BACK-ANALYSIS OF PILE LOAD TEST RESULTS – A CASE STUDY

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Abstract: Caution is required in selecting the safe load carrying capacity of bored piles, even if a few test piles indicate substantially higher capacity than theoretically estimated from static analysis. The consequences of failure of working piles should be evaluated carefully to select suitable safe load carrying capacity for design. Use of pile capacities higher than the computed values should be backed up by sufficient static and dynamic pile load tests and integrity tests. A case study illustrating static and dynamic load tests on piles installed in alluvial sands demonstrates the design methodology to be followed.

INTRODUCTION

With the advent of tall multi-storeyed buildings, geotechnical engineers face the challenge of coming up with an innovative and economic foundation and yet ensuring that risk is minimal. While designing piles for safe loads in excess of the theoretical capacity assessed from the IS codes, it should be backed up by sufficient testing to validate the load carrying capacities used in the design.

The paper presents a case study of static and dynamic load tests on RCC bored cast-in-situ piles for a mixed land-use project (commercial, retail and studio apartment spaces) in Noida, UP. The buildings planned consist of a double basement, ground floor and 12-40 upper floors.

STRATIGRAPHY

The project area belongs to the Indo-Gangetic alluvium. Excavation had been carried out to about 6 m depth. The soils below the excavated level consist predominantly of silty fine sand / fine sand with some discontinuous layers of sandy silt / clayey silt at various depths to 40 m depth. Groundwater was encountered at about 1.5 m depth below the excavated level (7.5 m depth below EGL) . Fig. 1 presents a pictorial summary of typical borehole profiles.

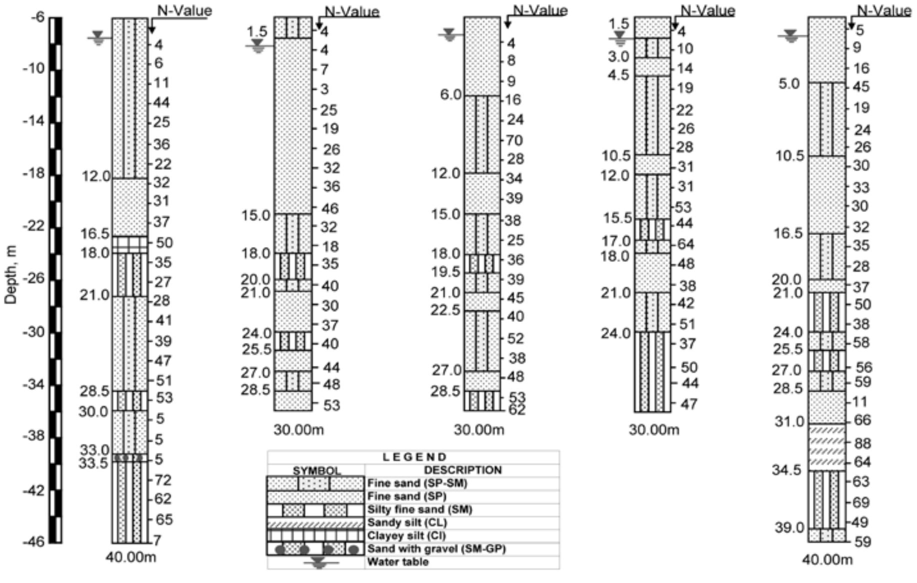

Fig. 1: Typical Borehole Profiles

FOUNDATION SYSTEM

The basement floor is planned at 8.85 m depth below adjoining road level (2.85 m below the excavated level). It was decided to provide 1000 mm diameter RCC bored cast-in-situ piles to support the towers. A RCC raft is planned over the piles so as to have hybrid piled-raft behaviour. The cut-off level for the piles shall be at about10 m depth below road level.

