Visakhapatnam Chapter

Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam

Estimation of Mobilized Shaft Resistance of Bored Piles from Pile Load Test

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Abstract. The distribution of load along the pile length is required to assess the performance of pile. Most of the studies of pile load tests are mainly aimed at overall behaviour of pile. Few tests report load transfer along the pile length under axial loading conditions. These are valuable to analyse the mobilization of shaft resistance and to estimate the load transfer mechanism during application of load. Present study analyses one such report which presents variations of axial loads with depth for few test piles. Mobilized shear stress as a function of displacement of pile is estimated for all these test piles and a near unique shear stress – displacement relation obtained.

Keywords: Axial Load distribution, Bored piles, Pile load tests, Settlements, Shear stress- displacement mobilization.

1 Introduction

Deep foundations such as piles are generally used to transfer heavy loads to a greater depth. Bored pile is one type of pile foundations. It is the most preferred type of pile in India because of its ease of construction, low vibration and flexibility of size to suit for different soil and loading conditions. Design of these bored piles involves consideration of two aspects, viz., ultimate capacity and settlements under applied loads. Coyle and Reese (1966) explain the behaviour of bored pile in clayey soils and Reese et al. (1969) for drilled shafts in clayey soil to understand the pile behaviour in detail. Many approaches are available to predict the bearing capacity of piles. But in situ pile load tests such as static and dynamic pile load tests with proper instrumentation is necessary to validate the estimate and to understand the load transfer behaviour of pile (Reese and Stoke 1984).

Many studies have been carried to study and analyse the load transfer mechanism and settlements using in situ pile load tests. Yousif (2012) has performed pile load tests on

bored piles to study the behaviour of piles in stratified soils and some correlations were developed with respect to CPT and SPT values. Seo and Prezzi (2007) analyse load transfer mechanism and settlement of various piles (Elkasabagy and Naggar, 2015) for different soil conditions. Comodromoset al. (2003) examined the bearing capacity and stiffness of single and pile group. Han and Prezzi (2017) performed similar analysis in multi-layered soils. Analysis based on Plaxis 3Dwas also adopted by Mert and Ozkan (2019) to predict pile capacity and settlement of bored piles.
Present study is carried out on bored piles in Sudan where the strata consist of clayey sand overlying highly plastic clay. Variation of axial load with displacement and distribution of axial load with depth have been reported (Yousif, 2012) based on which the shear stress mobilization with displacement has been evaluated.

2 Methodology

The test site is located on the bank of the Blue Nile as shown in Fig. 1 (Yousif, 2012). In-situ and laboratory tests were performed to determine the index properties of soil. The results obtained from the laboratory tests; the ultimate bearing capacity of pile was estimated. This will be used to know the application of load during pile load test.

Fig. 1. Test Location

Four boreholes were drilled and four CPT soundings were performed up to 15m depth. Five bored piles (TPA1, TPA2, TPA3, TPB1 and TPC1) were considered for the analysis. Each of these test piles installed at various soil conditions with different geometrical details. The piles (TPA1, TPA2, TPA3) of diameter 0.2 m, with embedded lengths of 3.5

m, 5 m and 6m. The piles (TPB1, TPC1) are of diameter 0.3 m and 0.4 m with embedded length of 3.5 m. These details are presented in Table 1.

Table 1. Details of test piles

S. No	Pile Reference	Diameter of pile (m)	Length of pile (m)
1	TPA1	0.2	3.5
2	TPA2	0.2	5
3	TPA3	0.2	6
4	TPB1	0.3	3.5
5	TPC1	0.4	3.5

For the sake of brevity, the subsoil conditions along the embedded length of the pile TPA1 only is presented in Fig. 2. This figure details the subsoil conditions in addition to SPT and CPT results (ASTM D1586, ASTM D3441) of test piles. The top layer is medium dense light brown clayey sand. Beneath this layer is very stiff to hard light to dark brown silty clay of high plasticity in which the pile is resting.

