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Studies on Skin Friction in Piles under Tensile and Compressive Load

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Introduction

Pile foundations are often required to resist tensile forces. For example, foundations of structures, such as tall chimney, transmission line tower, jetty structure, mooring system for ocean or submerged platform are subjected to tensile/uplift force. There has been considerable debate over the relative magnitude of pile skin friction under tensile loading compared with that under compressive loading. In most soil types, it is generally assumed that the skin friction resistance of a pile is identical under both tensile and compressive loading primarily due to insufficient database (Karft, 1990; Olson, 1990, Toolan et al., 1990). Fellenius (2002) feels that the current state of art does not demonstrate that a difference exists in pile shaft resistance under tensile and compressive load. Present Indian Standard code IS:2911 Part I (Sect.1-3) (1979) recommends that the skin friction resistance in tensile and compressive loading is the same. However, there are widespread experimental evidences that in sand, the skin friction resistance is significantly lower for tensile loading than for compressive loading (Beringen et al., 1979; Rao and Venkatesh, 1985; Brucy et al., 1991; Lehane et al., 1993; De Nicola and Randolph, 1993; Chow et al., 1997; O'Neill, 2001; Elhakim and Mayne, 2002).

In order to evolve a sound basis for the estimation of uplift resistance

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of pile based on experimental evidence, the present investigation consisting of a comprehensive model test programme and compilation of available field and laboratory test data on the subject has been carried out. Table 1 presents results of earlier investigators.

TABLE 1 : Ratio of Skin Friction under Tensile to Compression Loading, Q_{st}/Q_{sc}

Reference	Type of Pile	Soil Description	ϕ	L/D	Q_{st}/Q_{sc}
Field Test					
Mohan et al. (1963)	Driven cast in-situ R.C.C. vibro pile	Fill of 2.4 m thickness followed by medium sand upto 9.5 m then silt with 'Kankar'. Water table was about 2 m depth from G.L.	33°	34	0.73
Vesic (1970)	Driven pipe pile with bottom closed	Deep deposit of medium to dense sand. Water table was at 1.5m depth from G.L.	35° *	33	1.06
Gregersen et al. (1973)	Driven precast concrete piles	Loose sand. Water table at about 2 m from G.L.	28° *	29 33 + 57 57**	0.47 0.49 0.70 0.61
Chandrasekaran et al. (1978)	Bored R.C.C. pile	Medium dense sandy silt.	30° *	20	0.71
Beringen et al. (1979)	Driven Pile	Very dense, highly over consolidated sand. Water table at 3 m below ground surface.	38° *	20	0.63
Ismael and Klym (1979)	Bored cast in-situ R.C.C. pile	Fine to medium sand with some silt and traces of clay. Ground water table at 0.5 m depth.	34°	6	1.00
Brucy et al. (1991)	Driven Pile	Compact Sandy deposit Ground water table at 5 m depth.	35° *		0.85
Lehane et al. (1993)	Driven pipe pile with bottom closed.	Fine medium dense sand. Ground water table at 3 m depth.	33°	58	0.83
Hussein et al. (1994)	Driven pre-cast R.C.C. pile.	Alternate layers of loose and medium dense sand underlain by stiff clay.	30° *	42	0.74
		Very loose to loose sand followed by soft to firm clay. This was underlain by medium dense clayey sand.	30° *	54	0.73

TABLE 1 : Continued...

Reference	Type of Pile	Soil Description	ϕ	L/D	Q_{st}/Q_{sc}
Field Test					
Chaw et al. (1997)	Driven pipe pile	3 m very dense hydraulic sand fill over about 30 m of medium to very dense sand. Ground water table at about 4 m depth.	38° *	34	0.63 0.66 0.81
Model Test					
Broms (1963)	Displacement type steel pipe pile.	Submerged loose uniform sand.	28°	20-40	0.37
		Submerged medium dense sand.	33°		0.47
Rao and Venkatesh (1985)	Displacement type steel pipe pile	Dry coarse sand.	36°	10-20	0.57
		Dry coarse sand.	40°	10-20	0.29
		Submerged coarse sand.	34°	10-20	0.45
		Submerged coarse sand	39°	10-20	0.69