Computed Safe Pile Capacities

As per the static pile capacity analysis using reasonably conservative soil parameters, the safe vertical compressive pile capacity for a 1000 mm diameter 30 m long pile works out as 300 Tonnes. This value is typical of the capacities used on most projects in the surrounding areas within a 4-5 km radius of the project. However, the builder wanted to use higher capacities to economize the design. To assess the capacities that can probably be achieved if good quality pile free from defects is constructed, higher soil parameters were assigned to the dense sand at deeper depths. Lower and upper bound pile capacities were computed to assess the range of pile capacities that can possibly be achieved. The design profile selected for the analysis is as follows:

Table 1. Design profile used for pile capacity analysis

Depth below excavated level, m		Soil Classification	c, kN/m^2	ϕ, degrees	δ, degrees	γ, kN/m^3	K
From	To						
0.0	6.0	Fine sand	0	30	30	17.0	1.0
6.0	13.5	Fine sand	0	36	31	18.0	1.1
13.5	22.0	Fine sand	0	38	33	18.5	1.2
22.0	30.0	Silty fine sand	0	40	35	19.0	1.3
30.0	40.0	Silty fine sand	0	45	40	19.5	1.5
40.0	45.0	Silty fine sand (assumed)	0	45	40	19.5	1.5

where:

c = cohesion intercept

ϕ = angle of internal friction

δ = angle of friction between soil and pile

γ = bulk density of soil

k = coefficient of earth pressure

Design Groundwater level: At pile cut-off level

For computation of the lower bound pile capacity, a factor of safety of 2.0 was applied on the ultimate skin friction resistance and the end bearing capacity was ignored (for the worst case if the pile tip has muck at the bottom, the end bearing resistance mobilized shall be small). The upper bound, the best case scenario, was computed considering skin friction and full end bearing resistance; FS = 2.0 for the shaft resistance and FS = 2.5 for the end bearing resistance. Table 2 presents the computed pile capacities for 1000 and 1200 mm diameter piles:

Table 2. Computed pile capacities for 1000 and 1200 mm diameter piles

Pile Diameter, mm	Effective Pile Length below COL, m	Lower bound Safe Pile Load Carrying Capacity, Tonnes	Upper bound Safe Pile Load Carrying Capacity, Tonnes
1000	30	330	890
	35	434	996
1200	30	450	1433
	35	604	1587

STATIC AND DYNAMIC PILE LOAD TESTS

Test Piles

Eight piles were installed and load tested as listed below:

- 4 Nos. 1200 mm diameter initial piles,
- 3 Nos. 1000 mm diameter initial piles, and
- 1 No. 1000 mm diameter routine / production pile

Static Pile Load Test Results

Table 3 below presents the results of the static load tests on the 1200 mm diameter piles:

Table 3. Results of Static Load Tests on 1200 mm diameter bored pile

Pile No.	Pile Dia., mm	Pile length below Test Level, m	Depth below COL, m	Maximum Test Load Applied, MT	Pile Head Displacement, mm	Interpreted Safe Capacity, MT	Type of slurry used	Remarks
TP-1	1200	42.2	40.0	782	131.25	317	Bentonite	Possible construction defects
TP-2		37.2	35.0	612	144.80	280	Bentonite	
TP-3		36.2	34.0	1632	127.64	613	Composite*	
TP-4		36.2	34.0	1700	21.24	1000	Composite*	

* polymud + Alfabond (a thickening agent) and bentonite

A photograph of the load test set up is presented on Fig. 2. The test results are plotted on Fig. 3.

Fig. 2: Load Test Set-up

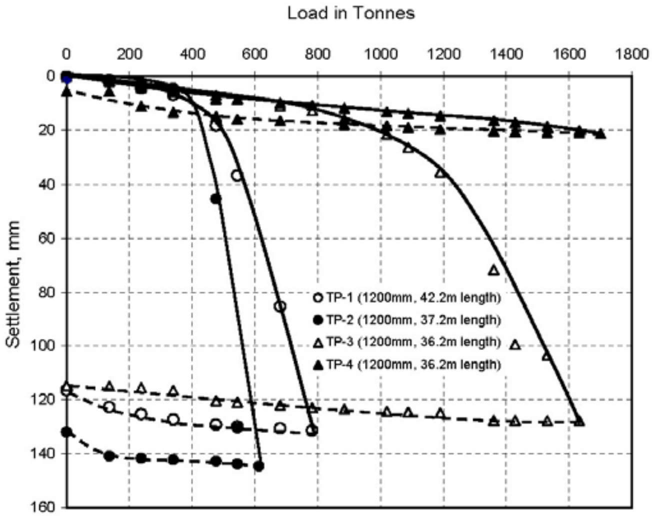

Fig. 3: Load-settlement Curves – 1200 mm diameter piles

Table 4 below presents the results of the static load tests on the 1000 mm diameter piles:

Table 4. Results of Static Load Tests on 1000 mm diameter bored pile

Pile No.	Pile Dia., mm	Pile length below Test Level, m	Depth below COL, m	Maximum Test Load Applied, MT	Pile Head Displacement, mm	Interpreted Safe Capacity, MT	Type of slurry used	Remarks
TP-1	1000	38.0	35.0	856	120.58	353	Polymer	
TP-2		33.0	30.0	1510	35.66	686	Polymer	
TP-3		33.0	30.0	1510	24.24	860	Polymer	Gravel pad provided at pile bottom
TP-4		33.0	30.0	1334	14.82	>890	Polymer	

The test results are plotted on Fig. 4.

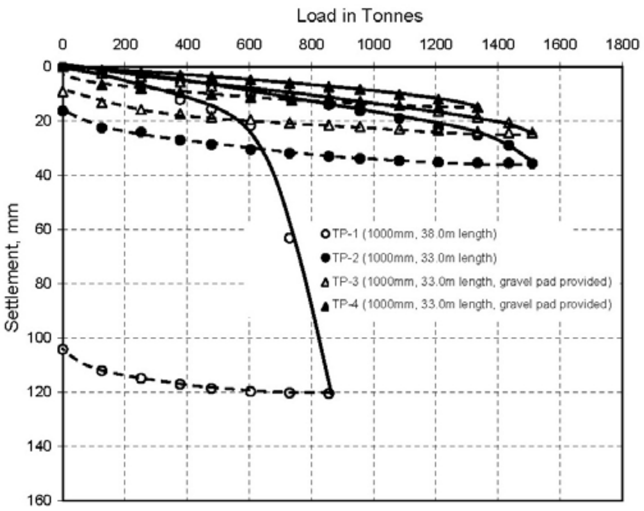

Fig. 4: Load-settlement Curves – 1000 mm diameter piles

The pile load test results are fairly inconsistent / scattered. There is no clear trend in the pile performance with increasing pile diameters and length. Many piles (especially TP-1, 2 & 3 of 1200 mm diameter piles; and TP-1 of 1000 mm diameter) seem to have significantly underperformed on site, indicating possible structural defects in the pile and / or poor bottom cleaning. Considering the poor performance of the 1200 mm diameter, the builder decided not to use 1200 mm diameter piles.

On the contrary, some of the piles (such as TP-2, 3 & 4 of 1000 mm diameter) performed rather well, and indicate interpreted safe pile capacities significantly in excess of the anticipated theoretical capacities. Therefore, it was decided to use 1000 mm diameter bored piles for the project. It was also decided to restrict pile length to 33 m below test level (30 m below cut-off level) since the longer piles indicated lower capacities.

The inconsistency in the pile performances on site make it difficult to arrive at a safe pile capacity which can be used for design. Although the contractor and builder attributed the lower capacity solely to the use of bentonite as drilling fluid, the authors are of the opinion that it is important to validate each of the load test results, and correlate them to the pile and strata conditions.

Extrapolation of Test Results

Since some of the piles were not tested to failure, the test results have been extrapolated mathematically treating the load-settlement curve as a hyperbola (Kaniraj & Samantha, 1996) to assess the likely ultimate capacity. This concept has been effectively used to extrapolate the safe load carrying capacity of large diameter piles on several projects (Sanjay Gupta & Ravi Sundaram, 1999). The equation used for the hyperbolic model is as follows:

$$\frac{S'}{Q'} = a + bS'$$

where

$S' = s/D$	s = settlement	D = Pile diameter
$Q' = Q/Q_r$	Q = Applied Load	Q_r = Reference Load

a and b are constants determined from a linear regression analysis of S'/Q' and S'.

