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Defects in Bored cast-in-situ Piles and their Remediation – A case study from India

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Abstract

This paper presents an in-depth case study on the defective construction of a pile foundation and its remedial measures. Typically, projects do not anticipate defects severe enough to impact the project timeline, nor do they allocate time for defect analysis, design rectification, preparation of drawings and repairing. In such a scenario, it becomes essential to adopt expedited processes for defect analysis and solution for remedial works. This paper provides critical insights in to identifying and remediating defects in bored cast-in-situ pile construction at a project site in Uttarakhand, India.

Keywords

Pile foundation, Bored Cast-in-situ, Low strain test, High strain test, Static test, Piled raft

Introduction

Case study is for the defects encountered during the construction of pile foundation for the main plant RCC building, which measures 31m x 37 m in size and is of 35 m in height with multiple levels of equipment-supporting floors. A piled raft was conceptualized and designed with a group of 340 piles. Due to lose silty soil at the bearing level, the raft's contribution to the foundation capacity was not considered. Each pile was 600 mm in diameter and 18 m in length. Poor construction supervision and inappropriate construction methods were practiced at site and that led to the complex situation where everything was uncertain about the integrity of piles and pile capacity. The client reviewed the field inspection report closely and raised concerns about whether the constructed foundation achieved the intended design strength. The client directed the project team to perform a thorough quality check of piles, certify their adequacy and provide design and drawings for corrective measures. This case study comprehensively details the entire process encompassing defect analysis, the formulation of mitigation designs and the execution of remedial measures.

Scope of Study

1. Review and analysis of the constructed pile foundation to identify the quality issues
2. Review of the existing geotechnical investigation report to assess soil conditions and their implications on the pile foundation
3. A Cost and time-optimized sequential approach for defects analysis using low-strain integrity testing, and evaluate capacity through high strain dynamic testing.
4. Reassess and redesign the piled raft foundation, incorporating proposed modifications to the original design to achieve the design strength.
5. Recommend suitable corrective measures for implementation to restore the foundation for the intended design loads.
6. Conclusions and lessons learnt.

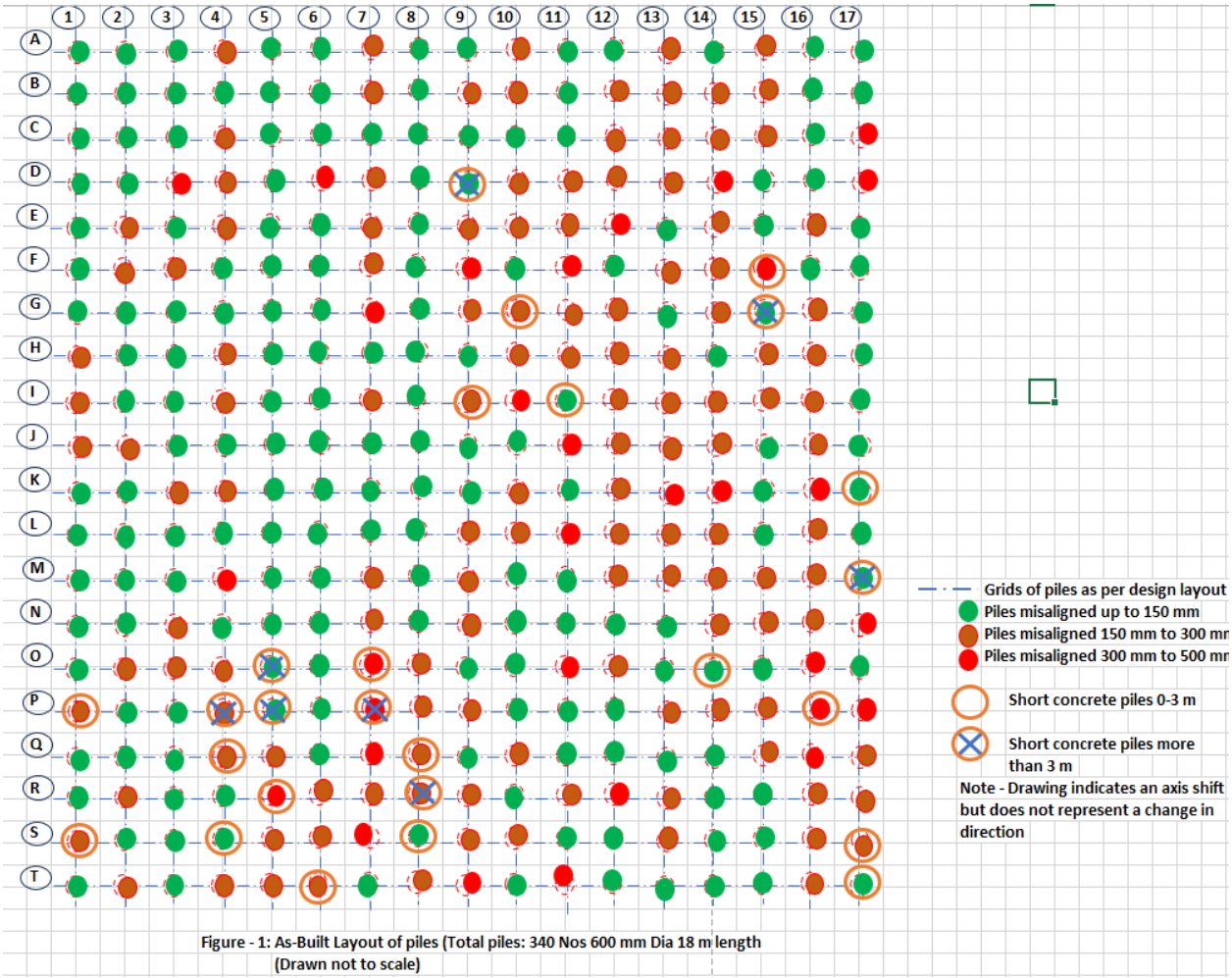


Figure - 1: As-Built Layout of piles (Total piles: 340 Nos 600 mm Dia 18 m length (Drawn not to scale)