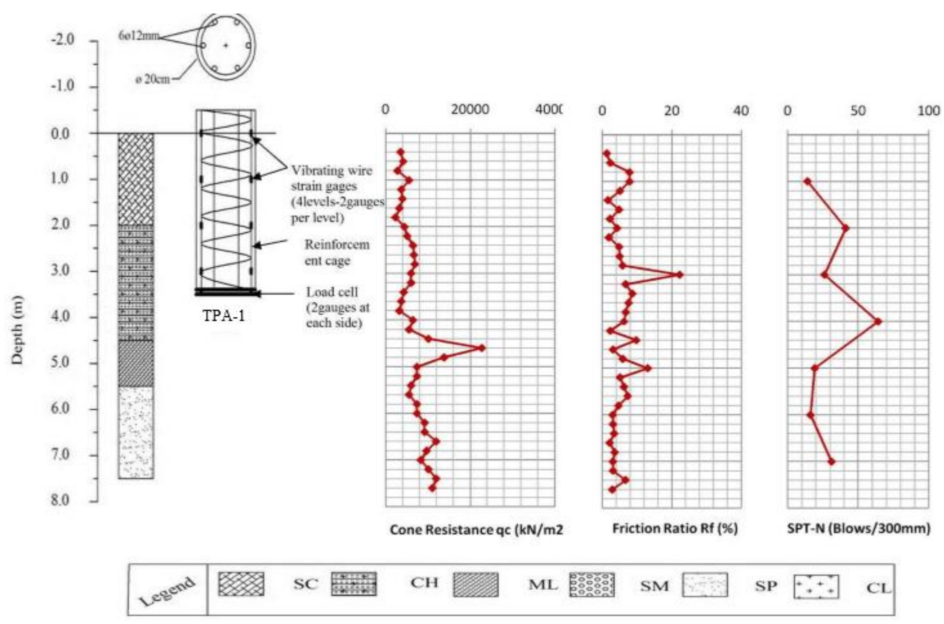


Fig. 2. Instrumented details of pile TPA1, subsoil condition (SPT N values, CPT) (Yousif, 2012)

Test PilesTPA1, TPB1 and TPC1 encounter the same soil conditions along the shaft length. The remaining test piles, TPA2 and TPA3 experienced additional soil strata such as low plastic silt followed by silty sand. The summary of all the test pile (TPA2, TPA3, TPB1, TPC1) sub-soil conditions are presented in Table 2.

Table 2. Soil profile for test piles (TPA1, TPA2, TPA3, TPB1 and TPC1)

Pile Reference	Embedded length (m)				
	SC	CH	ML	SM	CL
TPA1	0- 2	2-3.5	-	-	-
TPA2	0-2	2-4.5	4.5-5	-	-
TPA3	0-2	2-4.5	4.5-5.5	5.5-6	-
TPB1	0-2	2-3.5	-	-	-
TPC1	0-2	2-3.5	-	-	-

Note*: SC-Clayey sand, CH-High plastic clay silt, ML-Low plastic silt, SM-silty sand, SP-Poorly graded sand, CL-Low plastic clay.

Hydraulic jack was used to apply the load at pile head with several load increments. Each load was maintained for a minimum of one hour or until the rate of settlement of the pile top decreased to 0.25mm/hour. The rate of settlements at pile head was measured using dial gauges. All the test piles were instrumented with strain gauges at four levels, each with two gauges (ref Fig. 2) to get the strains at each level for determining loads. The load versus strains readings of all the test piles are shown in Fig. 3. From the strain gauge readings loads are estimated and their variations along the shaft length with several load increments are plotted in Fig. 4.