IS: 2911 (Part 4) – 2013 specifies that the safe load on the pile may be taken as the lower value determined by the following two criteria:

1. Two-thirds of the load corresponding to settlement of 18 mm
2. Half the load corresponding to settlement of 50% of pile diameter.

The following table presents the interpreted safe pile capacity based on extrapolated curves.

Table 5. Safe pile capacity from extrapolated curves

Pile No.	Q_{18mm}	$2/3*Q_{18mm}$, MT (Criterion 1)	$Q_{0.1D}/2$, MT (Criterion 2)	Interpreted Safe Pile Capacity, MT
TP-1	Pile tested to failure			**353**
TP-2	1030	687	1221	**687**
TP-3	1278	852	1489	**852**
TP-4	1523	1015	1390	**1015**

Low Strain Pile Integrity Tests

Low strain integrity tests were performed on all the test piles. Typical test results for two of the 1000 mm diameter piles are presented in Fig. 5.

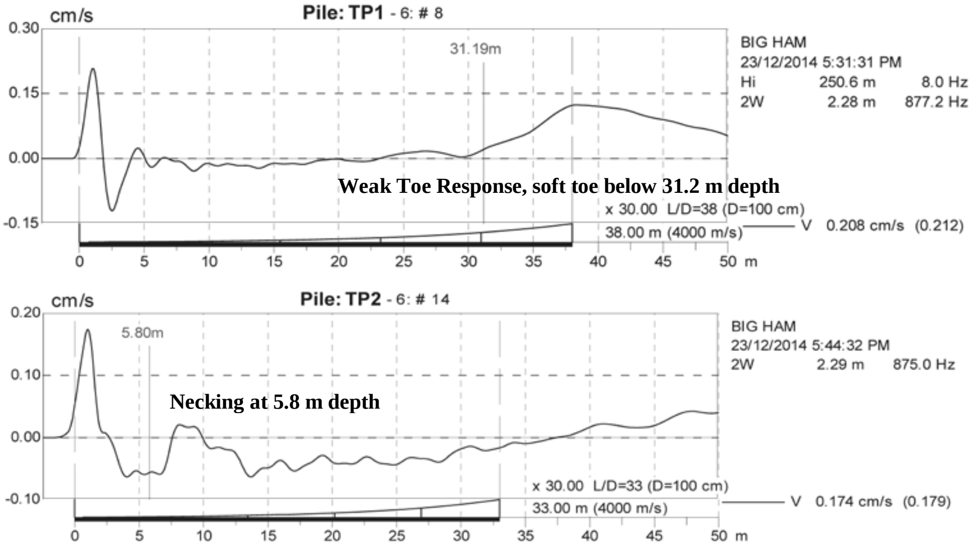

Fig. 5: Typical Results – Low-Strain Pile Integrity Tests on 1000 mm diameter piles

The interpretation of the integrity of the pile shat and toe are summarized in table 6:

Table 6. Interpretation of PIT

Pile No.	Pile Length below test level, m	Comments on PIT Results	Test Conclusion
TP1	38	Reduction of pile impedance below about 30-31m depth. This could indicate reduction in pile cross-section, weak concrete or "soft toe" condition below this depth. Might explain the *'plunging behaviour'* observed during the static load test	Pile integrity is OK to about 30-31m depth. "*Soft Toe*" condition suspected at about 30-31m depth.
TP2	33	Minor reduction in pile impedance (probably necking) at about 5-6m depth	Pile length and integrity are OK.
TP3	33	Pile shaft seems fairly uniform	Pile length and integrity are OK.
TP4	33	Increase in pile impedance (possibly bulging) between 15m and 25m depths, followed by a return to nominal diameter	Pile length and integrity are OK.

