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A new design chart for estimating friction angle between soil and pile materials

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Abstract. Frictional forces between soil and structural elements are of vital importance for the foundation engineering. Although numerous studies were performed about the soil-structure interaction in recent years, the approximate relations proposed in the first half of the 20th century are still used to determine the frictional forces. Throughout history, wood was often used as friction piles. Steel has started to be used in the last century. Today, alternatively these materials, FRP (fiber-reinforced polymer) piles are used extensively due to they can serve for long years under harsh environmental conditions. In this study, various ratios of low plasticity clays (CL) were added to the sand soil and compacted to standard Proctor density. Thus, soils with various internal friction angles (ϕ) were obtained. The skin friction angles (δ) of these soils with FRP, which is a composite material, steel (st37) and wood (pine) were determined by performing interface shear tests (IST). Based on the data obtained from the test results, a chart was proposed, which engineers can use in pile design. By means of this chart, the skin friction angles of the soils, of which only the internal friction angles are known, with FRP, steel and wood materials can be determined easily.

Keywords: skin friction; pile materials; design chart; direct shear test; interface shear test; surface roughness

1. Introduction

Friction between soil and pile materials emerges as an important component in the designs made by geotechnical engineers. Frictional forces between structure and soil are taken into consideration in the design of civil engineering constructions such as retaining walls, sheet piles, diaphragm walls and piles. As is known, the effect of pile point tip resistance on the bearing capacity is ignored particularly in loose sand soils and the bearing capacity is fully taken equal to the skin friction. Hence, it is understood how important it is to determine right the skin friction angle used extensively in the engineering calculations.

Many designers consider the skin friction angle (δ) as equal to 2/3 of the internal friction angle (ϕ) of soil in their designs (Terzaghi and Peck 1948). However, it is known that δ can vary in the event of frictions between the same soil and different materials. Even today, skin friction angles (δ) between soil and pile materials are not exactly known and designs are made with the use of

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approximate values. δ values used in designs are of prime importance in the determination of pile number, diameter and length. A low δ value prevents making economic designs and increases project costs considerably. On the other hand, a high δ value leads to security problems.

Wood was used as a driven pile material up to the beginning of the 20th century. However, the use of wood decreased almost non-existing in present day due to increasing costs. Nowadays, steel is often used as the driven pile material. Plastic composite materials have also been started to be used in recent years as alternative to steel. Today, FRP (fiber-reinforced polymer) material is ever-increasingly used due to the reasons such as being economic, having high tensile and compressive strengths and its resistance to harsh environmental conditions.

Potyondy (1961) performed interface shear tests (IST) on the soils prepared in four different sand/clay ratios and determined the friction angles of wood, steel and concrete materials. Upon analyzing the IST results, it is seen that the critical value for the cohesion is the situation where sand/clay ratio is 1. The cohesion increases rapidly in all values above this ratio. Uesugi and Kishida (1986) analyzed the friction between mild steel and dry sand by using IST in their study. They determined that the type and mean grain diameter of sand (D_{50}) had important effects on friction. Pando *et al*. (2002) analyzed the friction angles between FRP and concrete surfaces by using two different sand types which are round and angular. They stated that the shapes of sand grains are of much more efficient in FRP material, which has softer surface comparing to concrete. The highest skin friction angles were measured between concrete surfaces and sand. There are many studies where the frictions between geosynthetics and sands were examined thorough IST (O'Rourke *et al*. 1989, Izgin and Wasti 1998, Frost and Han 1999, Palmeira 2009). Lavanya *et al*. (2014) study of skin friction between CFRP (carbon fibre reinforced polymer) and gravel soil. They determined that skin friction is depended on direction of CFRP. In the literature, it is seen that the ring shear test is also used for determining the angle of friction (Rinne 1989, Hammoud and Boumekik 2006). Some researchers worked on large scale direct shear box tests to determine skin friction of soil and various structural materials (Liu *et al*. 2009, Laskar and Dey 2011, Khan *et al*. 2014).