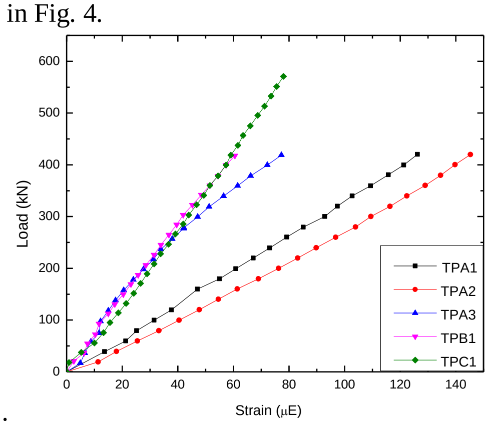
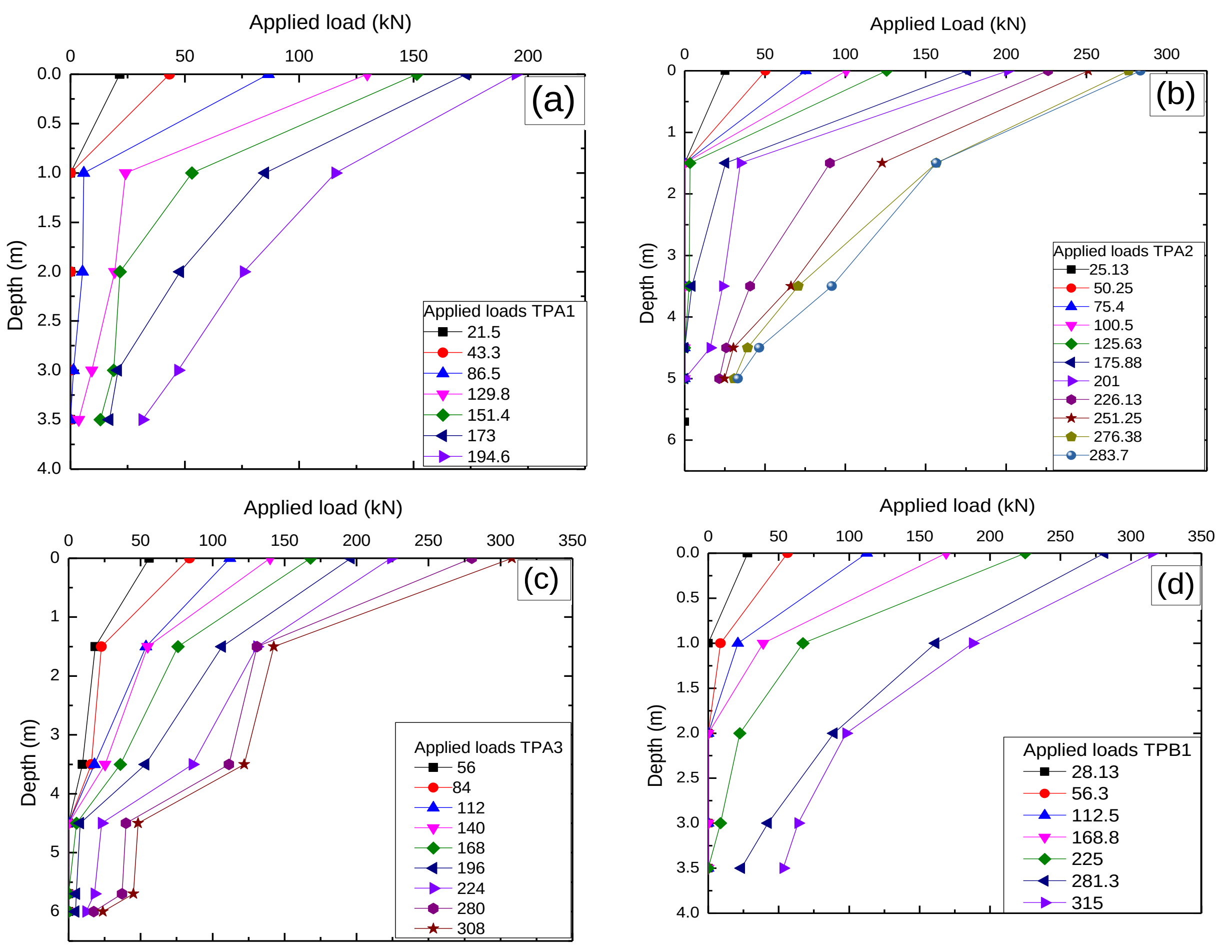


Fig. 3. Load vs strain gauge reading of all the test piles (Yousif 2012)

2.1. Load vs depth curves

The loads transferred along the shaft length of TPA1, TPA2, TPA3, TPB1 and TPC1 are presented in Fig. 4. In case of TPA1, TPA2 and TPB1 more than 50%, 85% and 70% of load has been transferred in the first segment i.e., from

0-1 m. For TPA3, 45-70% of the applied load has been transferred in the first segment. However, for TPC1 maximum load distribution has been observed in the second segment i.e. up to 85 % of load transmitted in the 1.0 to 2.0 m segment. Remaining loads were transferred to the successive segments.



