"Effect of Skin Friction on Torque Resistance of a Model Pile"

A

DISSERTATION

Submitted to

DELHI TECHNOLOGICAL UNIVERSITY, DELHI

In partial fulfillment of the requirement for the award of the degree of

Master of Technology
In
Geo-Tech engineering
In
Civil Engineering

Submitted by

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Under the Guidance of

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DELHI TECHNOLOGICAL UNIVERSITY

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Finally I express gratitude to my family for their love and encouragement. I have received so much personal support from family and friends.

Date: 28/07/2016 (Sushant Kamal)

Roll No. 2K14/GTE/19

CERTIFICATE

This is to certify that major project report entitled "**Effect of skin friction on torque resistance of a model pile of varying length"** is an authentic record of my own work carried out in fulfillment of the requirements for the award of Master of Engineering (Geotechnical Engineering), department of Civil Engineering, Delhi Technological University, Delhi under the guidance of Associate Prof. Naresh Kumar.

Dated: 28/07/2016 Sushant Kamal

Roll no: 2K14/GTE/19

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

Associate Prof. Naresh Kumar

Civil Engineering Department,

Delhi Technological University,

Delhi.

ABSTRACT

Tall buildings play a key role in current urban strategies and regeneration. Development of these building presents several problems related to the design and assessment of pile foundations. Among these combinations of vertical, lateral and torsional forces to the piles due to the eccentricity of wind action on vertical projections of multistoried tall buildings is of particular interest.

The Design and analysis of pile foundation present a complex problem to the engineers because of several factors that affect the foundation behaviour. Such factors include mode of loading, soil properties, pile geometry, placement and method of construction .The mode and magnitude of loads transferred from the super structures will influence the selection of pile foundation to resist the imposed loads. Torsional forces are also acting on the pile and IS 2911 for pile foundation has not considered torsional forces for pile designing but it should be considered.

Therefore, objectives of the present work are:

(1) Mechanism of applying torque to a model single pile.

(2)Experimentally to examine basic pile–soil interactions in the modal pile subjected to torque in the context of study torque/angle of twist.

A mechanism of applying torque to a single pile was fabricated. Experiments on single pile were performed. Torque on a single pile was applied using the above said mechanism. Experiments were performed by increasing the depth of a modal pile. When we increased the depth of pile at regular intervals with the different torques for increasing angle of twist till the failure angle of twist is achieved.

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Chapter 1

INTRODUCTION

Some structures such as offshore platforms, tall buildings, electric transmission towers and bridge bents are subjected to lateral loads of significant magnitude due to wave and wind actions, high speed vehicles, or ship impacts. Considerable torsional forces can be transferred to the foundation piles by action of eccentric lateral loading. Insufficient design of the piles against these loads can result in catastrophic consequences. At least four multi-storey buildings have suffered permanent breakage due to wind actions and marked permanent deformations from torsion (Vickery 1979).

Large diameter bored piles are usually used to support bridges and tall buildings, because such piles can sustain large loads. However, various deformity can be left in a pile even though care is taken during pile construction. Wong (2004) conducted a real survey on quality assurance for bored pile built in Hong Kong. Among these all types of pile defects, cavities in the pile shaft, and soft toes (eg, soil inclusions and unbound aggregate), and short piles that are not founded at the deputed rock level are reported to occur sometimes. Poulos (1997, 2005) suggested that defects in bored piles can be divided into two categories: geotechnical defects and structural defects. Structural defects are those related to the strength, size and stiffness of the completed piles being less than assumed in design, such as honeycombs, necking, soil seams, and cracks along the shaft. Geotechnical defects are related to either construction related problems such as short piles, toe debris, and over break cavities or misassessment of in situ conditions during design.

Piers are key of bridges, which are commonly subjected to eccentrically horizontal loads from high speed vehicles, wind or even ship impacts. Therefore, torsional resistances of their foundations are very important for bridges. Insufficient design of the foundations against these loads leads to disastrous consequences.

Chapter 2

Literature Review

2.0 Torsion of circular shafts

2.1 Definition of Torsion: Consider a shaft rigidly clamped at one end and twisted at the other end by a torque T = F.d applied in a plane perpendicular to the axis of the bar such a shaft is said to be in torsion. SI unit of torque is N-m.

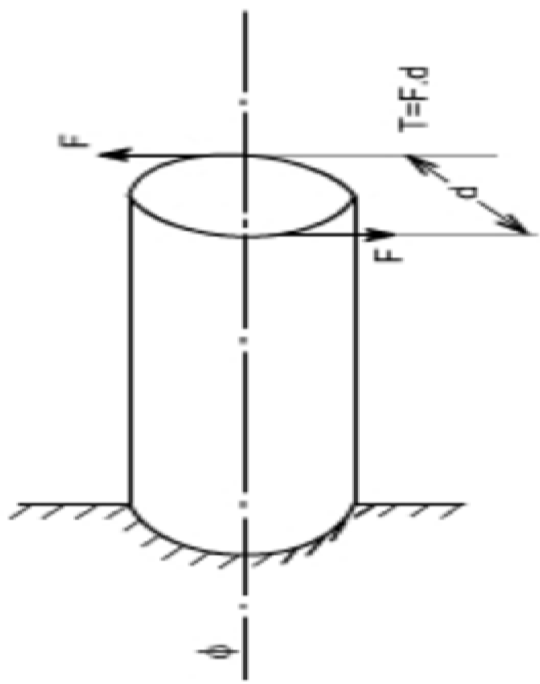


Fig2.0: Torsional force acting on circular shaft

2.2 Effects of Torsion: The effects of a torsional load applied to a bar are

(i) To impart an angular displacement of one end cross – section with respect to the other end.

(ii) To setup shear stresses on any cross section of the bar perpendicular to its axis.

2.3 Generation of shear stresses

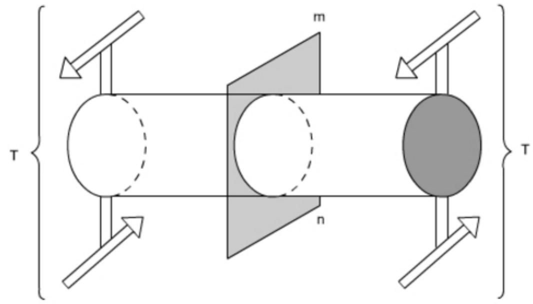


Fig2.1: Here the cylindrical member or a shaft is in static equilibrium where T is the resultant external torque acting on the member. Let the member be imagined to be cut by some imaginary plane ‘mn'.

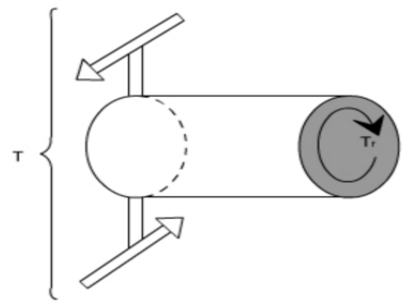


Fig2.2: When the plane ‘mn' cuts remove the portion on R.H.S. and we get a fig2.2. Now since the entire member is in equilibrium, therefore, each portion must be in equilibrium. Thus, the member is in equilibrium under the action of resultant external torque T and developed resisting Torque T_r.

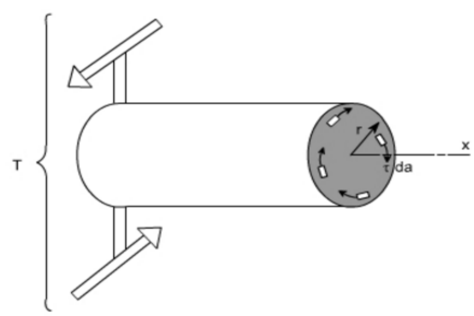


Fig2.3: The Figure shows that how the resisting torque T_r is developed. The resisting torque T_r is produced by virtue of an infinites mal shear forces acting on the plane perpendicular to the axis of the shaft. Obviously such shear forces would be developed by virtue of sheer stresses.

Therefore we can say that when a particular member (say shaft in this case) is subjected to a torque, the result would be that on any element there will be shear stresses acting. While on other faces the complementary sheer forces come into picture. Thus, we can say that when a member is subjected to torque, an element of this member will be subjected to a state of pure shear.

2.4 Twisting Moment

The twisting moment for any section along the bar / shaft is defined to be the algebraic sum of the moments of the applied couples that lie to one side of the section under consideration. The choice of the side in any case is of course arbitrary.

