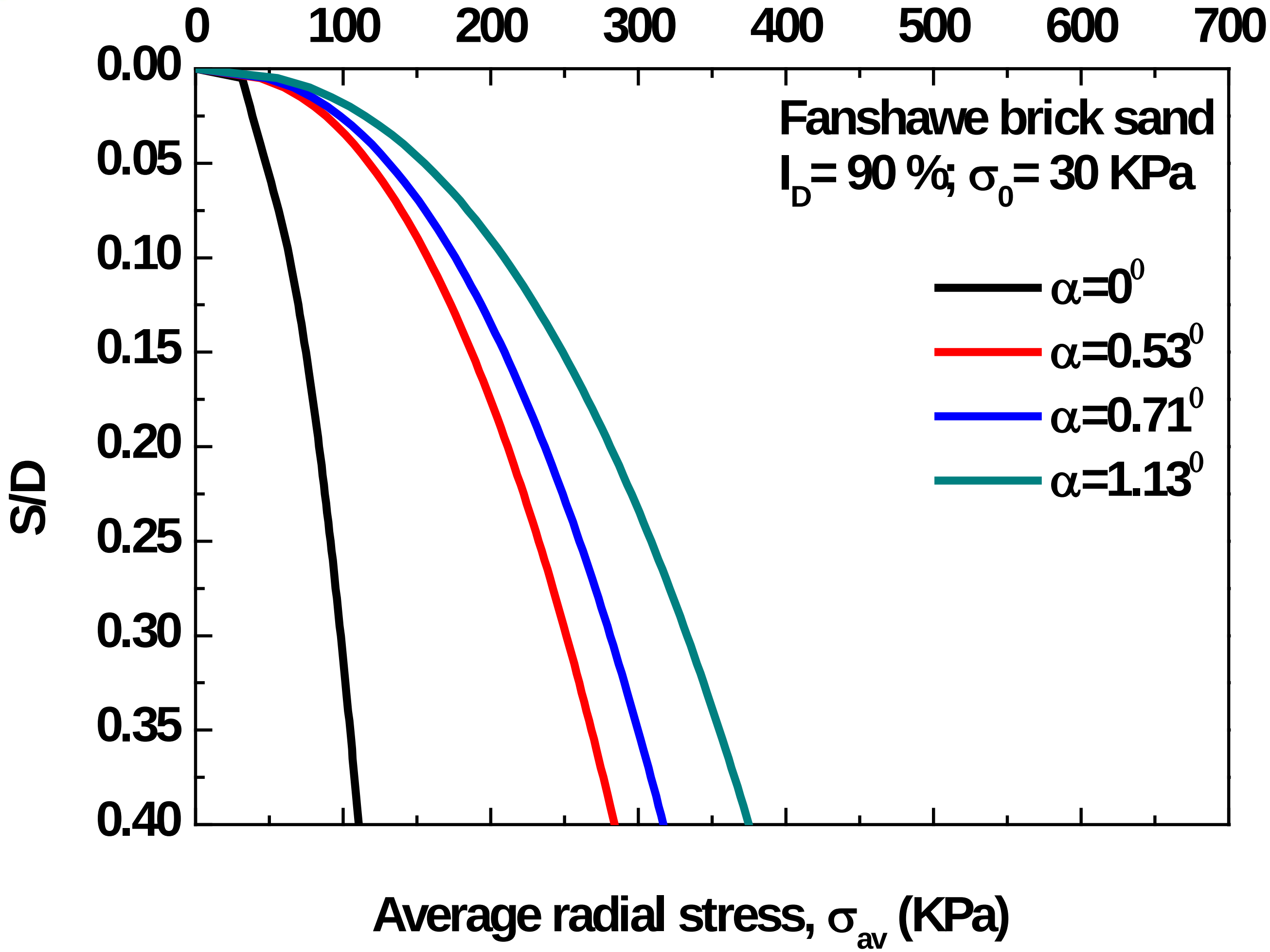
The **vertical shear stress** increases with increasing ***tapering angles*** for **different types of sandy ground.**



For **different ground** and **confining pressures**, the **skin friction** increases with the same ratio irrespective of soil type



Normalized shear stress of the most tapered pile shows remarkable improvement on skin friction.