* Inferred from N Values;

\+ Tapered Piles, average dia has been considered for L/D

** Top half is uniform and bottom half is tapered pile. Top dia has been considered for L/D

Experimental Programme

Tests on model piles embedded in sand beds in dry, moist and submerged conditions were carried out. Piles were subjected to both compressive and tensile loading. An arrangement to eliminate point resistance during compressive loading was designed and fabricated. A schematic view of the test setup is shown in Fig.1. The details of the test set-up and testing procedure are outlined here.

Test Bed Material

Locally available river sand was used as test bed material. It was a uniform fine sand containing 91% passing through 0.425 mm sieve and 2.7% passing through 0.075 mm sieve. The soil is classified as poorly graded sand (SP) as per IS:1498-1970.

Preparation of the Test Bed

The test bed was prepared in a steel cylindrical tank, 58 cm diameter and 90 cm height. The sand bed was prepared by rainfall technique. Sand was allowed to fall through a sieve of diameter equal to the diameter of the

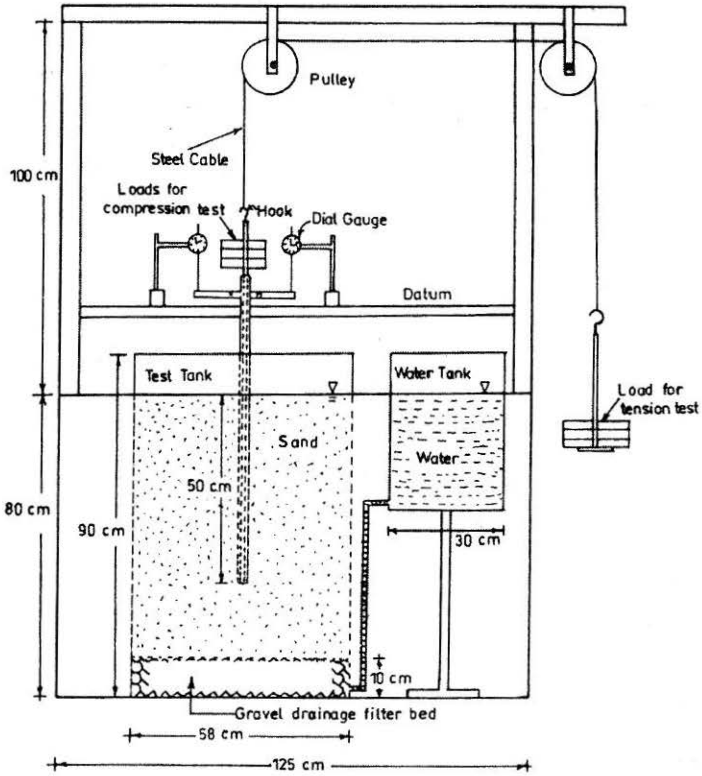

FIGURE 1 : Experimental Set-up

tank with sieve openings uniformly distributed over the area. A homogeneous sand bed was prepared by gradually filling the sand in the tank in 5 cm layers with the height of fall of 100 cm. To prepare a submerged test bed,

TABLE 2 : Properties of Sand in Test Bed

Parameter	Test Bed Condition		
	Dry	Submerged	Moist+
Soil Friction Angle, ϕ*	31°	29°	30°
Pile-Soil Friction Angle, δ**	11°	12°	11°
Unit Weight of soil	15.60 kN/m^3	9.90 kN/m^3	17.28 kN/m^3

* By direct shear test

** By direct shear test on soil-steel plate interface (smooth surface)

\+ There was variation of moisture content with depth; the average value of moisture content, w = 10.8%

water was allowed from the base of tank through an inlet by connecting it to a water reservoir and water level within the bed was allowed to rise upto the top of sand surface. The tank base was filled with a 10 cm layer of gravelly sand to facilitate rising of water level uniformly over the complete area of the tank. Moist condition of the test bed was created by draining the submerged sand through an outlet connected at the base. The properties of sand in the test beds prepared as above are given in Table 2.