2.5 Shearing Strain

If a generator a – b is marked on the surface of the unloaded bar, then after the twisting moment 'T' has been applied this line moves to ab'. The angle ‘γ' measured in radians, between the final and original positions of the generators is defined as the shearing strain at the surface of the bar or shaft. The same definition will hold at any interior point of the bar.

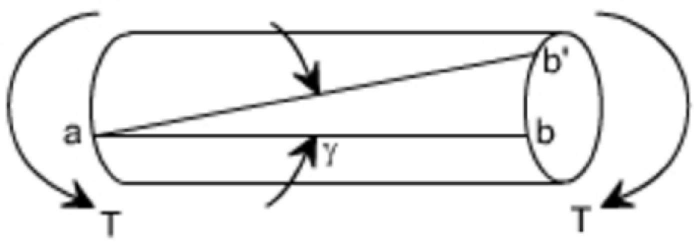


Fig2.4: shaft under torsion showing shearing strain

2.6 Modulus of Elasticity in shear

The ratio of the shear stress to the shear strain is called the modulus of elasticity in shear OR Modulus of Rigidity and is represented by the symbol G. SI unit is pascal (Pa).

$$G = \frac{\tau}{\epsilon}$$

2.7 Angle of Twist

If a shaft of length L is subjected to a constant twisting moment T along its length, than the angle ϴ through which one end of the bar will twist relative to the other is known is the angle of twist. ϴ in radian.

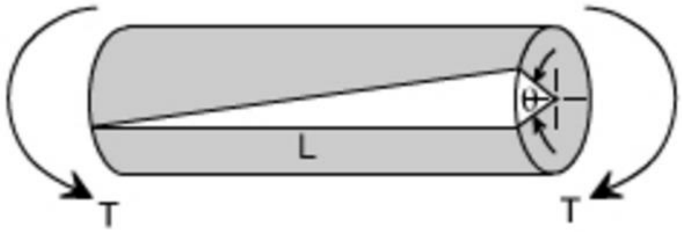


Fig2.5: shaft under torsional force

2.8 Relationship in Torsion

$$\frac{\tau}{R} = \frac{T}{J} = \frac{G\theta}{L}$$

T = Torsion force (N-m)

J = Polar moment of inertia (m^4)

Polar moment of inertia for hollow cylindrical shaft = $J = \frac{\pi}{32}\left(D^4 - d^4\right)$

D= external diameter

d= internal diameter

R = Radius of cross-section of circular shaft (m)

τ = Shear stress (MPa)

G = shear modulus (GPa)

Ɵ = Angle of twist (radian) {1 radian = $\frac{180}{\pi}$ degree}

L = Length of shaft (m)

Strain energy (U) of the modal cylindrical pile is equal to the work done by the load, provided no energy is gained or lost in the form of heat. (Joules) $U = \frac{1}{2}T\Theta$ (joules)

2.9 Torsional resistance of single pile in layered soil

The analysis and solutions presented are based on Randlph's (1981) simplified elastic model of a beam on elastic foundation using the Winkler approximation.

Fig. 2.6 shows a pile embedded in a two layered soil with homogeneous variation of shear modulus with depth in each layer and fig. 2.7 a pile embedded in two layered Gibson soil.

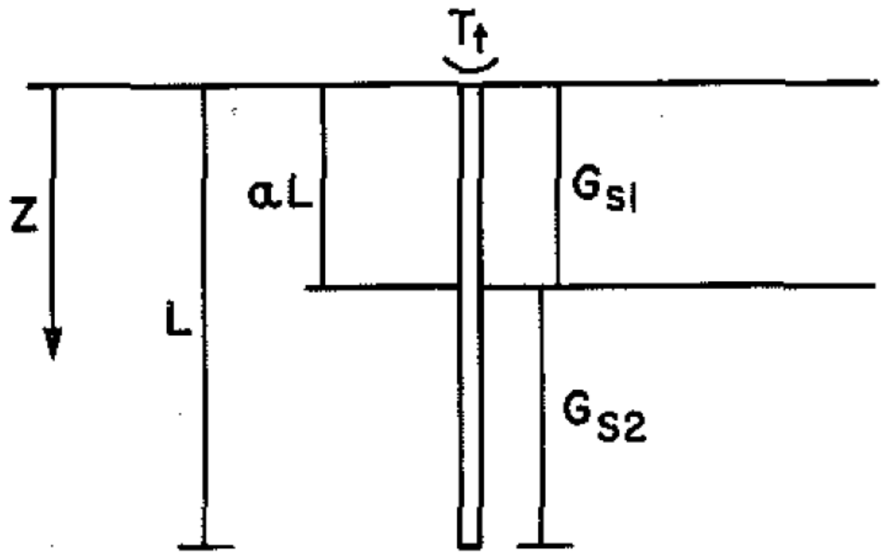


Fig 2.6: Pile in two layered soil: homogenous layers (Hache and Valsangkar 1988)

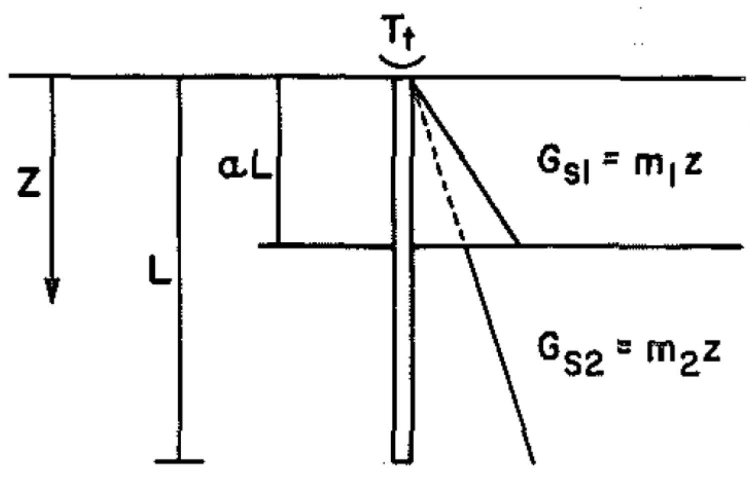


Fig 2.7: Pile in two layered soil: nonhomogeneous layers (Hache and Valsangkar 1988)

L = length of a pile

Z = downward depth of soil surface

aL = depth of soil layer 1

2.10 Numerical solution of single pile subjected to simultaneous torsional and axial loads

The application of eccentric horizontal forces on the structures causes torsional forces on the pile foundation, apart from other complex loading conditions such as pullout loads, moments, and so on. Examples of such loading includes bridge piers, high rise buildings, electric transmission towers and offshore structures subjected to wave forces and wind, ship impacts and high speed vehicles (Azadi et al. 2008).

When group of pile is subjected to torsion, the piles undergo lateral displacement along with twisting and thus the applied load is transmitted to the pile head in the form of torsional and lateral force components (Basile 2010).

Piles can be loaded to failure more simply by torsional loading compared to other modes of loadings, which necessitates the significance of analyzing pile-soil-pile interactive performance under torsion (Zhang and Kong 2006; Zhang 2010).

2.10.1 Numerical analysis

Idealized problem is presented in fig.2.8a,b,c. A single vertical floating cylindrical pile having internal diameter D_i and external diameter D.

Young's modulus E_p, torsional rigidity $J_P G_P$ is fix in a elastoplastic subsoil medium up to depth L below the ground surface. Under the simultaneous actions of axial load V_t and torque T_t , the vertical shear stresses $\tau_v(z)$ and interface horizontal $\tau_t(z)$,

Base stresses τ_b and σ_b are developed on vertical surface and the pile base. The primary objective is to assess the distribution of these stresses on the interface and then to compute displacements and other admissible parameters.