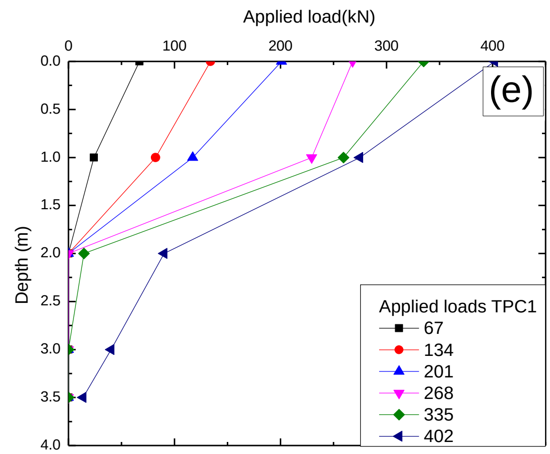
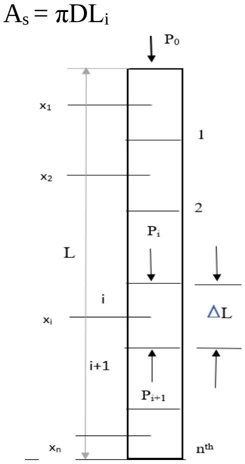


Fig. 4. Load distribution with depth of piles (a) TPA1, (b) TPA2, (c) TPA3, (d) TPB1 and (e) TPC1

The shaft resistance mobilized over each segment defined as the partial length of the pile between the corresponding strain gauge locations was calculated based on the loads estimated. The mobilized shaft resistance (τ_i) of each segment was calculated by dividing the pile into number of segments corresponding to strain gauge levels (Fig. 5). The load reduction over the segment is P_i-P_{i+1}, where P_i and P_{i+1} are the loads on top and the bottom of the segment. The mobilized shaft resistance, τ_i, is

$$\tau_i = \frac{P_i - P_{i+1}}{A_s} \qquad 2.1$$

where $A_s = \pi D L_i$



ΔL_i = Length of each segment
P_0= Load at top of the pile
P_i= Load at i^{th} depth of the pile
P_{i+1}= Load at $i+1^{th}$ depth of the pile

Fig. 5. Sketch of pile segments

Test pile A1 is divided into four segments corresponding to strain gauge locations as 0-1 m, 1-2 m, 2-3 m, 3-3.5 m. The stress evaluated for each segment is indicated at the center of the segment x_1, x_2, x_3,..x_n. The applied load (P_i) was 21.6 kN at pile top. The load at depth 1.0 m, P_{i+1} was 0 kN. The load transferred, (P_i-P_{i+1}) over the segment 0-1 m is 21.6 kN.
The area of the segment (A_s) 0-1 m is