Test Piles

Model piles were prepared from smooth mild steel pipes having outer diameter, D = 25 mm, inner diameter, 15 mm and a length of 800 mm. The length of embedment of pile, L in sand was 500 mm resulting L/D as 20. Piles with smooth as well as rough surface were used in the tests. The rough surface of the pile was made by applying test sand glued over the pile surface and allowed to dry before use so that the pile soil friction angle is close to the ϕ value of the soil.

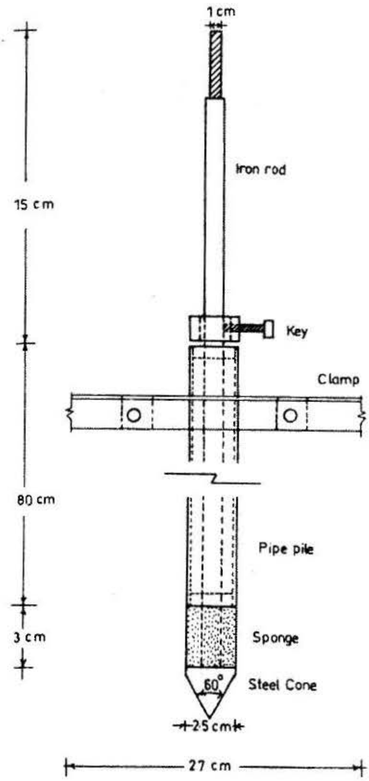

FIGURE 2 : Dessign Detail of the Pile

Arrangement to Eliminate Base Resistance

The arrangement (Fig.2) consists of an iron rod (10 mm diameter) passing through the pipe pile and screwed to a steel cone (60° tip angle) at the base. A cylindrical sponge of 30 mm length was made and attached in between the cone and the pipe pile with glue. The pile can be locked or unlocked to the rod through a key.

The pile was kept locked to the central rod during pile installation. Before a compression load was applied, the pile was unlocked and the sponge was kept in expanded position, thus creating a gap between the pile base and the cone (Fig.3a). Compression load was then applied directly on the pile so that the base movement was effected due to the compression of the sponge,

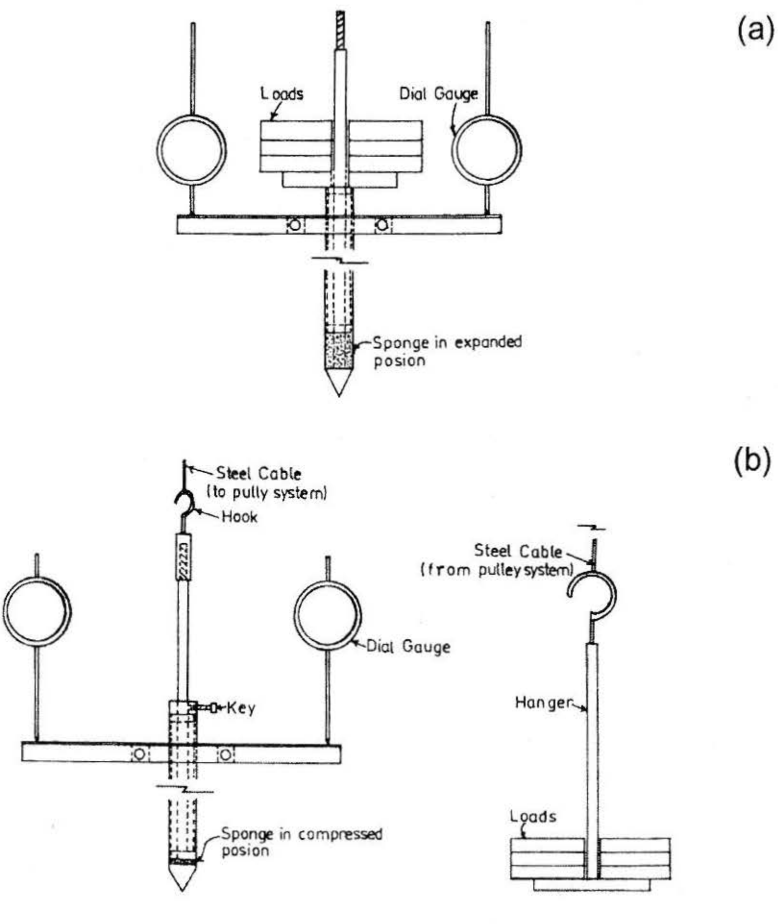

FIGURE 3 : Pile Loading Arrangement under (a) Compressive Loading, (b) Tensile Loading