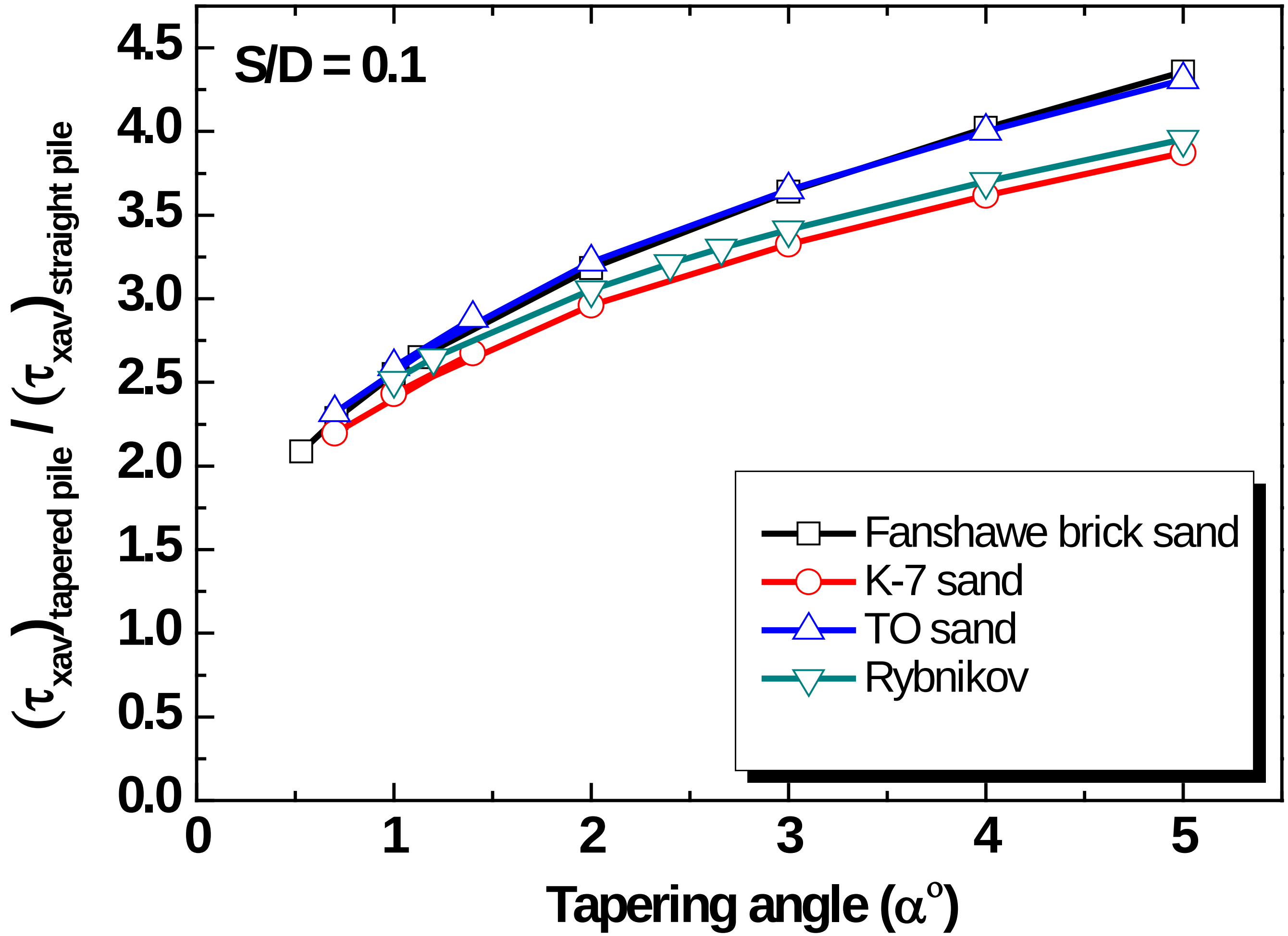


Average radial stress of ***the most tapered pile*** increased remarkably with settlement ratios.