$$A_s = \pi\times0.2\times3.5 = 2.2 \text{ m} \qquad 2.2$$

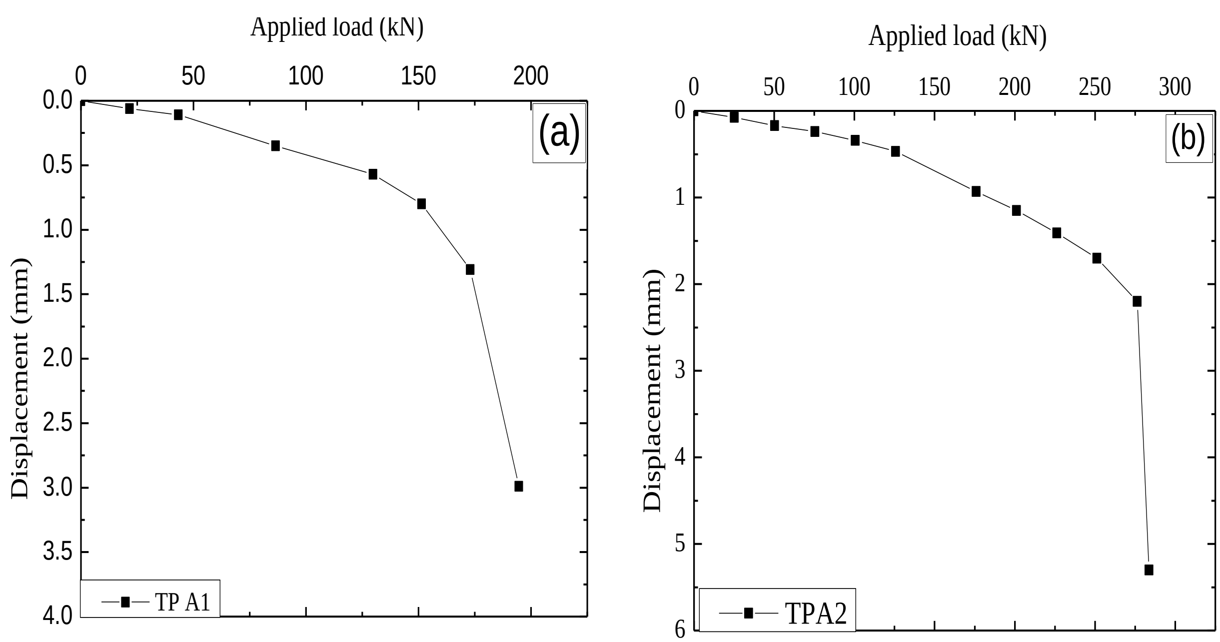
The shaft resistance, τ_1, of TPA1 at x_1 (i.e. segment 0-1 m) is

$$\tau_1 = (P_i-P_{i+1})/A_s = 9.83 \text{ kPa}$$

The analysis has been repeated for each strain gauge level and for all the test piles TPA2, TPA3, TPB1 and TPC1.

2.2 Applied load vs Displacement

The load versus settlement plots for all the test piles are shown in Fig. 6. Observed maximum settlements close to or at failure were 3 mm for TPA1, 5.3 mm for TPA2, 3.9 mm for TPA3, 4.3 mm for TPB1 and 2.7 mm for TPC1.