When studies in the literature are analyzed, it is often seen that the frictions of clean sands (without clay-silt) and construction material surfaces were determined (Frost and Han 1999, Pando *et al*. 2002, Sakr *et al*. 2005, Gireesha and Muthukkumaran 2011, Tiwari and Al-Adhadh 2014). However, clean sands are rarely seen in nature. Therefore, mixing various ratios of sand and clay soils will enable more realistic results to be obtained in the in laboratory of the soils encountered in the field.

Clayey sand soils containing various ratios (0%, 20%, 30%, 40% and 45%) of clay were used in laboratory studies. The formed soils have different internal friction angles, skin friction angles between these soils and FRP, steel and wood were determined. As a result of the tests performed, a chart was proposed, which shows the relationship between the internal and skin friction angles. By means of this chart, the skin friction angles between soil and pile materials (FRP, steel, wood) can be determined based only on the internal friction angles of soils.

2. Material and method

The index properties of the sand and low plasticity clay (CL) soil used in the tests were determined and given in Table 1. Black basalt originated river sand (specific gravity 2.77) used in the tests. The sieve analyses, Atterberg limits tests and specific gravity tests were performed according to standards (ASTM D422-63, ASTM D4318-10 and ASTM D854-14).

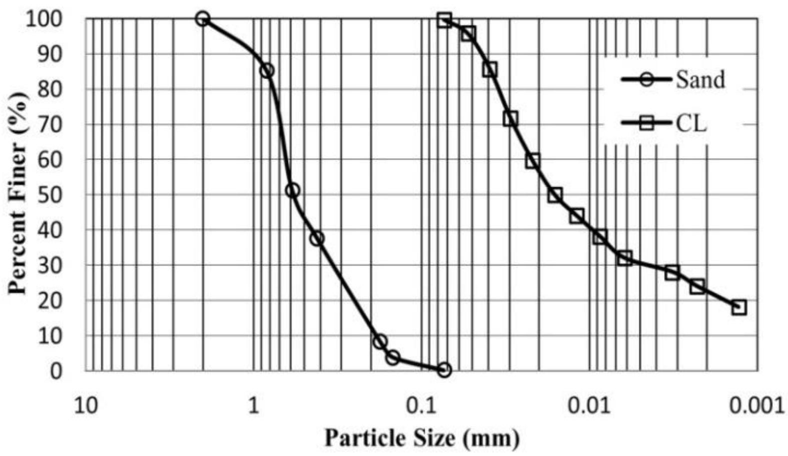

Fig. 1 Grain size distribution of tested soils

Table 1 Index properties of soils

	Sand	CL
D_{30} (mm)	0. 33	0.0045
D_{50} (mm)	0.57	0.016
Liquid limit, w_L (%)	-	30
Plastic limit, w_P (%)	-	15
Specific gravity, γ_S	2.77	2.68

Table 2 Mixing ratios and optimum moisture content

Mixture	Clay (%)	Sand (%)	Soil group (USCS)	w_{opt} (%)
m_0	0	100	SP	6.0
m_{20}	20	80	SC	9.0
m_{30}	30	70	SC	10.0
m_{40}	40	60	SC	11.5
m_{45}	45	55	SC	13.0

Table 3 Properties of pile materials

	FRP (50% glass content)	Steel (st37)	Wood (pine)
Compression strength (Mpa)	200	240	8.5
Tensile strength (Mpa)	240	360	8.5
Tensile Elasticity Modulus (Gpa)	23	210	10
Density (gr/cm^3)	1.8	7.85	0.6

CL at the ratios of 0%, 20%, 30%, 40% and 45% in weight were mixed in the sand soil and optimum water content values (w_{opt}) were determined by performing standard Proctor tests on these mixtures (ASTM D698-12). w_{opt} values and soil classification according to Unified Soil Classification System (USCS) are shown for each mixtures in Table 2. The mechanical properties of the FRP, steel and wood materials used in the tests are shown in Table 3.