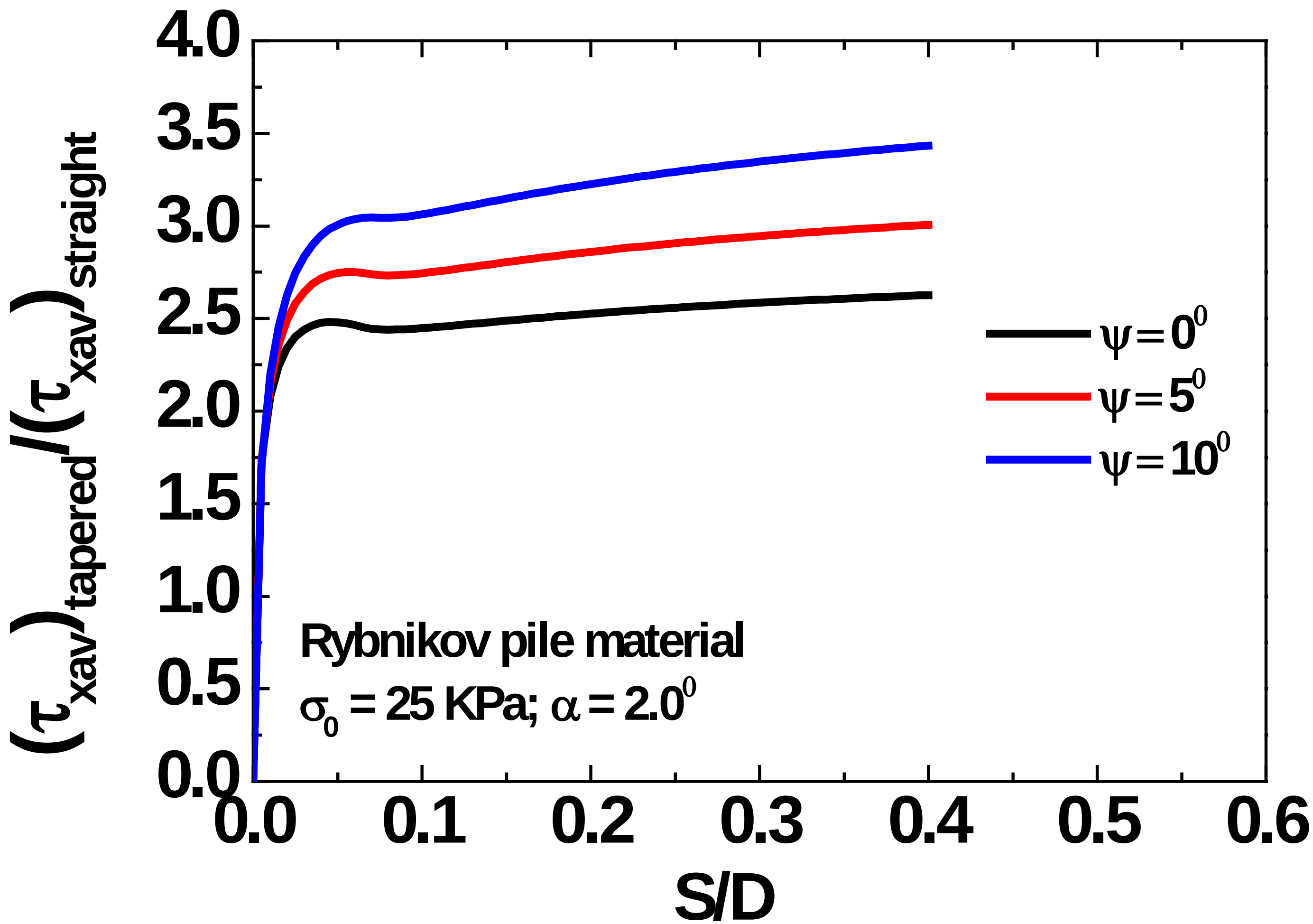
Parametric Study and Validity of the Model

A real type Rybnikov (1990) pile and prototype pile (Sakr et. al, 2004, 2005, and 2007) are accomplished to check and validate the applicability of the proposed model.