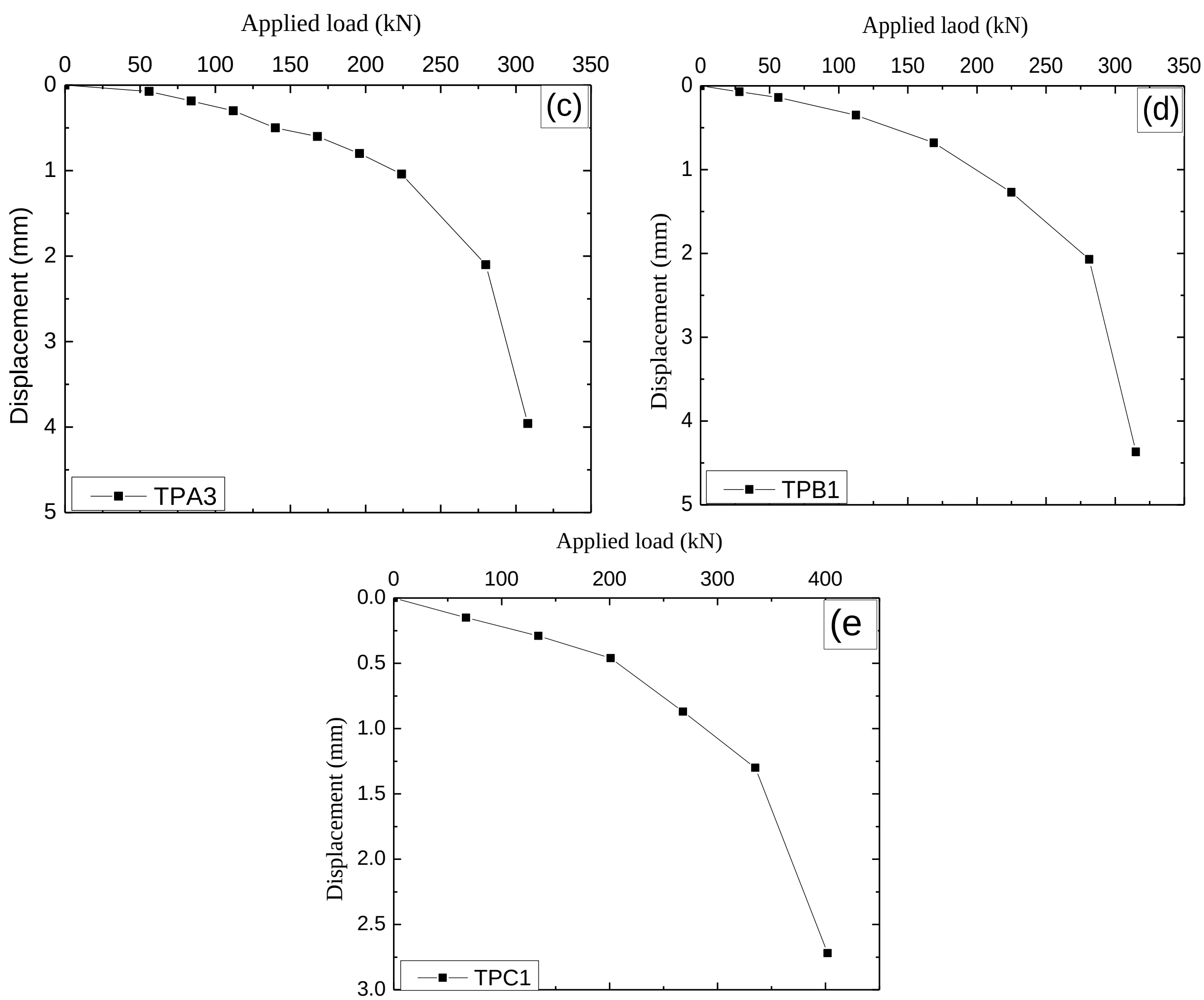
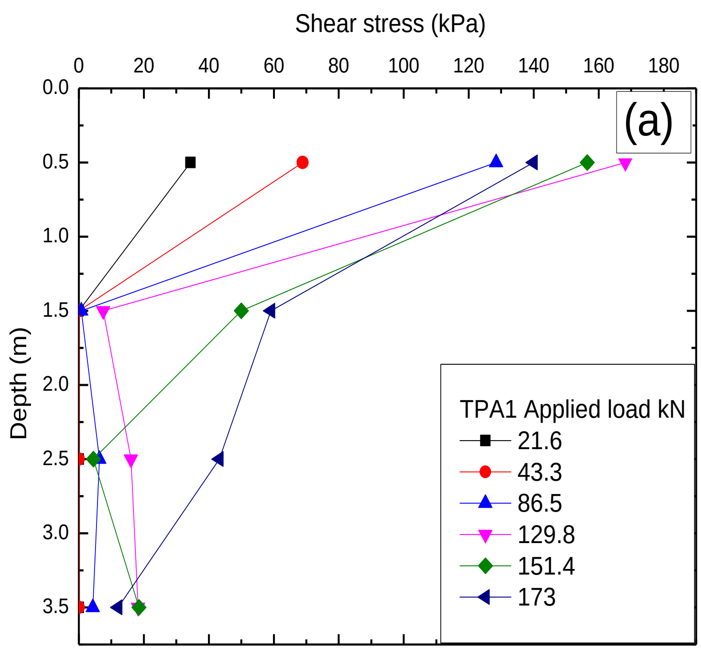


Fig. 6. Load - Displacement plots for piles (a) TPA1, (b) TPA2, (c) TPA3, (d) TPB1 and (e) TPC1 (Yousif, 2012)

3. Results and Discussion

3.1. Shear stress distribution along the length of pile.

The estimated shear stresses in the segments of all piles (TPA1: 0-1 m, 1-2 m, 2-3 m, 3-3.5 m; TPA2: 0-1.5 m, 1.5-3.5 m, 3.5-4.5 m, 4.5-5 m; TPA3: 0-1.5 m, 1.5-3.5 m, 3.5-4.5 m, 4.5-5.7 m, 5.7-6 m; TPB1: 0-1 m, 1-2 m, 2-3 m, 3-3.5 m; TPC1; 0-1 m, 1-2 m, 2-3 m, 3-3.5 m) are shown in Fig. 7 from the strains measured for each applied load. Fig. 7(a) shows variations of shear stress distributions with depth of test pile TPA1 for applied loads, 21.6 kN, 43.3 kN, 86.5 kN, 129.8 kN, 151.4 kN and 173 kN. For test pile TPA2, for an applied of 21.6 kN the shear stress was 34.4 kPa over 0-1 m segment (Fig. 7b). TPA3 shows similar behaviour (Fig. 7c) up to 2.5 m depth for applied loads of 56 kN, 84 kN, 112 kN, 140 kN, 168 kN and 196 kN.