Table 4 Values of R_a, R_y and R_z of used pile materials

	R_a	R_y	R_z
FRP	2.04	13.90	7.92
Steel	1.53	11.10	6.91
Wood	2.43	17.61	12.53

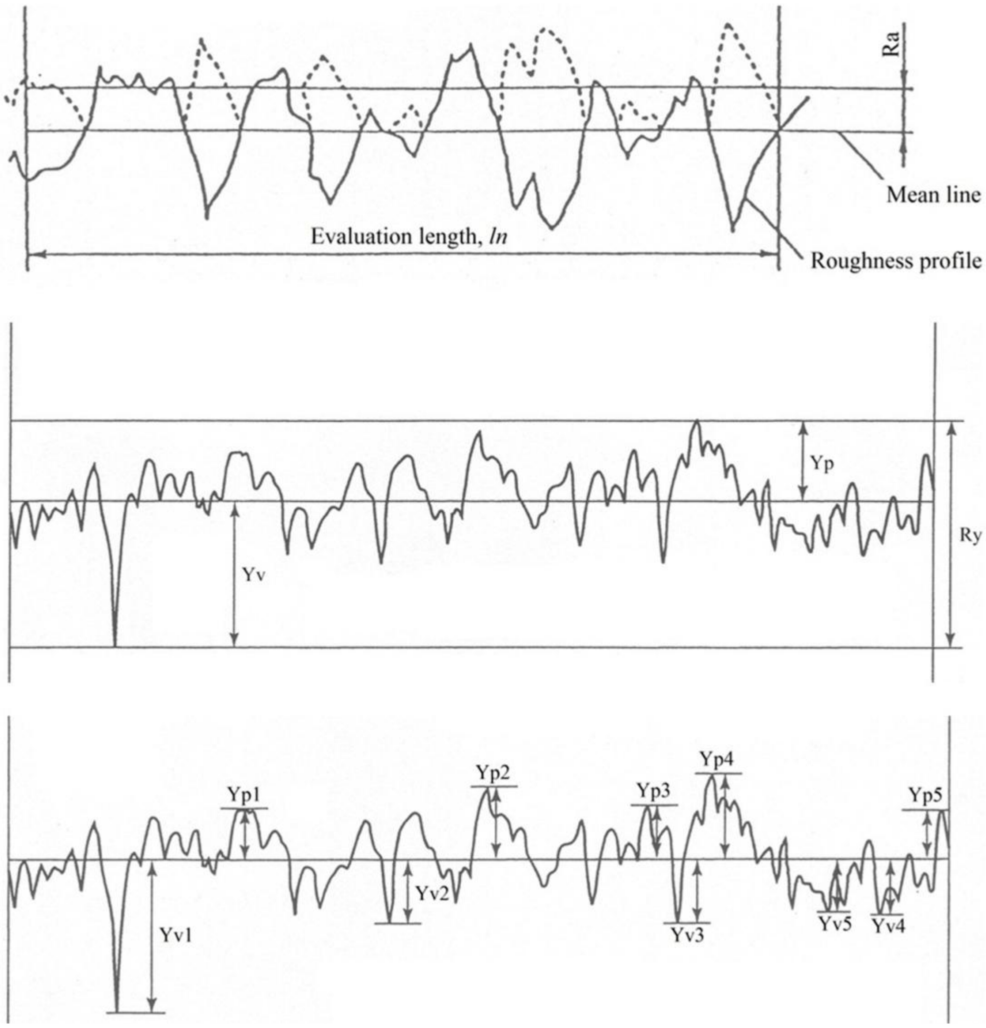

Fig. 2 Determination of surface roughness parameters (R_a, R_y and R_z)

Mutitoyo SJ-201 surface roughness tester was used to determine the surface roughness of the FRP, steel and wood materials. The mean surface roughness parameters obtained as a result of the measurements performed are shown in Table 4. The surface roughness parameters were calculated by using Fig. 2 and Eqs. (1)-(3).

$$R_a = \frac{1}{N}\sum_{i=1}^{N}|Y_i| \tag{1}$$

$$R_y = Y_p + Y_v \tag{2}$$

$$R_z = \frac{1}{5}\sum_{i=1}^{5}Y_{pi} + \frac{1}{5}\sum_{i=1}^{5}Y_{vi} \tag{3}$$

Where, R_a is the arithmetic mean of the absolute values of the profile deviation (Y_i) from the mean line, R_y, is the sum of height Y_p of the highest peak from the mean line and depth Y_v of the deepest valley from the mean line, R_z is the sum of the mean height of the five highest profile peaks and mean depth of five deepest profile valleys measured from a line parallel to the mean line.