High Strain Dynamic Pile Load Test

For a better assessment of the pile behaviour, a dynamic pile load test was performed on TP-3 in accordance with ASTM D4945-12. Four strain transducers and two accelerometers were attached to the pile head. They were mounted on opposite sides of the pile for cancellation of bending effects during each strike of the hammer. A 5.1 tonne hammer falling through heights varying from 0.5 to 2.5 m was used to conduct the test.

The signals of strain and acceleration were conditioned and processed by a Pile Driving Analyzer (PDA) illustrated on Fig 6. Dynamic testing on the pile was conducted by striking the piles by several blows during the re-striking process as shown in Fig.7. Complete dynamic measurements were obtained for each hammer blow delivered to the pile. The PDA investigates driving stresses, pile integrity, hammer performance, and bearing capacity.

Fig. 6. Pile Driving Analyzer (PDA)

Fig. 7. Hammer Impact on Pile

A selected PDA field record of force and velocity data for a blow delivered to the piles was further analyzed using the CAPWAP (CAse Pile Wave Analysis Program) computer software. The analysis involved applying the measured pile top velocity time record to the top of a lumped-mass and spring wave equation model of the pile.

After performing the CAPWAP analysis, the soil-pile model is evaluated to assess the maximum soil resistance mobilized during the test. The results showed that the pile tested had achieved a mobilized capacity of 1231 MT. This included a mobilized shaft resistance of 840.8 MT and a mobilized toe resistance of 390.2 MT. The simulated equivalent static load settlement curve is illustrated on Fig. 8.