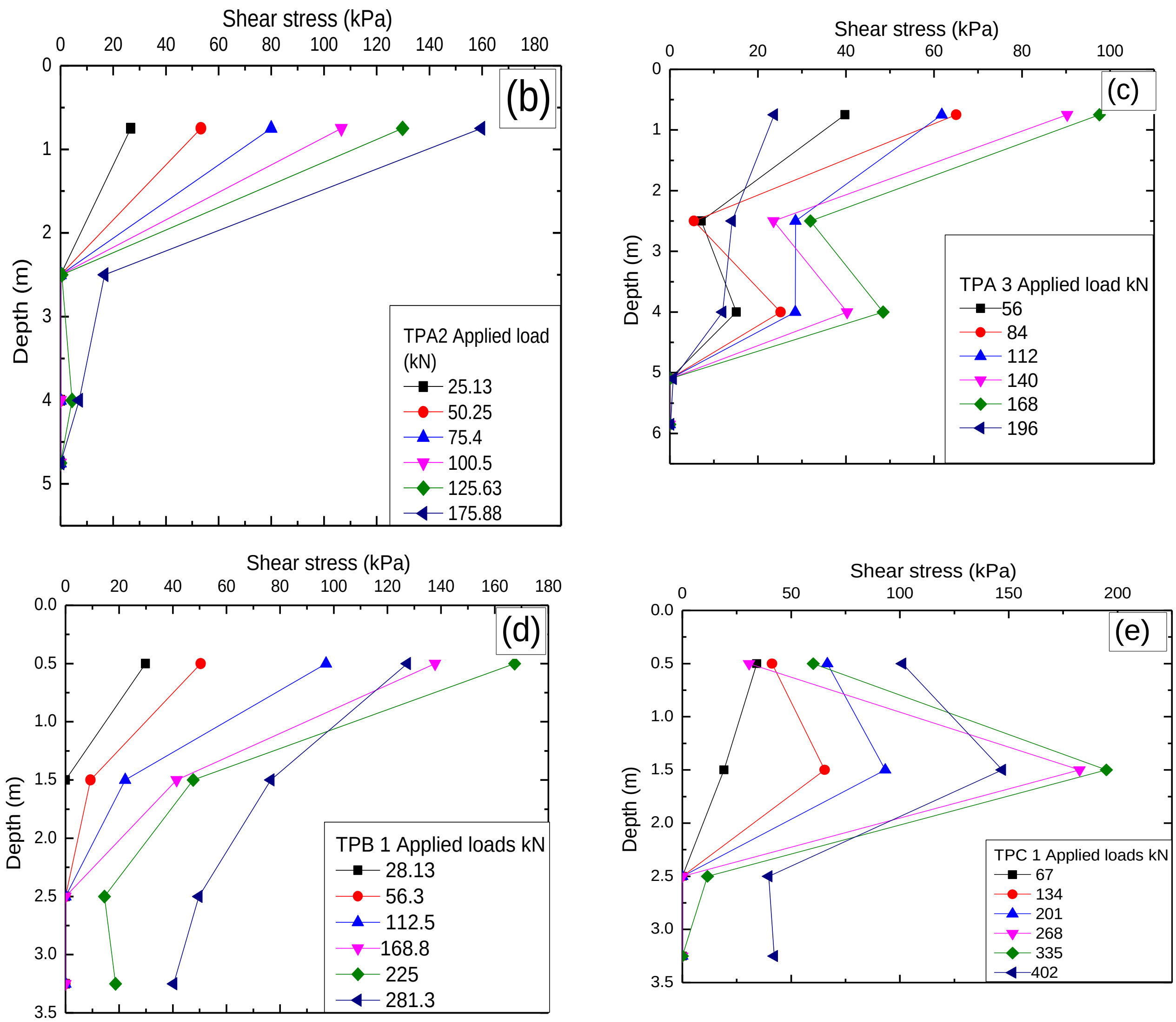


Fig. 7. Shear stress variation along the pile length in segments (a) TPA1, (b) TPA2, (c) TPA3, (d) TPB1 and(e) TPC1