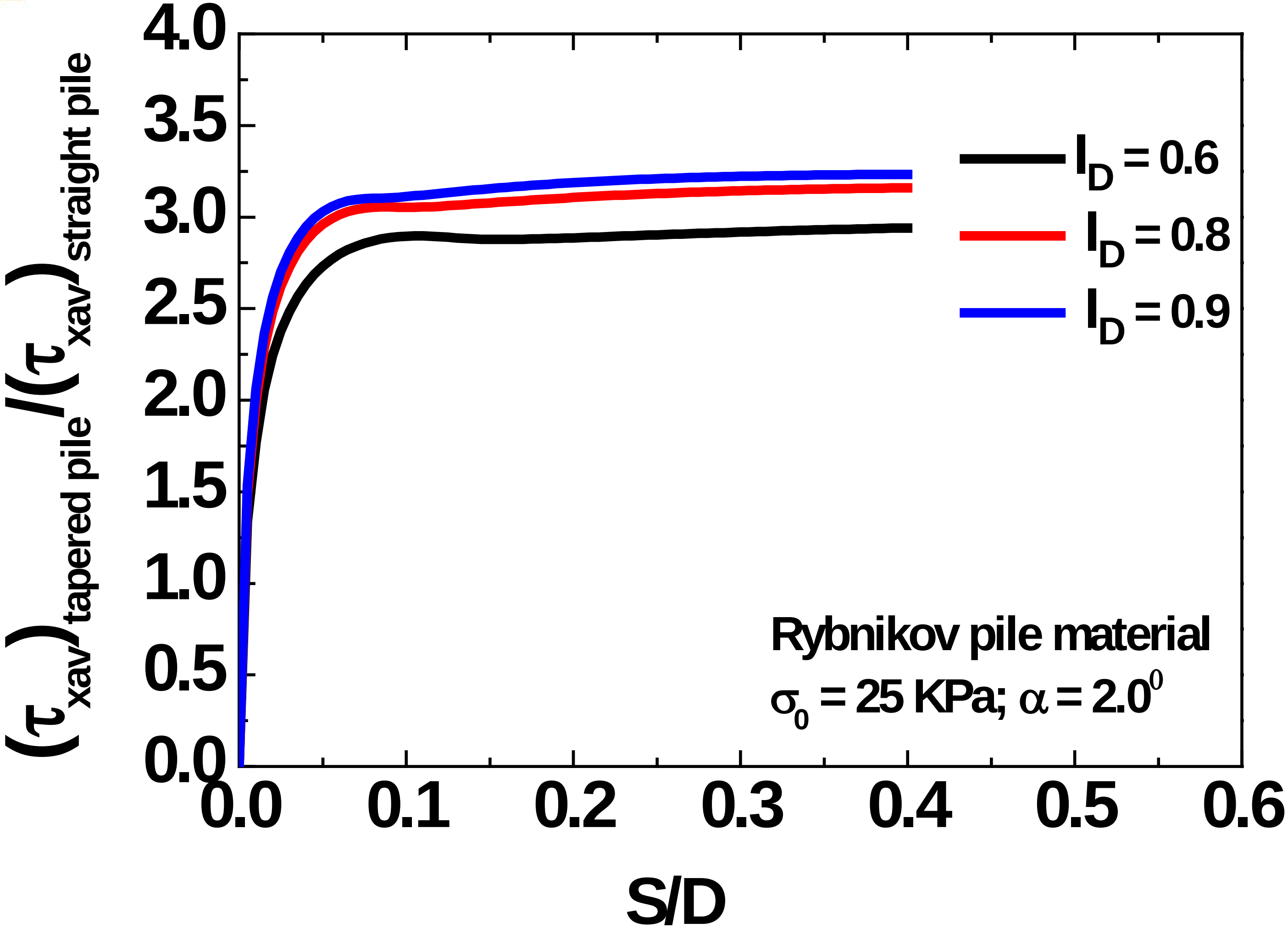
Parameters	Rybnikov Pile Material								
	Default (α = 2)	α = 0	α =1.2	α = 2.4	α = 2.66	α = 1	α = 3	α = 4	α = 5
G, MPa	Formula	Formula	Formula	Formula	Formula	Formula	Formula	Formula	Formula
C, KPa	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
c_i, KPa	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
ϕ^o	Iteration	Iteration	Iteration	Iteration	Iteration	Iteration	Iteration	Iteration	Iteration
ψ^o	Iteration	Iteration	Iteration	Iteration	Iteration	Iteration	Iteration	Iteration	Iteration
L, mm	4500	4500	4500	4500	4500	4500	4500	4500	4500
α^o	2	0	1.2	2.4	2.66	1	3	4	5
I_D	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
σ_o, KPa	25	25	25	25	25	25	25	25	25
ϕ'_{cv}	32°	32°	32°	32°	32°	32°	32°	32°	32°