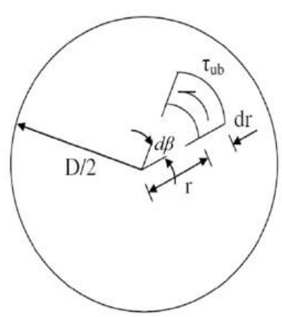


Fig 2.8a: Idealized problem: determination of base resistance
(Basack and Sankhasubhra Sen 2014)

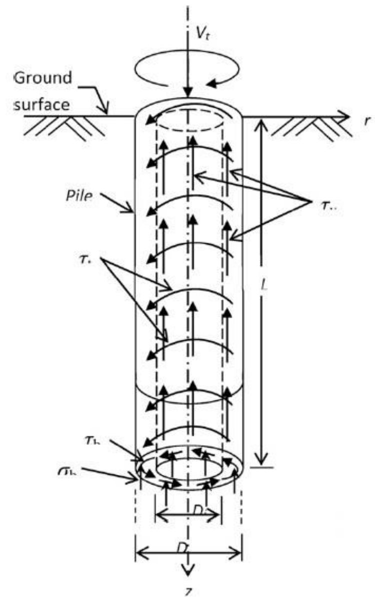


Fig 2.8b: Idealized problem: interface stresses on pile (Basack and Sankhasubhra Sen 2014)

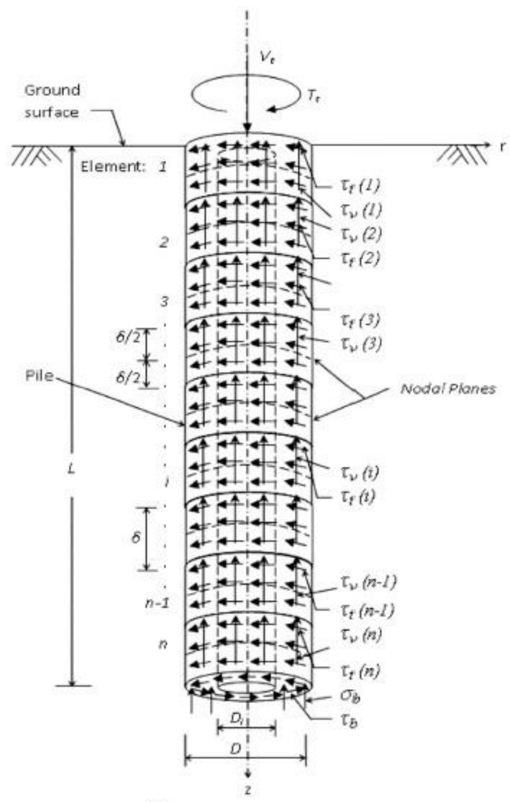


Fig 2.8c: Idealized problem: boundary-element discretization of the pile

(Basack and Sankhasubhra Sen 2014)

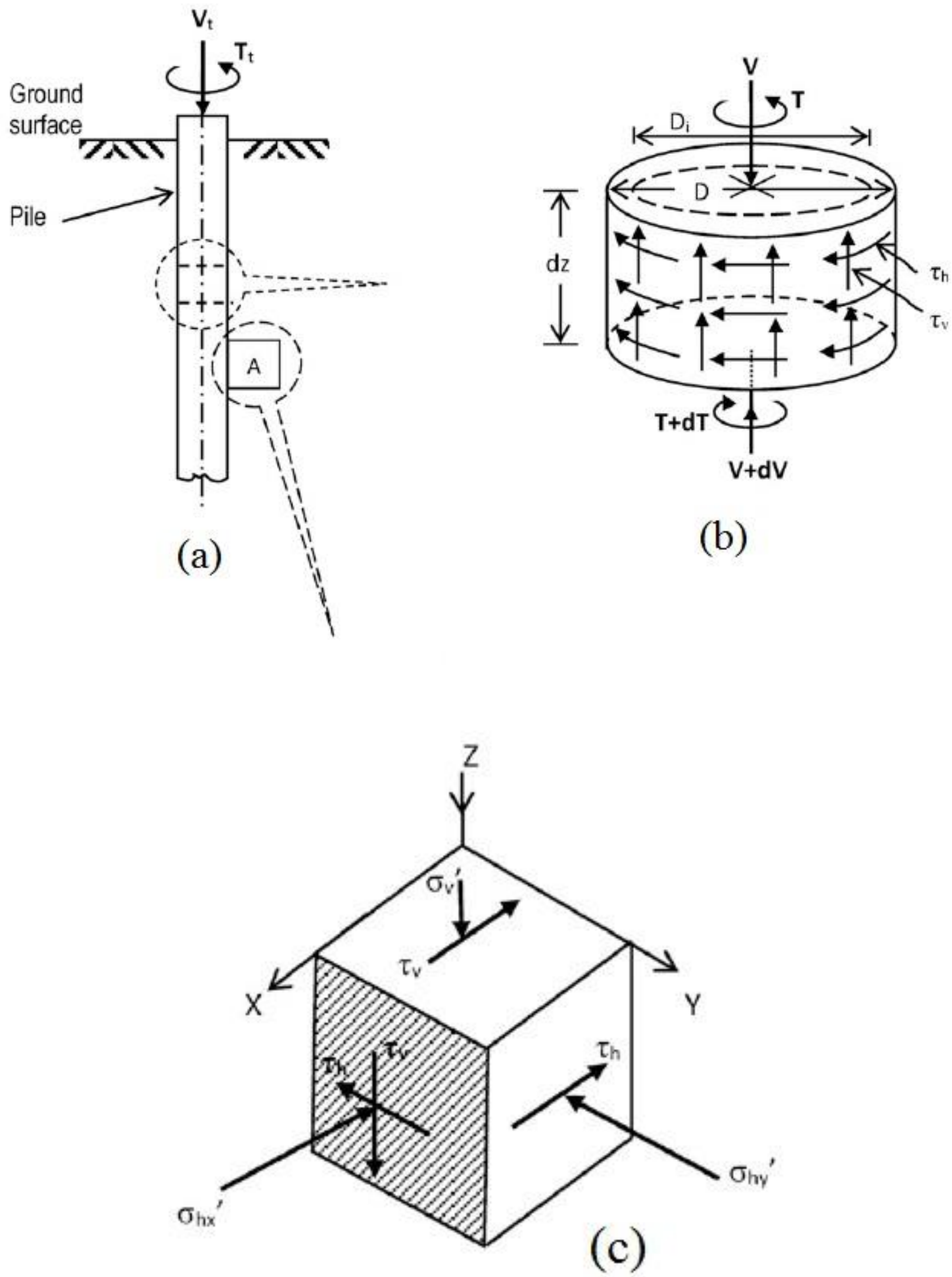


Fig 2.9: Theoretical considerations :(a) pile under combined loading ;(b) pile element with stresses on surface ;(c) typical soil element (Basack and Sankhasubhra Sen 2014)

Boundary element solution for picture pile-soil interactive performance under simultaneous axial loads and torsion has been developed, considering soil nonlinearity and effect of pile soil slippage. Comparison of BEM results with experimental data available and existing solutions justifies the power of the proposed model. From selected parameter study, the ultimate torsional pile capacity is found to be affected by axial load.

The ground line torque twist response has been observed as hyperbolic and continuously degrading with increase in the axial load.

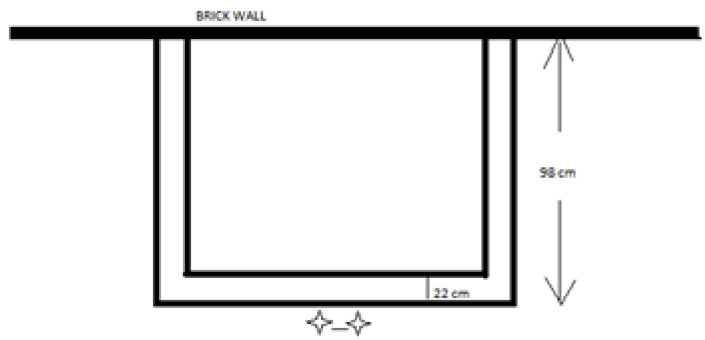
In cases of clay and sand, the horizontal and resultant shear stresses increases linearly with depth until a peak value is attained, following a sharp curvilinear decrement. The vertical shear-stress profiles are curvilinear and decrease with depth. Profile for twist angle is parabolic.

Chapter 3

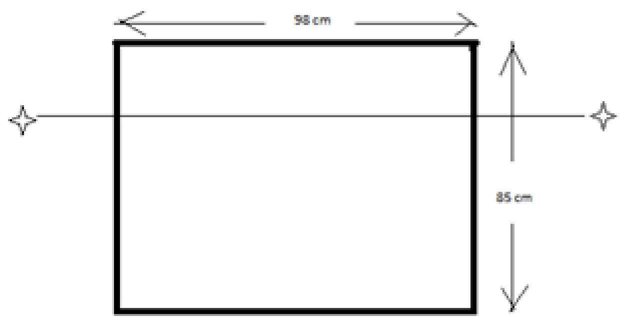
Experimental Setup

3.0 Construction of pit

Suitable site was selected, in the soil mechanics laboratory. Fig shows the construction of pit. Construction of pit was done by myself and my cousin brother Er. Prashant Kumar.