thus eliminating the base resistance. When tensile load was applied, the sponge was kept compressed initially so that the pile base touches the cone. The pile was locked with the central rod and tensile load applied through the rod by gravity loading using a pulley arrangement as shown in Fig.3b.

Method of Pile Installation

Two methods of pile installation were adopted for model tests. To represent bored pile (non displacement pile), the pile was placed in position inside the tank held by a guide and then the sand bed was prepared. To represent the driven pile (displacement pile), the sand bed was prepared and then the pile was statically pushed using a lever arm system with the help of a guide to ensure that the pile was driven vertically.

Test Procedure

Maintained load method as suggested by IS:2911:Part IV (1985) was adopted for load tests on piles. The pile and the test bed, after final preparation, were allowed to take a rest period of about 1 hour in dry condition, 18 hours in submerged and moist conditions before conducting the test. The test pile was loaded in increments and the displacement was recorded by 2 dial gauges with 0.01 mm least count.

Test Results and Analysis

The load vs displacement curve for various test conditions are shown in Figs.4 to 6. Figure 4 shows the results of the tests in dry sand bed, Fig.5 for submerged bed and Fig.6 for moist sand bed. These results are summarised in Table 3 for the various test pile-soil conditions. The results show the influence of surface roughness of pile, method of pile installation and the type of loading on the relative magnitude of ultimate skin resistance of piles.