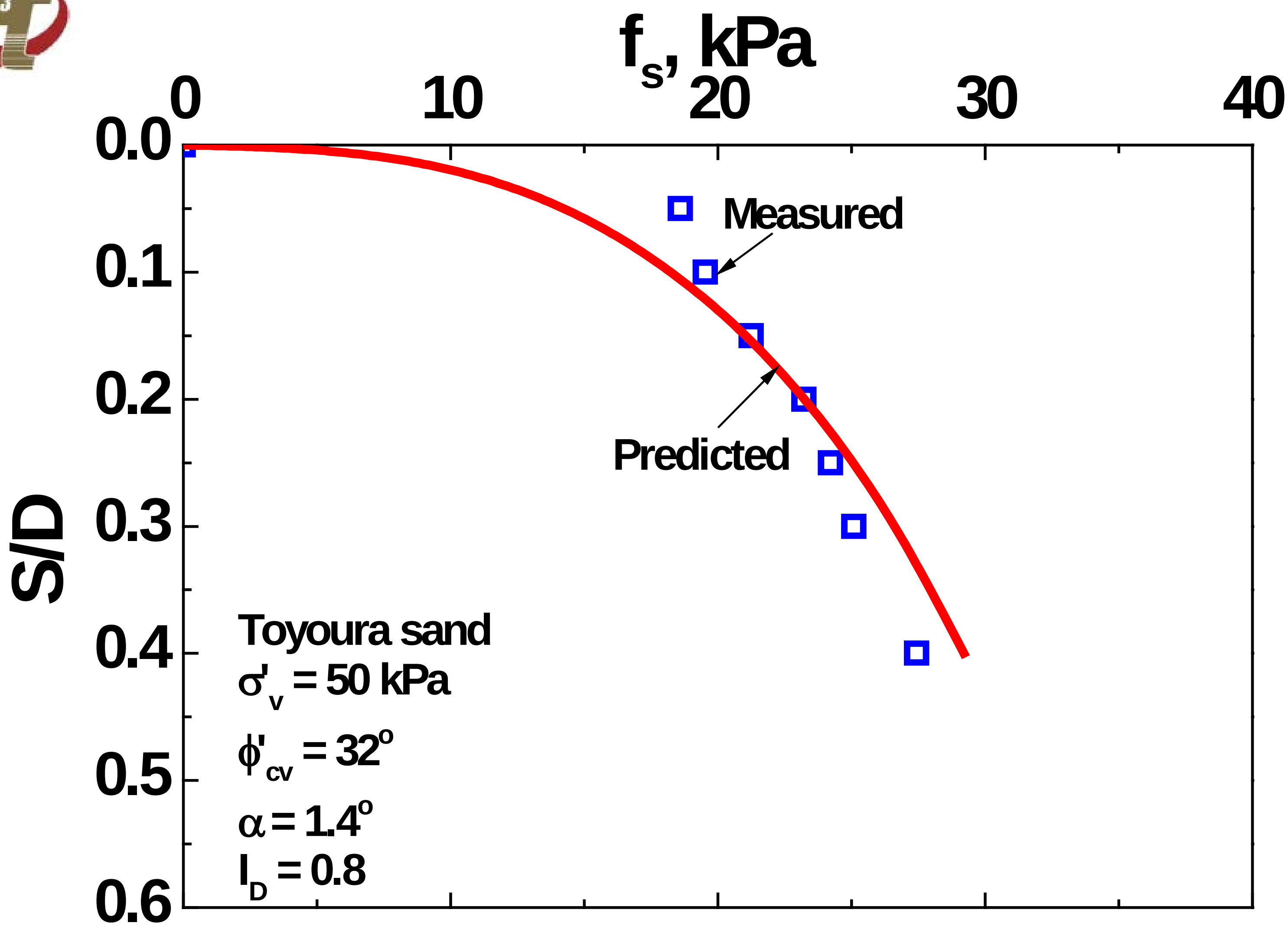
Skin friction increased remarkably together with ***increasing tapering angle*** at settlement ratio of 0.1.