Cross section plan view of pit



Side view of brick pit

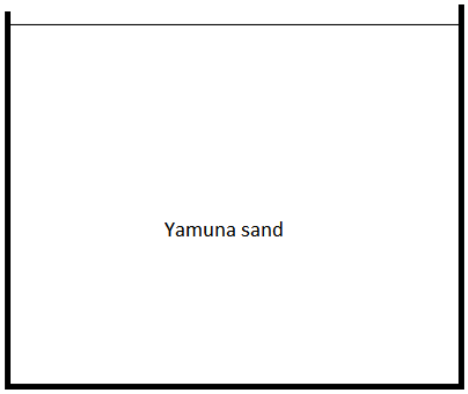
fig 3.1: real image of pit on left and plan view, side view of pit on right

Pit has length, breadth and depth of 98cm, 98cm, and 85cmrespectively. Local building material such as cement, fine aggregates and coarse aggregates were transported to the site. Approximately 1 cubic meter of Yamuna sand was transported to the site of interest. Transported Yamuna sand was laid on the dry floor in layers. Then sand was dried under sun for a weak.

3.1 Drying and filling of Yamuna sand

Approximately, 1 cubic meter of Yamuna sand was filled in the pit. It was transported to the site in polypropylene bags from building materials shop near DTU College. I have filled the pit in three layers. On the first day 3 bags of sand was transported to the site and then dried up for next 7 days and after drying it was filled in the pit. Similarly in next filling of 3 bags of sand it was firstly dried for one weak and then filled in the pit. Then at last pit was filled with 4 dried sand bags ,total 10 Yamuna sand bags was filled in the pit to complete nearly 1 cubic meter sand volume.

Fig 3.2: Yamuna sand in brick made pit



3.2 Placing of girders and inclined pulley

After filling the sand in the pit, the girders were transported to the site. I have used two T – shaped steel channel sections which are 1.10 m in length each. They were fixed on the brick wall pit and each girder was hold fasted about 10 cm inside the laboratory wall.

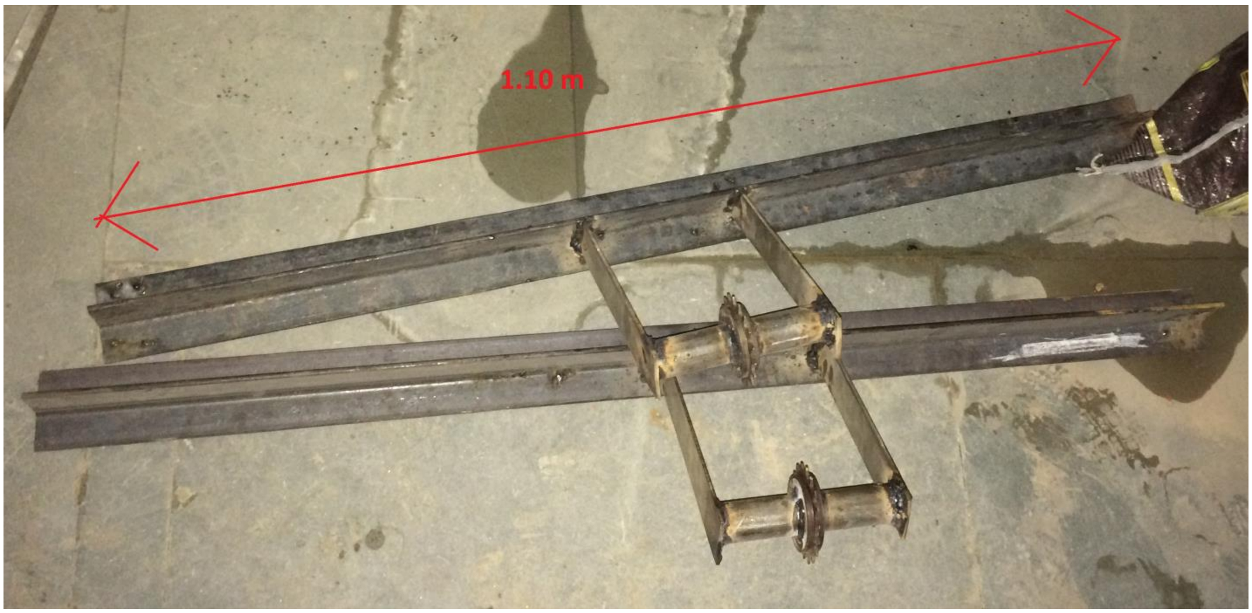


Fig3.3: girders with pulley welded together

Fig3.4: girder fixed on top of brick wall and pulley inclined at 45° with vertical

Fig3.5: myself drilling hole in wall to insert a part of girder

Each girder was welded with inclined rods on which pulley was fixed. Rods were 45° inclined with vertical as shown in the fig3.4.

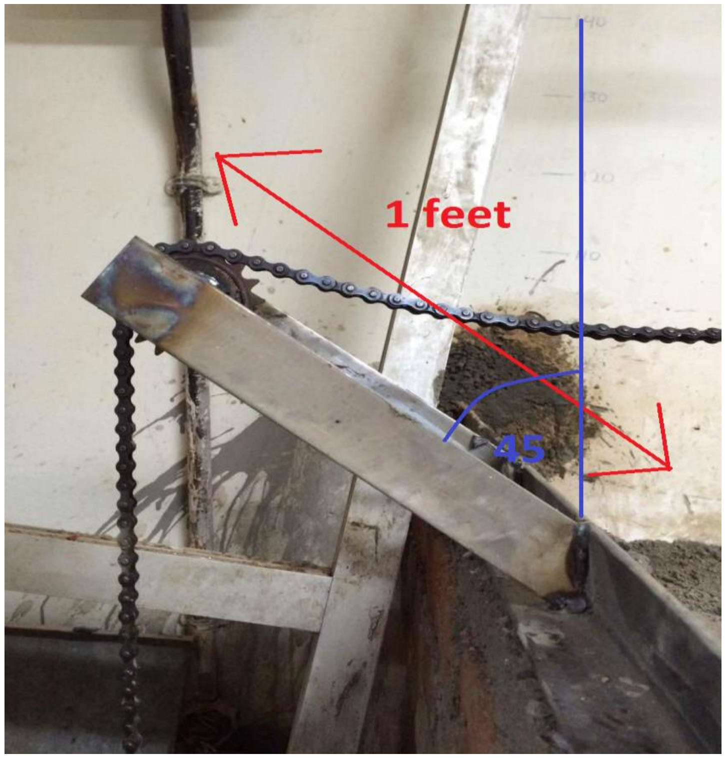


Fig3.6: pulley making an angle of 45° with vertical

Fig3.7: chain in high tension carrying heavy load to apply torque on pile

3.3 Manufacturing of single pile

Single pile was manufactured. Mild steel pile was used for manufacturing of the pile. Steel pile used is hollow of 30 mm diameter and 90 cm length.

Fig3.8: steel modal pile of 90cm length

A solid cone of mild steel is attached to the end of the hollow pile. Cone is provided so it can be driven into the soil easily. Solid cone is made with the help of cutter and lathe machine as shown in fig 3.9.

fig3.9: manufacturing of pile

3.4 Arrangement to apply pure torsional force on the pile

Two sprockets are welded on the top most end of the steel pile .they are welded up and down in horizontal and chain is wrapped around each sprocket. Mechanism is made in such a manner that when both chains are pulled together by same force they will produce combined additive torsional force acting on the pile and steel pile will rotate.

Fig3.10: welding of sprockets on modal steel pile

Fig3.11: complete view of apparatus.

Fig3.12: fixing girders together with steel rods

When loads are hanged on both the opposite sides of the chain, chain will be in tension and as per increasing load, torque acting on the pile also increases simultaneously. While torque acting on the pile, pile rotates on its longitudinal axis and angle of twist is calculated as shown in fig 3.13.

Fig3.13: calculation of angle of twist

3.5 Experimental procedure

Arrangement was also made so that standard weights may be loaded with the help of pulley and high tensile chains. Photo shows the arrangement of pile. Experiment is done on loose Yamuna sand. each day one set of experiment were performed, which included tests results and showing in graphical manner how angle of twist varies with defined loads while increasing the depth of the pile.

For each addition of weight on a hanger, angle of twist was noted in a field book.