Unit skin resistance, f_s in a pile is given by,

$$Q_s = \left(K\sigma'_v \tan\delta\right)A_s \qquad (1)$$

where,

Q_s = ultimate skin resistance

K = coefficient of lateral earth pressure

σ'_v = average effective vertical stress at mid depth of the pile

δ = pile-soil friction angle

A_s = area of the embedded portion of the pile shaft

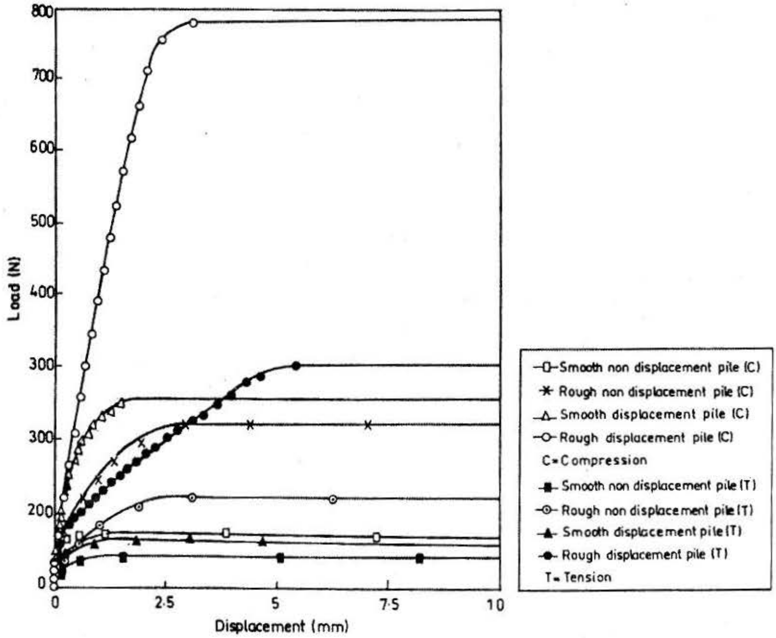

FIGURE 4 : Load-Displacement Curve in Dry Condition

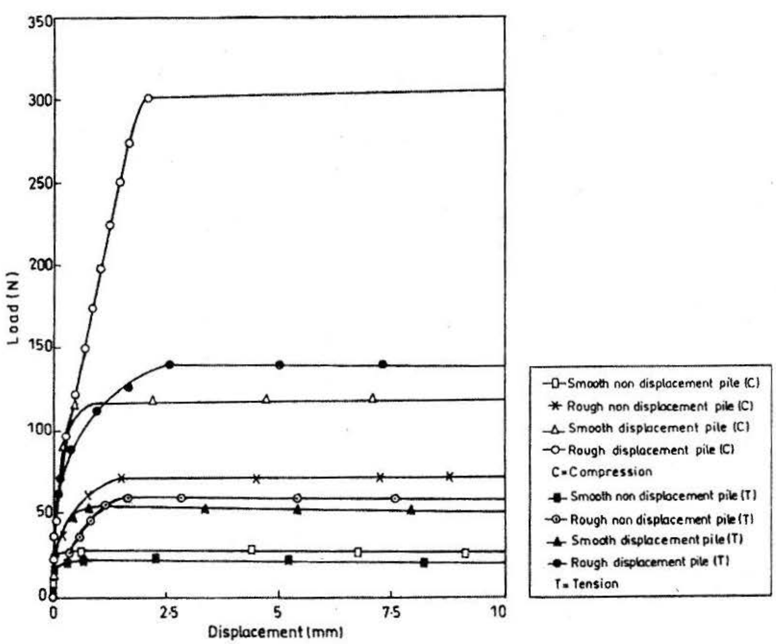

FIGURE 5 : Load-Displacement Curve in Submerged Condition

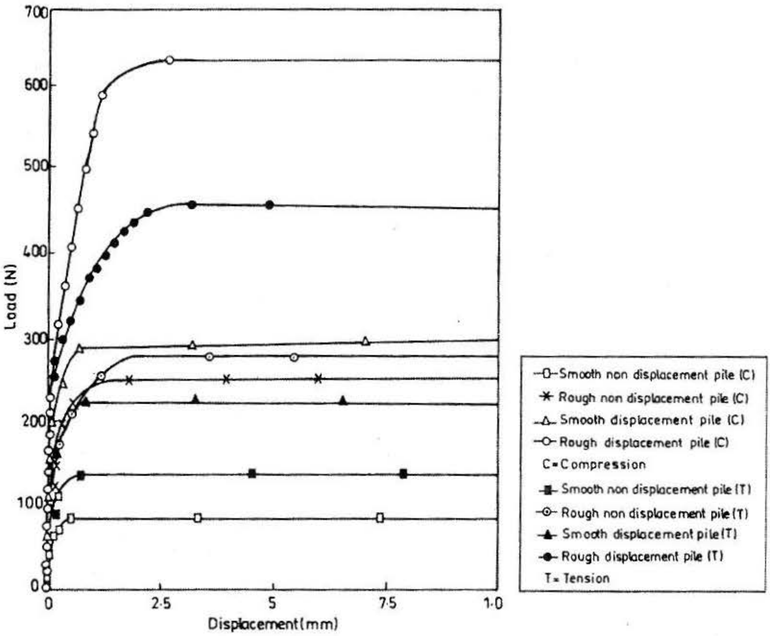

FIGURE 6 : Load-Displacement Curve in Moist Condition

TABLE 3 : Ultimate Skin Friction Resistance under Various Conditions of Test Bed

Type of Loading	Ultimate Skin Resistance, Qs (N)			
	Non displacement pile		Displacement pile	
	Smooth	Rough	Smooth	Rough
(a) Dry Condition				
Compressive	74.5	224.9	256.5	781.3
Tensile	41.2	127.1	67.1	306.2
(b) Submerged Condition				
Compressive	27.4	71.5	116.7	301.6
Tensile	22.6	60.4	53.8	140.7
(c) Moist Condition				
Compressive	83.8	249.2	290.3	632.0
Tensile	136.0	279.2	223.5	458.3

The effective vertical stress, σ'_v is known to increase linearly up to a depth of about 15 to 20 D (McCarthey, 1988; IS:2911-Part I, 1979) and remains more of less constant thereafter. In the present case as the model piles have a L/D ratio of 20, a linear variation of σ'_v with depth is assumed to hold good up to the full length of the pile.