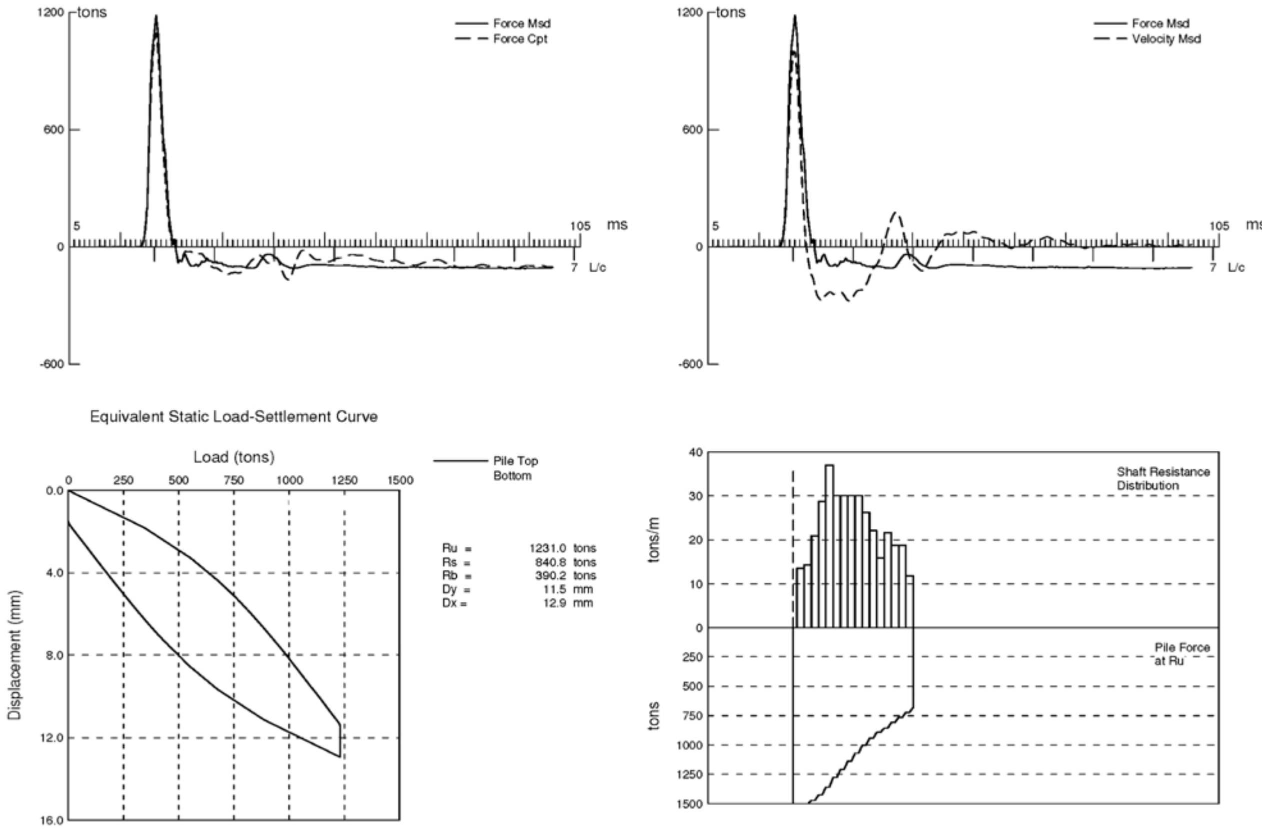

Fig. 8: CAPWAP Analysis and Equivalent Static Load-Settlement Curve

Applying a factor of safety of 2 on the maximum mobilized capacity, the safe load carrying capacity for the 33 m long pile works out as 616 MT. Since the maximum displacement at pile head as per the CAPWAP analysis is about 12.9 mm, the safe load is probably higher, estimated to be on the order of 650-680 MT. Higher impact could not be applied on the pile since pile head had developed some cracks due to over-stressing.

EVALUATION OF TEST RESULTS

Reviewing the test results, the safe load carrying capacity for the 33 m long 1000 mm diameter RCC bored pile may range from a lower bound value of 300 Tonnes to an upper bound value ranging from 650 to 852 tonnes. Using safe capacities substantially in excess of the calculated static pile capacity requires a careful assessment of the reliability of the construction methodology and consistency in quality of construction. The selection of appropriate value of the safe pile capacity becomes a challenge and contentious issue. While the builder would like to pick the highest possible value to save on foundation costs, caution needs to be exercised considering the consequences of failure.

The authors are of the opinion that the design load on such piles may be increased substantially beyond the computed values. However, to ensure reliability of the design capacities, sufficient load tests should be done, probably more than the IS code requirements.

Since it is not practical to load test every pile, there is a niggling concern that some piles with lower capacity may go unidentified, resulting in some risk to the building. To minimize such a risk, the percentage of static routine load tests needs to be more than 2% recommended in IS: 2911 (Part 4) - 2013.

This has to be coupled with low strain integrity tests on 100% of the working piles plus sufficient dynamic pile load tests. Cross-hole sonic logging / acoustic testing (CHUM) is also being increasingly used to assess the quality of concrete. Conducting dynamic load tests on 5 to 10% of the working piles may further help in enhancing reliability.

It is difficult to specify how many piles should be tested to reliably assess the safe load carrying capacity. But as further test results become available, the decision has to be carefully taken to ensure economy in design as well as safety and reliability of the capacity of the working piles.

Ideally, a greater percentage of integrity testing should be performed on the first few production piles installed, in order to check the pile integrity early on in the project. If any of the tested piles show compromised integrity, additional testing as well as re-design of the piling scheme will be needed.

Using safe capacities in excess of 600-650 Tonnes (twice the computed safe capacity) needs a proper and effective quality assurance plan coupled with sufficient load tests. On projects with stringent the time targets, the higher quantum of testing is often viewed as an obstruction to the work progress. Therefore, caution needs to be exercised in careful selection of pile capacity.

CONCLUDING REMARKS

While it is very satisfying that the actual safe load carrying capacity of the test piles exceeds more than two times the computed safe capacity, using the higher values in the design should be backed up with sufficient load tests and integrity tests. If any pile fails at a lower capacity, the number of tests should be suitably increased.

For each pile that has lower capacity than the design value, an assessment should be made regarding the number of piles that are suspect and the further testing plan as well as the design should be modified accordingly. If required, additional piles may have to be installed.

REFERENCES

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ASTM: D 4945 - 12 "*Standard Test Method for High-Strain Dynamic Testing of Piles*".