Mathematically,

$$F = m \times g \text{ (N)}$$

$$T = 2 \times F \times r \text{ (N-m)}$$

Where, F = Applied force (N)

m = Mass loaded on hanger (kg)

g = Acceleration due to gravity (9.81 m/s²)

T = torque applied (N-m)

r = $\frac{1}{2}$[External pile diameter] + [thickness of the sprocket + $\frac{1}{2}${thickness of the chain}] = 3.5cm

Fig3.14: complete upper view of mechanism

Fig3.15: elevation view of mechanism producing torque in pile

Chapter 4

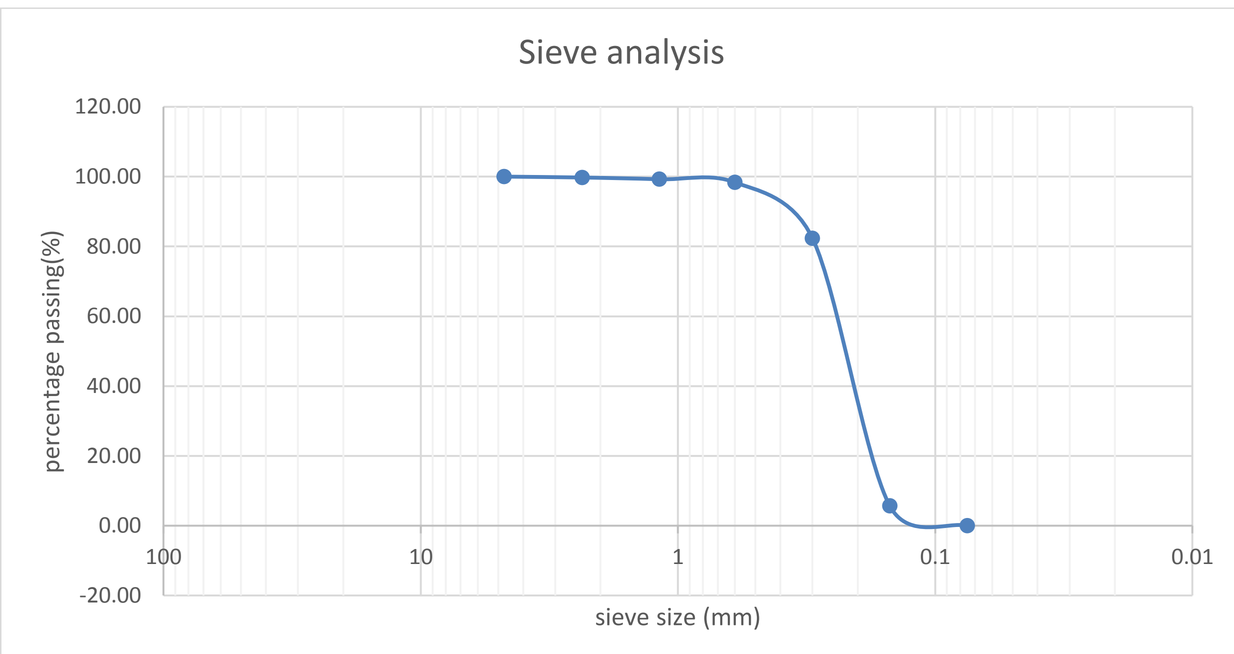
Results and discussion

4.0 Sieve analysis

Sieve analysis was performed in the laboratory of the sand sample taken from the site of interest and observation sheet is prepared as follows:-

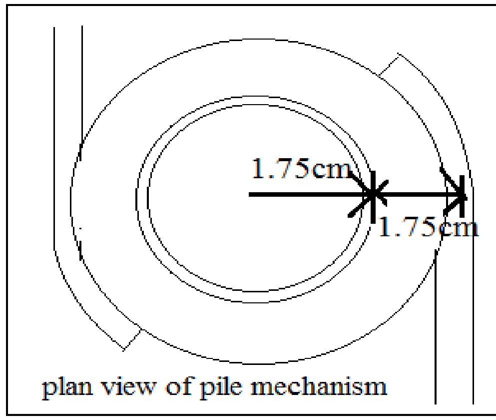
S.No.	IS Sieve	Particle size D(mm)	Mass retained(g)	%Retained	Cumulative% retained	Cumulative% finer(N)
1.	4.75mm	4.75mm	0	0	0.00	100.00
2.	2.36mm	2.36mm	2.6	0.26	0.26	99.74
3.	1.18mm	1.18mm	4.70	0.47	0.76	99.24
4.	600µ	0.600mm	8.75	0.88	1.67	98.33
5.	300µ	0.300mm	154.25	15.43	17.64	82.36
6.	150µ	0.150mm	740.80	74.08	94.34	5.66
7.	75µ	0.075mm	54.60	5.46	100.00	0.00

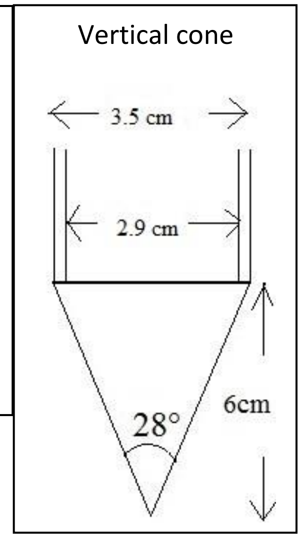
Table 4.1: Sieve analysis



Graph 4.0: sieve analysis

4.1 Experimental study of single pile

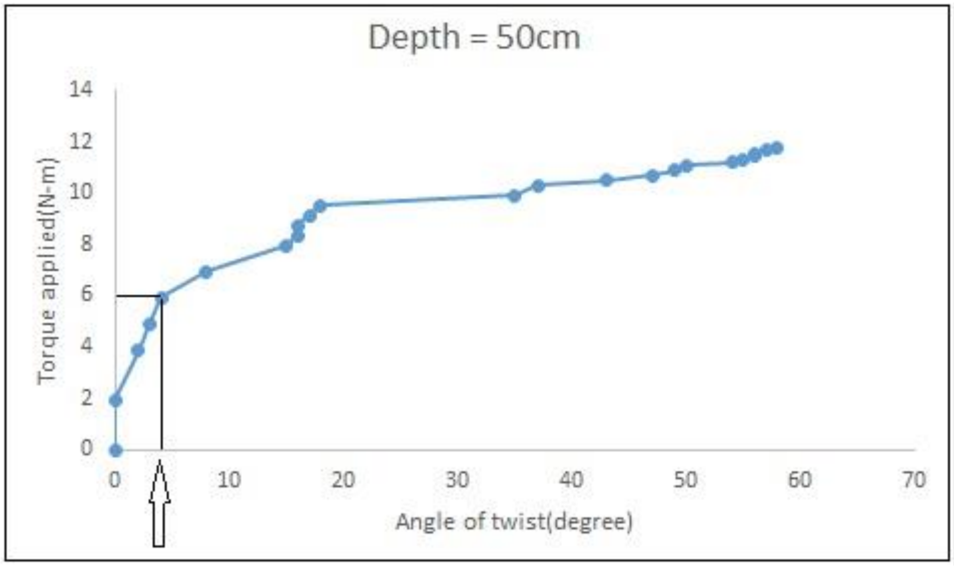




1. External pile diameter = 3.5 cm
2. Pile length = 90 cm
3. Pile depth inside Yamuna sand = 50 cm
4. Pile material = stainless steel
5. Pile thickness = 3 mm
6. Length of the spoke for measuring angle = 8cm
7. Thickness of the sprocket + $\frac{1}{2}${thickness of the chain} = 1.75 cm
8. r = $\frac{1}{2}$[External pile diameter] + [thickness of the sprocket + $\frac{1}{2}${thickness of the chain}] = 3.5cm

S no.	Mass (kg)	Force = mg (N)	Torque =2 x F x r (N-m)	Angle of twist Θ (degree)	Angle of twist Θ (radian)	Strain energy U = $\frac{1}{2}$TΘ (joule)
1	2.82	27.66	1.94	0	0	0
2	5.64	55.33	3.87	2	0.035	0.067
3	7.13	69.95	4.90	3	0.052	0.127
4	8.62	84.56	5.92	4	0.070	0.207
5	10.11	99.18	6.94	8	0.140	0.486
6	11.6	113.80	7.97	15	0.262	1.044
7	12.17	119.39	8.36	16	0.279	1.166
8	12.74	124.98	8.75	16	0.279	1.221
9	13.31	130.57	9.14	17	0.279	1.357
10	13.88	136.16	9.53	18	0.314	1.496
11	14.45	141.75	9.92	35	0.611	3.031
12	15.02	147.35	10.31	37	0.646	3.330
13	15.30	150.09	10.51	43	0.750	3.941
14	15.58	152.84	10.70	47	0.820	4.387
15	15.86	155.59	10.89	49	0.855	4.655
16	16.14	158.33	11.08	50	0.873	4.836
17	16.31	160.00	11.20	54	0.942	5.275
18	16.48	161.67	11.32	55	0.960	5.434
19	16.65	163.34	11.43	56	0.977	5.584
20	16.82	165.00	11.55	56	0.977	5.642
21	16.99	166.67	11.67	57	0.995	5.806
22	17.16	168.34	11.78	58	1.012	5.961

Table4.2: torque applied and twist angle for depth 50cm of modal pile



Graph4.1: measured torque-twist angle curve for modal pile depth 50cm in sand

$\frac{torque}{angle\ of\ twist} = \frac{5.92}{4} = 1.48 = Z_{C1}$ (Critical torque factor, for pile depth 50cm), failure point of soil at 4° angle of twist.