For test pile TPB1, stress variation can be observed from Fig. 7(d) for loads of 28.13 kN, 56.3 kN, 112.5 kN, 168.8 kN, 225 kN and 281.3 kN. Stress was 29.9 kPa at 0.5 m (i.e. 0 - 1 m) for 28.13 kN load. The stress becomes 0 kPa at 1.5 m and shear stress was fully mobilized over 2.5 m long segment. For the test pile TPC1 the applied loads were 67 kN, 134 kN, 201 kN, 268 kN and 335 kN. In this case maximum stress was mobilized beyond 2.5 m. All the test pile performances were similar. Shear stress has been fully mobilized over the top 2.5 m depth in most cases. Table 3 presents the mobilized shaft resistances of all the test piles at maximum applied load.

Table 3. Shaft resistances at maximum applied load

Time	Segments (m)	Shaft Resistance (kPa)
TPA1	0-1	125
	1-2	64
	2-3	46
	3-3.5	50
TPA2	0-1.5	135
	1.5-3.5	52
	3.5-4.5	72
	4.5-5	42
TPA3	0-1.5	176
	1.5-3.5	16
	3.5-4.5	117
	4.5-5.7	4
	5.7-6	113
TPB1	0-1	135
	1-2	95
	2-3	36
	3-3.5	23
TPC1	0-1	101
	1-2	147
	2-3	40
	3-3.5	42

3.2 Mobilization of shear stress with displacement

The displacements are interpolated from the load-displacement plots for all the test piles. The shear stress-displacement plot is derived and shown in Fig. 8. The initial slopes of the shear stress-displacement curves for all the five test piles (TPA1, TPA2, TPA3, TPB1, TPC1) are linear up to shear stress of 40 kPa and close to each other indicating a unique response. The initial shaft-ground interface stiffness is of the order of 80 MN/m^3. The shear stress – displacement responses become non-linear for higher shear stresses. The ultimate shear stress gets mobilized within a displacement of hardly 3 mm. The ultimate or maximum shear stress ranges between 85 to 90 kPa except for Pile TPA-3 for which the ultimate shear stress is less than 80 kPa.

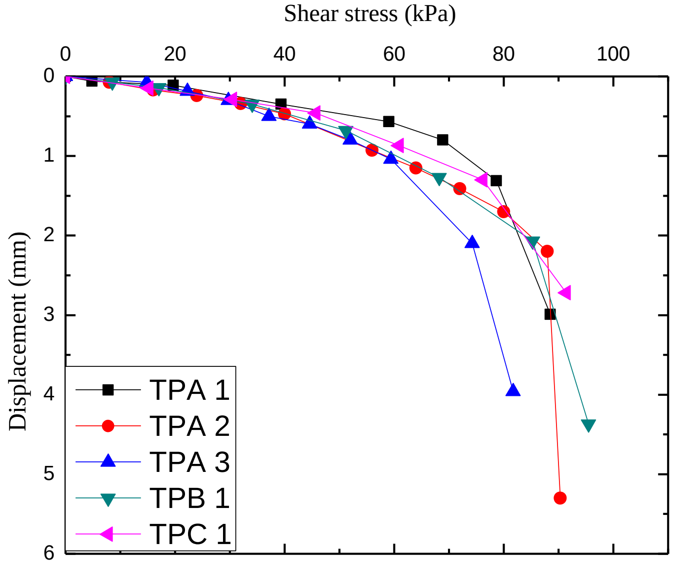


Fig. 8. Shear stress vs displacement responses of all test piles

4 Conclusions

In this study, axial load distribution with depth arrived at by measuring strains at depth have been analysed to arrive of mobilization of shaft response with displacement. The shear stress at low to smaller stresses increases linearly with displacement and non-linearly with higher displacement reaching the ultimate value at about 3 mm displacement.

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