When the results presented in Table 3 are examined in the light of the Eqn.1, the following observations can be made.

(i) The skin resistance under moist condition of soil bed is expected to be about two times that under submerged condition in view of the effect of σ'_v. However, model test results show it is about three times of that under submerged condition. It is possible that the apparent cohesion due to capillarity exhibited in partially saturated sands contributed to this additional resistance.

(ii) Skin resistance under tensile loading, though should be the same as under compressive loading as per Eqn.1, it is found to be less than that under compressive loading. However, in the case of non-displacement pile under moist condition, it is found to be more than that under compressive loading. This may be due to the fact that for piles in moist condition under tensile load, the shape of failure surface is not cylindrical one along pile surface. Model studies have revealed that in moist sand, the failure surface extends beyond the pile surface thus resulting more area of failure surface in comparison to that of for piles under compressive load. Additionally, the soil close to the pile surface tends to dilate during upward movement of pile resulting in negative pore pressure and thus increased resistance.

The pile capacity under tensile loading in the case of displacement piles, however, was observed to be less than that under compressive loading. This may be because, the above effects were probably absent due to the presence of gap between the pile surface and the soil, particularly near the top soil surface, resulting from the installation and loading procedure adopted in the tests.

(iii) The increased skin resistance observed in displacement piles and rough piles is consistent with the known fact on the effect of these on soil parameters, i.e. K in displacement pile is more than that in non displacement pile and δ in rough piles is more than that in smooth piles.

The above observations bring out a point of practical importance, which needs to be noted when interpreting the results of a pile load test. A pile at the time of the load test, may pass through partly or wholly through a partially saturated sand deposit, and may exhibit a load capacity, which is inclusive of the additional resistance due to apparent cohesion in the partially saturated zone. If this is not corrected appropriately taking into account the effect of submergence as observed above, it may result in the estimation of pile capacity on the unsafe side. This error could be very severe in the case of load tests under tensile loading as the observed tensile capacity under submerged condition is about $1/4^{th}$ of that under moist condition.

Table 4 gives the ratio of skin friction resistance of pile under tensile to compressive loading. The ratio depends on the ground condition and the method of pile installation but seems independent of the surface roughness of the pile.

The values of the ratio Q_{st}/Q_{sc} shown in Table 4 are plotted together with other experimental results from both field and model pile load tests (Table 1) and are shown in Fig.7 for various ground conditions. The recommendation of IS:2911 Part I (Sect.1-3) (1979) on this ratio is also shown in Fig.7.

Figure 7 shows that though the data points are scattered, the ratio, Q_{st}/Q_{sc} is less than 1. Major part (length) of the piles in the field tests reported in Table 1 is under submerged condition. The average of Q_{st}/Q_{sc} values for these field tests give a value of 0.68. The average value of Q_{st}/Q_{sc} for the model test data for submerged condition is obtained as 0.6. These values are comparable. Similarly, the data suggests a value of Q_{st}/Q_{sc} as 0.87 for moist condition and 0.48 for dry condition. The ratio of skin friction seems independent of the soil friction angle. In the field situation, the dry condition rarely occurs. So based on the present study and other reported results, the ratio of the pile skin friction resistance under tensile loading to compression loading may be taken as 0.87 in moist condition and to 0.60 in submerged condition of soil bed. Taking the same value of skin

TABLE 4 : Ratio of Skin Friction Resistance under Tensile to Compression Loading Q_{st}/Q_{sc}

Sand Condition	The Ratio of Skin Friction Resistance under Tensile to Compressive Loading			
	Non displacement pile		Displacement pile	
	Smooth	Rough	Smooth	Rough
Dry	0.55	0.57	0.26	0.39
Moist	1.62	1.12	0.77	0.73
Submerged	0.82	0.84	0.46	0.47