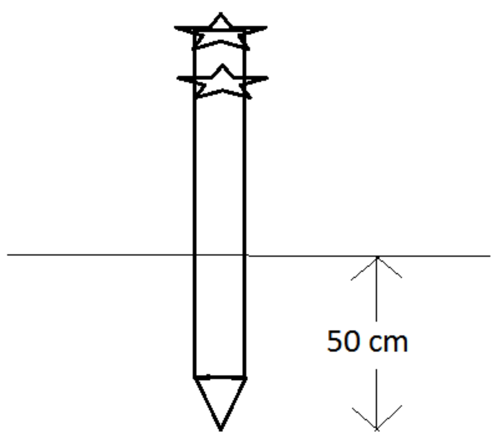
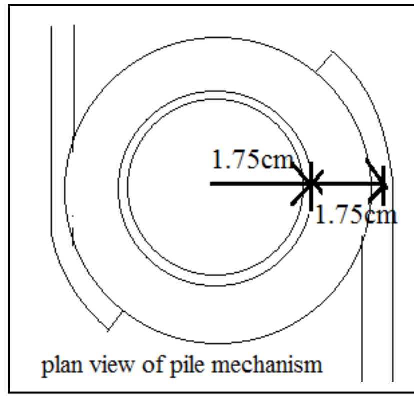
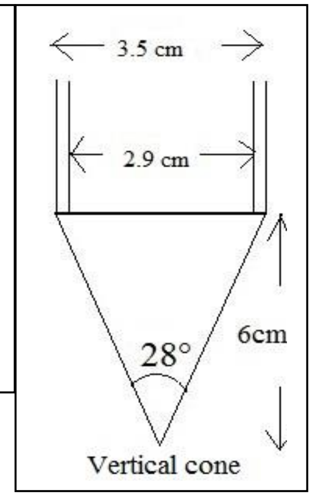


Fig4.1: pile interested inside sand to 50cm of depth

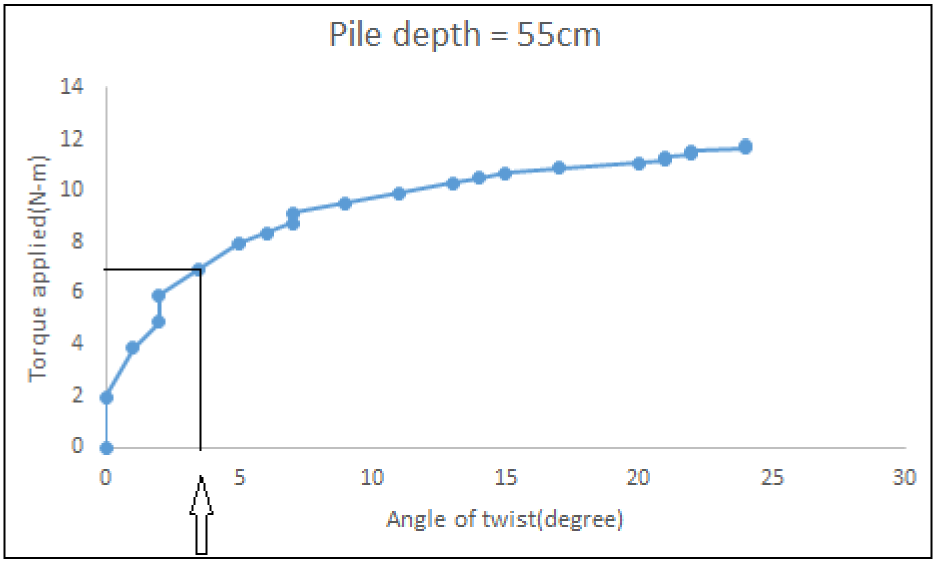




1. External pile diameter = 3.5 cm
2. Pile length = 90 cm
3. Pile depth inside Yamuna sand = 55 cm
4. Pile material = stainless steel
5. Pile thickness = 3 mm
6. Length of the spoke for measuring angle = 8cm
7. Thickness of the sprocket + $\frac{1}{2}${thickness of the chain} = 1.75 cm
8. r = $\frac{1}{2}$[External pile diameter] + [thickness of the sprocket + $\frac{1}{2}${thickness of the chain}] = 3.5cm

S no.	Mass (kg)	Force = mg (N)	Torque =2 x F x r (N-m)	Angle of twist Ө	Angle of twist Ө (radian)	Strain energy $U = \frac{1}{2}TΘ$ (joule)
1	2.82	27.66	1.94	0°	0	0
2	5.64	55.33	3.87	1°	0.017	0.033
3	7.13	69.95	4.90	2°	0.035	0.086
4	8.62	84.56	5.92	2°	0.035	0.104
5	10.11	99.18	6.94	3.5°	0.061	0.212
6	11.6	113.80	7.97	5°	0.087	0.347
7	12.17	119.39	8.36	6°	0.105	0.439
8	12.74	124.98	8.75	7°	0.122	0.534
9	13.31	130.57	9.14	7°	0.122	0.558
10	13.88	136.16	9.53	9°	0.157	0.748
11	14.45	141.75	9.92	11°	0.192	0.952
12	15.02	147.35	10.31	13°	0.227	1.170
13	15.30	150.09	10.51	14°	0.244	1.282
14	15.58	152.84	10.70	15°	0.262	1.402
15	15.86	155.59	10.89	17°	0.297	1.617
16	16.14	158.33	11.08	20°	0.349	1.933
17	16.31	160.00	11.20	21°	0.367	2.055
18	16.48	161.67	11.32	21°	0.367	2.077
19	16.65	163.34	11.43	22°	0.384	2.195
20	16.82	165.00	11.55	22°	0.384	2.218
21	16.99	166.67	11.67	24°	0.419	2.445
22	17.16	168.34	11.78	24°	0.419	2.468

Table4.3: torque applied and twist angle for depth 55cm of modal pile



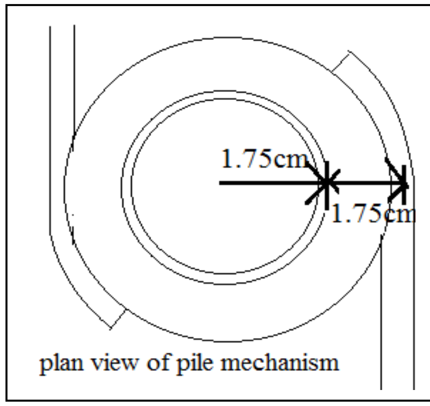
Graph4.2: measured torque-twist angle curve for modal pile depth 55cm in sand

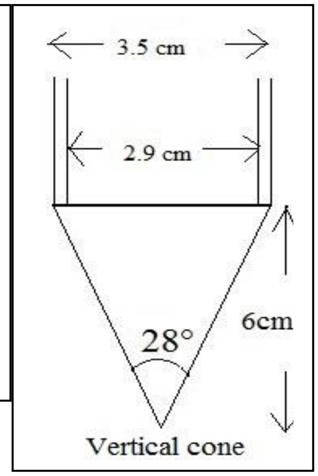
$\frac{Torque}{Angle\ of\ twsit} = \frac{6.94}{3.5} =$ 1.98=Z_{C2}(critical torque factor, for pile depth 55cm), failure point of soil at 3° angle of twist.