When the surface roughness tests were analyzed, it was seen that wood material was the roughest and steel material was the smoothest.

The direct shear test (DST) was performed to determine the internal friction angles (ϕ) of the soil mixtures (ASTM D3080 / D3080M-11). Interface shear tests (IST) were performed in order to determine the skin friction angles (δ) between the prepared soil samples and FRP, steel and wood materials (ASTM D5321/D5321M-14). Test setups can be seen in Figs. 3 and 4. DST and IST tests were performed at a rate of 0.5 mm/min horizontal displacement. Samples prepared at the standard Proctor density and optimum water content were used in DST and IST tests and the results obtained from the tests are shown in Table 5.

Skin friction angle is calculated by using $\delta = 2\phi/3$ equation in most projects. But every material have different skin friction angle with soils. Especially for FRP and wood this equation gives considerably lower δ values than test results. For example, for ϕ = 35° it is calculated that δ = 23.3°. This δ value determined from laboratory tests for FRP and wood as 32.0° and 34.0°

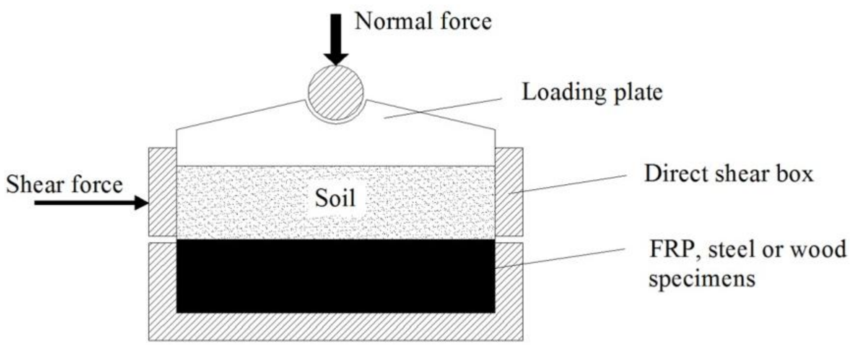

Fig. 3 Sketch of interface shear test setup

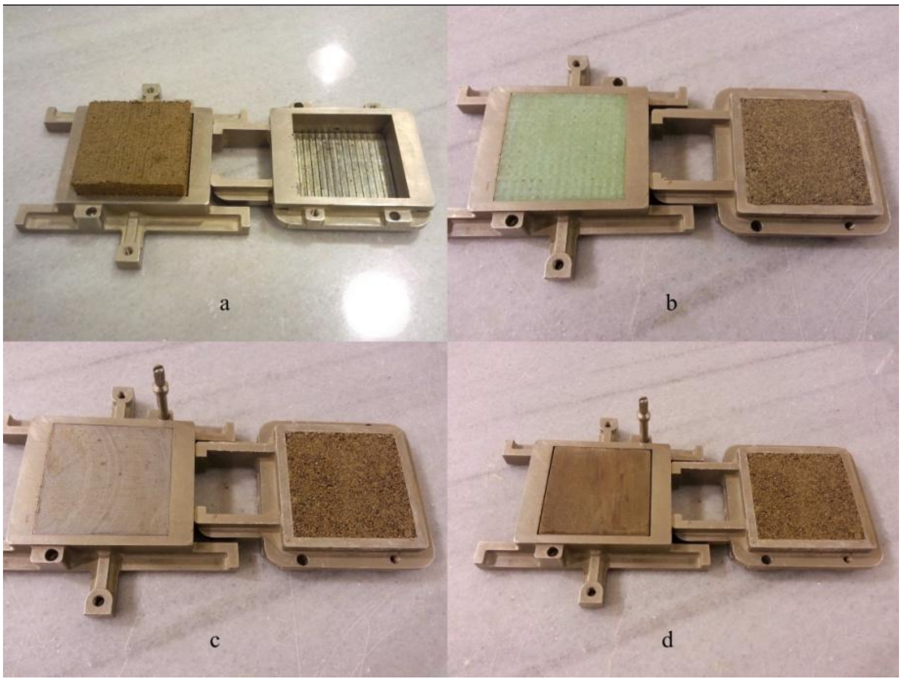

Fig. 4 Direct shear test and interface shear test setup; (a) DST (soil-soil); (b) IST (FRP-soil); (c) IST (steel soil); (d) IST (wood-soil)