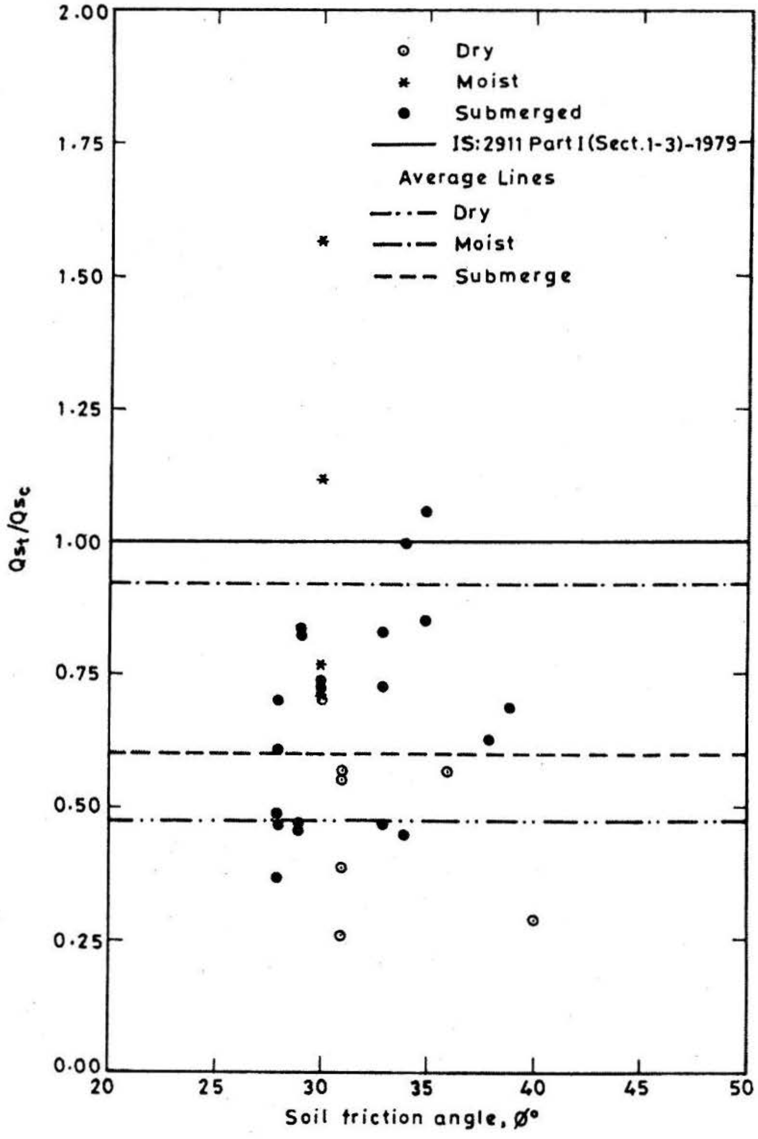

FIGURE 7 : Ratio of Skin Friction under Tensile to Compression Loading in Dry, Moist and Submerged Conditions

friction resistance under tensile and compressive loading (i.e. $Q_{st}/Q_{sc} = 1$) as suggested by IS:2911 Part I (Sect.1-3) (1979) appears to be on the unsafe side in the case of tensile loading.

Conclusions

Based on the present study the following conclusions are made:

1. The ultimate skin friction resistance under tensile loading in a pile is less than that under compressive loading.

2. The skin friction resistance under tensile loading in moist condition increases significantly compared with dry condition due to change of shape of failure surface and apparent cohesion inherent in partially saturated sand bed due to capillarity.

3. The ultimate displacement is about 5-10% of pile diameter for smooth pile and 12-22% for rough pile in dry condition. These values get reduced by about 50% in moist and submerged conditions.

4. The ratio of skin friction resistance under tensile to compressive loading Q_{st}/Q_{sc} is independent of soil friction angle. This ratio may be taken as 0.87 for piles in moist condition and 0.60 in submerged condition.

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