$Z_{C2} > Z_{C1}$

Fig4.2: pile interested inside sand to 55cm of depth

1. External pile diameter = 3.5 cm
2. Pile length = 90 cm
3. Pile depth inside Yamuna sand = 60 cm
4. Pile material = stainless steel
5. Pile thickness = 3 mm
6. Length of the spoke for measuring angle = 8cm

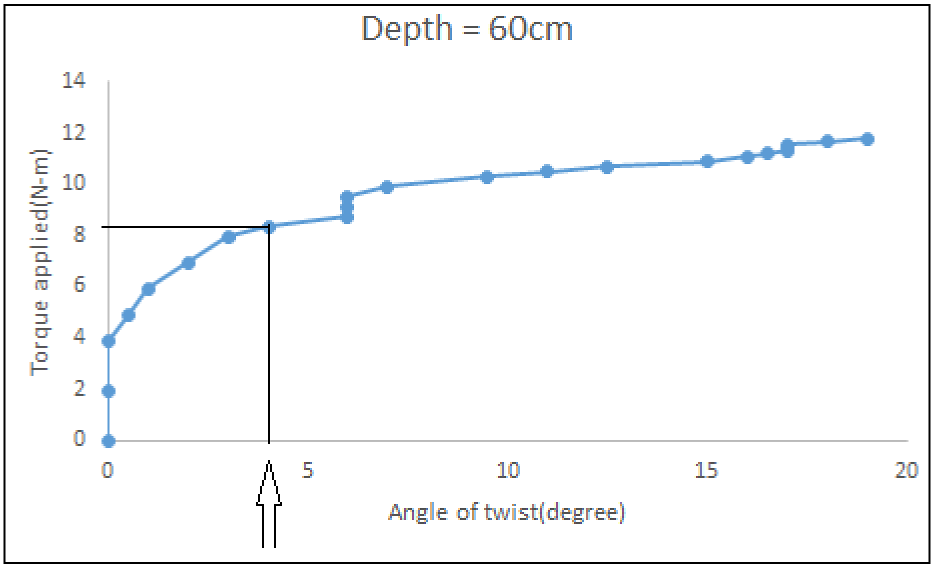




7. Thickness of the sprocket + $\frac{1}{2}${thickness of the chain} = 1.75 cm
8. r = $\frac{1}{2}$[External pile diameter] + [thickness of the sprocket + $\frac{1}{2}${thickness of the chain}] = 3.5cm

S no.	Mass (kg)	Force = mg (N)	Torque =2 x F x r (N-m)	Angle of twist Ø	Angle of twist Ø (radian)	Strain energy U = $\frac{1}{2}$TØ (joule)
1	2.82	27.66	1.94	0°	0	0
2	5.64	55.33	3.87	0°	0	0
3	7.13	69.95	4.90	0.5°	0.009	0.022
4	8.62	84.56	5.92	1°	0.017	0.050
5	10.11	99.18	6.94	2°	0.035	0.121
6	11.6	113.80	7.97	3°	0.052	0.207
7	12.17	119.39	8.36	4°	0.070	0.293
8	12.74	124.98	8.75	6°	0.105	0.459
9	13.31	130.57	9.14	6°	0.105	0.480
10	13.88	136.16	9.53	6°	0.105	0.500
11	14.45	141.75	9.92	7°	0.122	0.605
12	15.02	147.35	10.31	9.5°	0.166	0.856
13	15.30	150.09	10.51	11°	0.192	1.009
14	15.58	152.84	10.70	12.5°	0.218	1.166
15	15.86	155.59	10.89	15°	0.262	1.427
16	16.14	158.33	11.08	16°	0.279	1.546
17	16.31	160.00	11.20	16.5°	0.288	1.613
18	16.48	161.67	11.32	17°	0.297	1.681
19	16.65	163.34	11.43	17°	0.297	1.697
20	16.82	165.00	11.55	17°	0.297	1.715
21	16.99	166.67	11.67	18°	0.314	1.832
22	17.16	168.34	11.78	19°	0.332	1.955

Table4.4: torque applied and twist angle for depth 60cm of modal pile



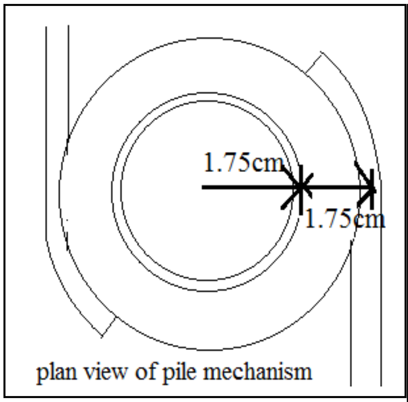
Graph4.3: measured torque-twist angle curve for modal pile depth 60cm in sand

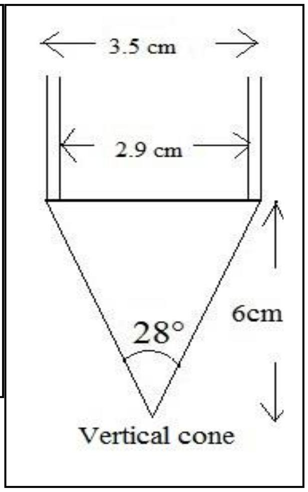
$\frac{Torque}{Angle\ of\ twsit} = \frac{8.36}{4} =$ 2.09=Z_{C3}(critical torque factor, for pile depth 60cm), failure point of soil at 4° angle of twist.

$Z_{C3} > Z_{C2} > Z_{C1}$

Fig4.3: pile interested inside sand to 60cm of depth

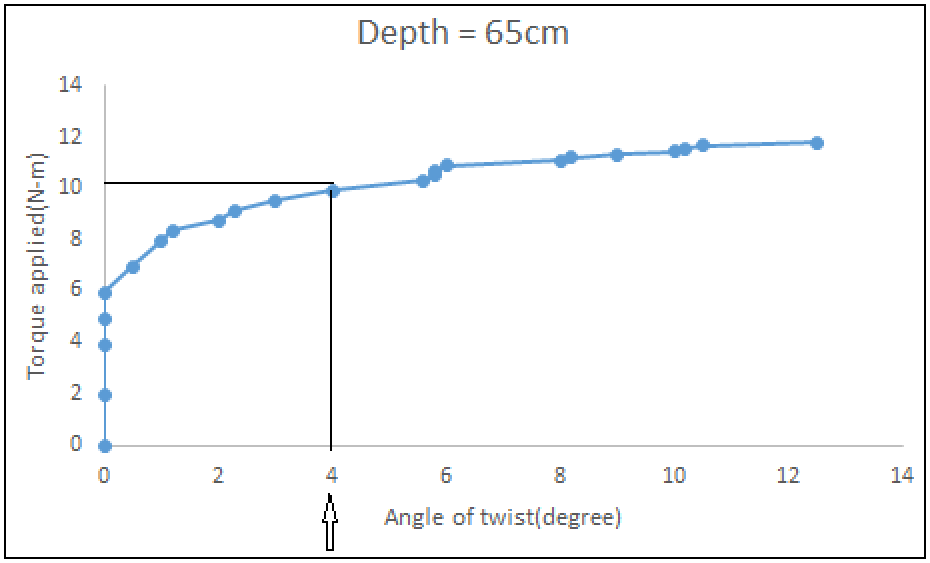
1. External pile diameter = 3.5 cm
2. Pile length = 90 cm
3. Pile depth inside Yamuna sand = 65 cm
4. Pile material = stainless steel
5. Pile thickness = 3 mm
6. Length of the spoke for measuring angle = 8cm
7. Thickness of the sprocket + $\frac{1}{2}$\{thickness of the chain\} = 1.75 cm
8. r = $\frac{1}{2}$[External pile diameter] + [thickness of the sprocket + $\frac{1}{2}$\{thickness of the chain\}] = 3.5cm





S no.	Mass (kg)	Force = mg (N)	Torque =2 x F x r (N-m)	Angle of twist Ø	Angle of twist Ø (radian)	Strain energy $U = \frac{1}{2}TØ$ (joule)
1	2.82	27.66	1.94	0°	0	0
2	5.64	55.33	3.87	0°	0	0
3	7.13	69.95	4.90	0°	0	0
4	8.62	84.56	5.92	0°	0	0
5	10.11	99.18	6.94	0.5°	0.009	0.031
6	11.6	113.80	7.97	1°	0.017	0.068
7	12.17	119.39	8.36	1.2°	0.021	0.088
8	12.74	124.98	8.75	2°	0.035	0.153
9	13.31	130.57	9.14	2.3°	0.040	0.183
10	13.88	136.16	9.53	3°	0.052	0.248
11	14.45	141.75	9.92	4°	0.070	0.347
12	15.02	147.35	10.31	5.6°	0.098	0.505
13	15.30	150.09	10.51	5.8°	0.101	0.531
14	15.58	152.84	10.70	5.8°	0.101	0.540
15	15.86	155.59	10.89	6°	0.105	0.572
16	16.14	158.33	11.08	8°	0.140	0.776
17	16.31	160.00	11.20	8.2°	0.143	0.801
18	16.48	161.67	11.32	9°	0.157	0.889
19	16.65	163.34	11.43	10°	0.175	1.000
20	16.82	165.00	11.55	10.2°	0.178	1.028
21	16.99	166.67	11.67	10.5°	0.183	1.068
22	17.16	168.34	11.78	12.5°	0.218	1.284

Table4.5: torque applied and twist angle for depth 65cm of modal pile



Graph4.4: measured torque-twist angle curve for modal pile depth 65cm in sand

$\frac{Torque}{Angle\ of\ twsit} = \frac{9.92}{4} =$ 2.48=Z_{C4}(critical torque factor, for pile depth 65cm), failure point of soil at 4° angle of twist.