Table 5 Direct shear test (DST) and interface shear test (IST) results

Mixture	Internal friction angle of soil, ϕ (°)	Skin friction angle, δ (°)		
		FRP	Steel	Wood
m_0	43.0	34.5	26.5	37.6
m_{20}	39.5	37.0	31.5	40.0
m_{30}	41.5	36.0	29.2	39.0
m_{40}	35.0	32.0	27.0	34.0
m_{45}	28.0	22.7	18.0	24.3

respectively. Therefore, as skin friction angle assumed lower values causes increase in number, diameter and depth of piles. Consequently non-economical designs can be made by using this equation.

3. Skin friction chart

The results obtained from the tests and then evaluated. A skin friction chart was suggested to be used in pile designs (Fig. 5). Thanks to this chart, design engineers will be able to determine the skin friction angles between the soil and FRP, steel and wood materials based on the internal friction angle of soil in the field.

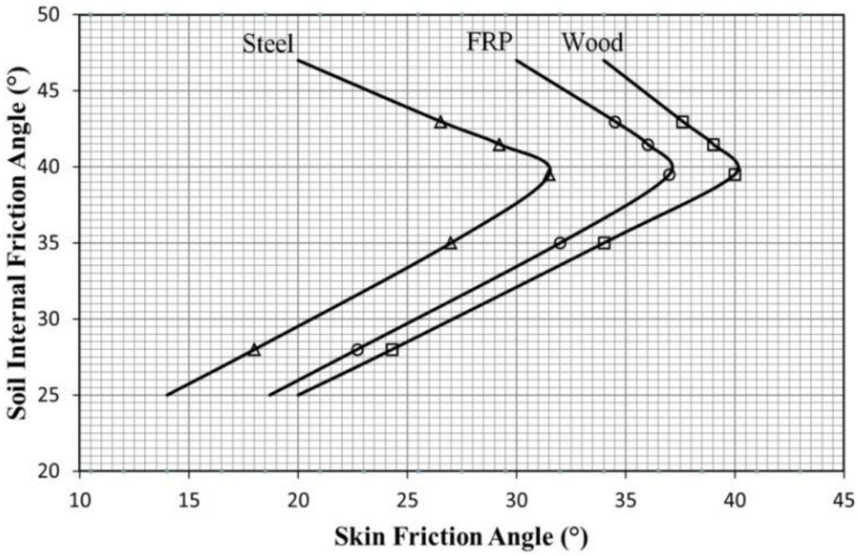

Fig. 5 Skin friction chart for FRP, steel and wood

4. Comparison with other studies in the literature

The results obtained through the chart and the studies carried out in the past years are shown in Table 6. When the table is analyzed, it is seen that the δ values obtained through the chart proposed and the values determined in the study performed by Potyondy (1961) show almost 100%

Table 6 Comparison between chart and other studies

Soil (ϕ) (°)	Potyondy (1961), δ (°)		Pando *et al.* (2002), δ (°)	Sakr *et al.* (2005), δ (°)		Tiwari *et al.* (2010), δ (°)		Tiwari and Al-Adhadh (2014), δ (°)		Skin friction chart, δ (°)			Similarities between literature and skin friction chart (%)		
	Steel	Wood	FRP	Steel	FRP	Steel	Wood	Steel	Wood	Steel	Wood	FRP	Steel	Wood	FRP
31.0	-	-		-	-	24.4	27.1	-	-	21.7	28.3	26.7	89	96	-
31.4	-	-	-	-	-	-	-	26.1	27.2	22.4	29.0	27.4	86	94	-
33.1	-	-	-	-	-	27.6	28.6	-	-	24.6	31.3	29.7	89	91	-
33.3	-	-	-	-	-	28.5	32.3	-	-	24.9	31.8	29.8	87	99	-
33.4	-	-	-	-	-	-	-	27.4	30.2	25.1	32.0	30.0	92	94	-
34.7	-	-	29.2	-	-	-	-	-	-	26.6	33.7	31.4	-	-	93
37.0	-	-	-	26.6	32.3	-	-	-	-	29.1	36.9	34.2	91	-	94
40.0	31.5	37.0	-	-	-	-	-	-	-	31.2	40.0	37.0	99	93	-
43.4	-	-	29.5	-	-	-	-	-	-	25.8	37.2	33.9	-	-	87
44.5	24.2	35.0	-	-	-	-	-	-	-	24.3	36.2	32.8	100	97	-