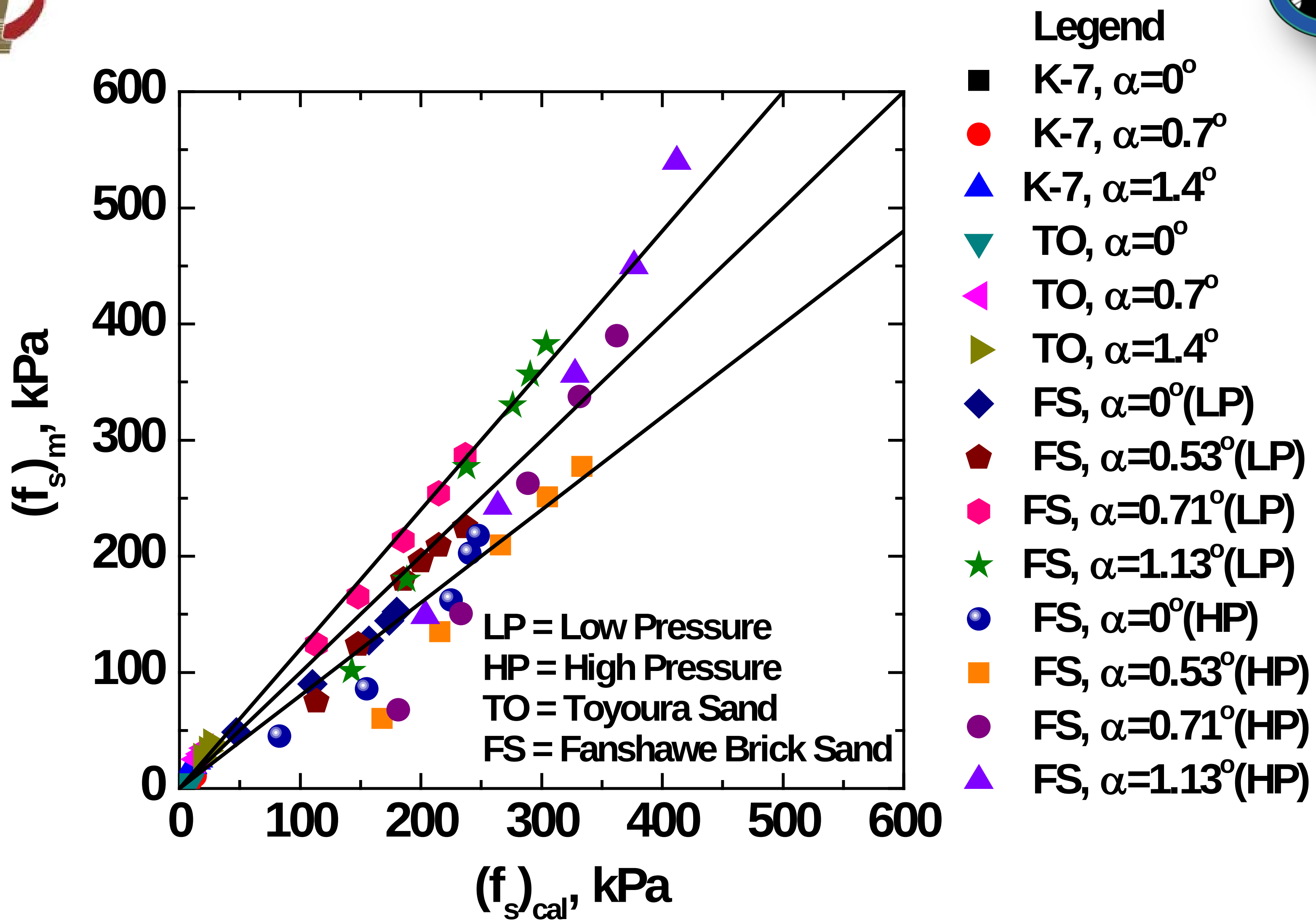
Normalized average vertical shear stress increased with ***increasing dilatancy angles***.



Normalized average vertical shear stress increased with ***increasing relative densities*** of the ground.



The measured and predicted ***skin frictions*** lie near to each other with increasing settlement ratios.



The measured and predicted ***unit skin frictions*** **validated** for different types of ***piles*** and ***sandy ground***.

Conclusions

- The mobilized mechanism of skin friction shows that the ***effective radius of the influenced zone*** around the pile shaft *increases* in line with increases in the tapering angle.

- The ***extended model*** with the inserted ***stress-dilatancy property*** can predict ***skin friction*** using *cylindrical cavity expansion theory* in closed form solution and can easily determine with simple fundamental properties of soils.

- The ***predicted*** skin friction using the extended model shows ***good agreement*** with ***measured*** skin friction from various sources.

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Thank you for

your kind attention !!!