$Z_{C4} > Z_{C3} > Z_{C2} > Z_{C1}$

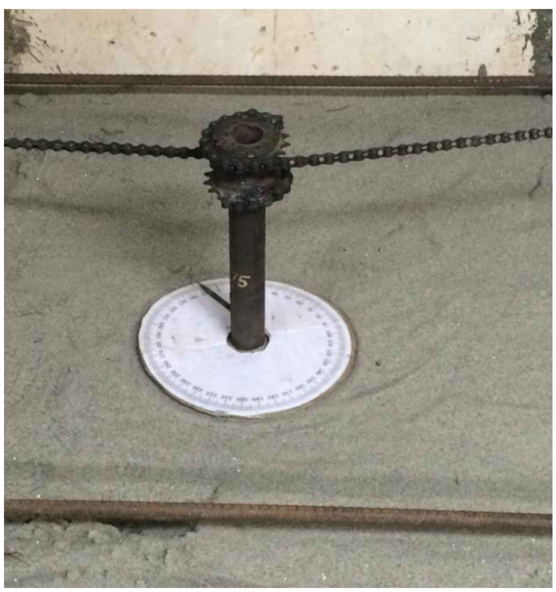
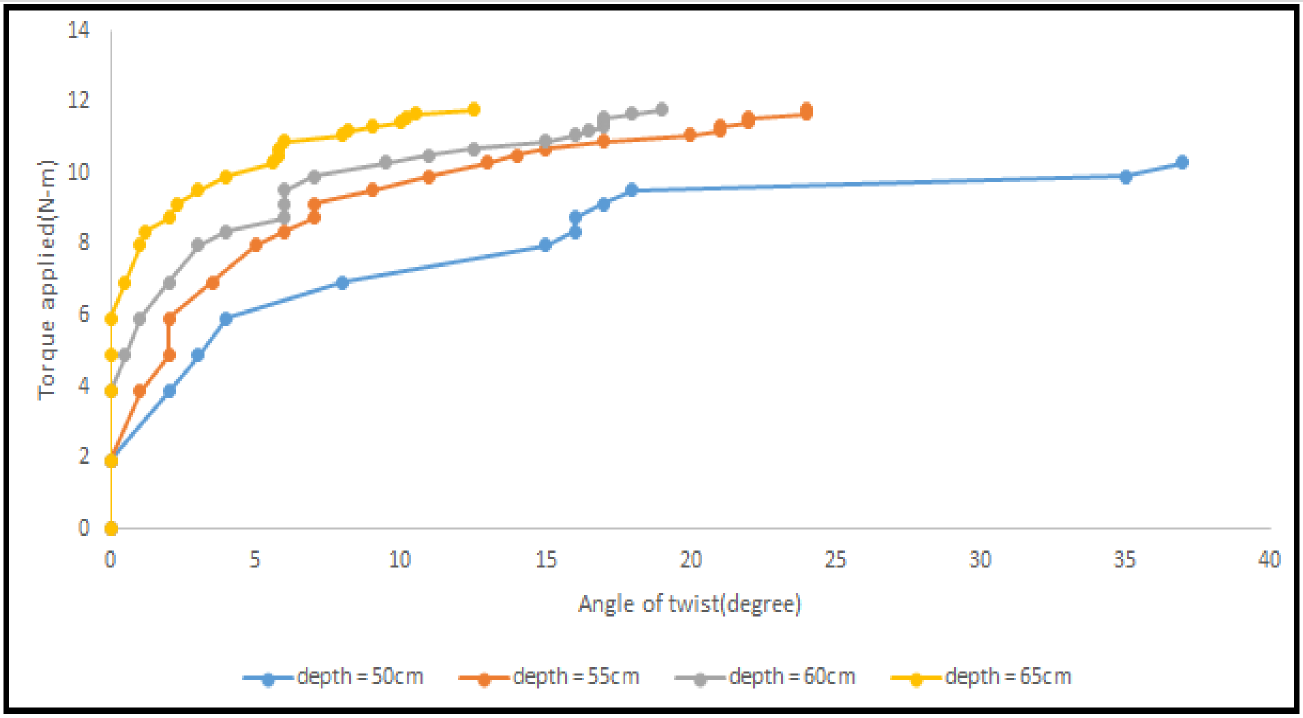
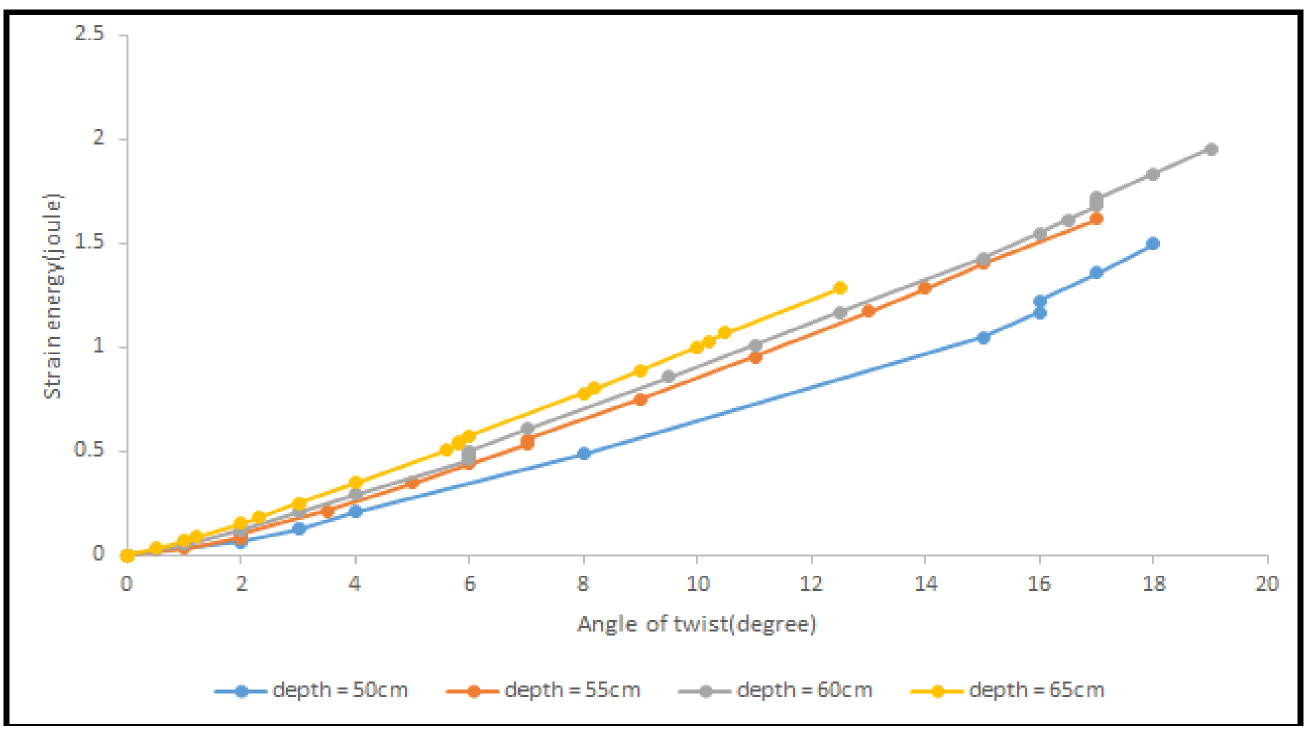


Fig4.4: pile interested inside sand to 65cm of depth



Graph4.5: torque-twist angle relation for different depth of modal pile



Graph4.6:Torsional strain energy-twist angle relation for different depth of modal pile

Conclusion

1. It is investigated that resistance of modal steel pile subjected to torque, increases with increase in angle of twist, till critical angle of twist i.e. generally 4°.
2. It has been observed that in working model, steel pile is resisted to rotating because of skin friction when torque is applied and at nearly 4° angle of twist, sand fails.
3. $\frac{torque\ applied}{angle\ of\ twist}$ $= Z_C$ (critical torque factor), Increases with increase in depth of modal steel pile up to critical angle of twist 4°.
4. $Z_{C4} > Z_{C3} > Z_{C2} > Z_{C1}$

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