similarity for steel, while this similarity is around 94% for wood. When results of the chart and the study of Pando *et al*. (2002) are compared, it is seen that the δ values obtained for FRP material show approximately 90% of similarity. When the results of the chart are compared with the study of Sakr *et al*. (2005), the δ values show 91% similarity for steel and 94% for FRP material. And when the results of the chart and the studies of Tiwari *et al*. (2010) and Tiwari and Al-Adhadh (2014) are compared, it is seen that δ values show 90% similarity for steel and 96% for wood.

Consequently, when δ values obtained from the chart and the studies performed in the past are compared, these values show similarity more than 90%. The slight differences around 10% are considered to arise from types of pile materials (glass ratio for FRP, steel hardness and wood types) used in the tests and the use of dry sand in most studies.

5. A practical example of determining of pile skin friction

$$R_S = K_\delta . C_F . p_d . \sin\delta . C_d . D \quad (4)$$

statement, which was given by Nordlund (1963) was used for determining the pile bearing capacity in terms of internal and skin friction angles. Here:

R_s: ultimate shaft capacity
K_δ: coefficient of lateral earth pressure
C_F: correction factor for K_δ
p_d: effective overburden pressure at center of pile
δ: interface friction angle between pile and soil
C_d: pile perimeter
D: pile length

For example, the skin friction angles measured through this chart for a sandy soil with ϕ =34° are 25.8°, 30.7° and 32.5° respectively for steel, FRP and wood. The pile length and diameter were taken respectively as 15 m and 0.5 m. K_δ = 1.89 was taken from the Nordlund design chart and δ / ϕ values were measured as 0.759, 0.903 and 0.956 and the C_F values corresponding to these values were obtained respectively as 0.860, 0.960 and 0.985 (Hannigan *et al*. 1996).

Consequently, the ultimate bearing capacity of steel, FRP and wood piles was calculated respectively as 1874 kN, 2454 kN and 2650 kN through the Eq. (4). The bearing capacities of FRP and wood piles are quite close to each other. However, it was seen that the bearing capacity of FRP piles are 31% more than steel piles.

5. Conclusions

The use of various pile materials considerably changes the angle of skin friction (δ). These changes affect the selections of pile diameter, length and number.

- Surface roughness tests were performed on the materials (FRP, steel and wood) used extensively in the construction of driven pile. It was seen that steel material was the smoothest and wood material was the roughest.
- Bearing capacity of FRP, steel and wood piles with same dimensions were calculated. Bearing capacity of FRP and wood piles are too close. In addition to this, the bearing

capacity of FRP piles is 31% more than steel piles.

- Interface shear tests were conducted on the interfaces between soils and these materials. The skin friction angles between the materials and various soils were measured.
- Soils with internal friction angles ranging between 28° and 43° were used in the tests performed. With the analysis of the data acquired, a chart is proposed which allows obtaining the angle of skin friction to occur between a soil, the internal friction angle of which is known, and various pile materials.
- Many studies performed in the literature and then these studies were compared with the chart proposed and it was observed conformity over 90% in the δ values obtained. In present day, engineers use equations that accept δ values equal for all pile materials ($\delta = 2\phi/3$). This hinders make more economic designs. Realistic skin friction angles (δ) can be determined by means of the chart proposed. Thus, more economic designs can be made by selecting suitable pile diameter, length and number.

When the internal friction angles (ϕ) of sand-clay mixture soils are analyzed, it was observed that ϕ decreases as the clay percentage increases. However, a slight increase occurred in ϕ in any cases where the clay content is around 30%. These slight increases in the internal friction angles of sand-clay mixtures with the increase of the clay content were observed by Dafalla (2013) and Bayoglu (1995) as well.

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