NGL: 219.90 m

Pile cutoff level as per design: 216.90 m

Pile bottom termination level: 198.90 m

Defects observed through visual inspection:

1. Short concrete in piles.
2. Misalignment of piles' location
3. Reinforcement below cut off level of piles

Piles misaligned up to 150 mm - 181 Nos
Piles misaligned 150 mm to 300 mm - 129 Nos
Piles misaligned 300 mm to 500 mm - 30 Nos
More than 90% of the piles were misaligned.
Short Concreted Piles (1 m to 2 m): 14 Nos
Short Concreted Piles (2 m to 3 m): 4 Nos
Short Concreted Piles (more than 3 m): 8 Nos
As per IS 2911, Piles should not deviate more than 75 mm or D/6 whichever is less from their designed positions at the working level.

Geotechnical data have been collected from the existing geotechnical investigation report, and the geotechnical conditions of the building site can be summarized as follows:

Stratigraphy and design profile

A surficial fill of sandy silt was encountered to about 1 m depth. Below this, the natural soils consist of loose silty fine sand to about 4.5 m depth. Below this, sandy silt/clayey silt is encountered to about 29.0 m depth. This is underlain by silty fine sand to the final explored of 30 m.

It is important to note that laboratory test program for soil strength assessment of the various layers were not sufficient. Only two direct shear test, three unconfined compression tests and two undrain unconsolidated triaxial tests were performed which are not sufficient to calibrate the soil strength assessment through field tests i.e. SPT N-values. In absence of sufficient lab tests data for drained and undrained soil strength assessment, pile capacity calculations in the soil investigation data, largely depend upon the SPT N-values.

The liquefaction potential for the site was calculated by simplified procedure as given by Seed and Idriss (1971), as described in NCEER Summary report [Youd and Idriss (2001)] and it was found that the soil up to 4.5 m depth is prone to liquefaction for the selected data of earthquake. IIT Bombay is of the opinion that the sub soil available at site is predominantly silt and clay having fines content more than 35% (see Fig 2.3). Hence, the mentioned procedure of Youd and Idriss (2001) for evaluation of liquefaction potential should not be applicable for this site. Hence, the liquefaction susceptibility at present site is re-estimated by using a more correct/suitable method for fine grained soils, i.e. Idriss and Boulanger (2008) method. In addition to this, available Cross-hole Seismic Test (CHST-1) data are also used to estimate liquefaction susceptibility to strengthen the confidence level of liquefaction potential evaluation for this site.

Table 1: Computed pile capacity

Pile Diameter,	Pile depth	Computed Pile Capacity, Tonnes		
mm	below COL,m	Compression	Pull out	Lateral
600	18	62	41	2.2

Table 2: Stratigraphy and design profile

Depth, m		Sample No.	SPT [1]		Symbol	SOIL DESCRIPTION	Depth of Strata, (m)	Grain Size Analysis				Atterberg Limits			Density and Moisture			Specific Gravity	Shear Tests			
From	To		Field Value, N_f	Corrected Value, N'				Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Liquid (%)	Plastic (%)	Plasticity Index (%)	Bulk Density (gms/cm^3)	Dry Density (gms/cm^3)	Moisture Content (%)		Type of Test	Confining Pressures, (kg/cm^2)	Cohesion Intercept, 'c' (kg/cm^2)	Angle of Internal Friction, ϕ (degrees)
0.00	0.50	DS1				Fill: Sandy silt with gravel		5	26	61	8											
0.50	0.95	SPT1	21	38			1.00					30.7	21.6	9.1								
1.50	1.95	SPT2	4	6		Loose grey silty fine sand (SM)		0	63	36	1											
2.25	2.55	UDS1													1.91	1.62	18.0	2.61	DS	0.5 ,1, 1.5	0.0	29.0
3.00	3.45	SPT3	5	7			4.50	0	58	40	2											
4.50	4.95	SPT4	6	6		Firm to stiff brown clayey silt, medium plastic (MI)						37.4	26.7	10.7								
5.25	5.55	UDS2				- firm, 4.5 to 7.5 m		0	5	71	24				1.90	1.56	22.0	2.68				
6.00	6.45	SPT5	8	8																		
7.50	7.95	SPT6	11	11		- stiff, 7.5 to 9.0 m						43.1	28.5	14.6								
8.25	8.55	UDS3						0	6	64	30				1.89	1.51	25.1		UC		0.7	
9.00	9.45	SPT7	6	6		- firm, 9.0 to 11.0 m																
10.50	10.95	SPT8	7	7																		
11.25	11.55	UDS4				Stiff brown clayey silt, medium plastic (MI)		0	1	79	20				1.94	1.56	24.0					
12.00	12.45	SPT9	10	10								47.1	28.1	19.0								
13.50	13.95	SPT10	11	11														2.69				
14.25	14.55	UDS5					15.00	0	3	83	14				1.97	1.55	27.1					
15.00	15.45	SPT11	12	11		Stiff to very stiff brown sandy silt with traces of gravel, low plastic						33.3	24.9	8.4								
17.25	17.55	UDS6				- ML, 15.0 to 18.0 m - stiff, 15.0 to 18.0 m		4	35	55	6				1.96	1.58	23.9					
18.00	18.45	SPT12	22	17		- CL, 18.0 to 20.0 m - very stiff, 18.0 to 20.0 m	20.00					26.4	19.4	7.0								
20.25	20.55	UDS7				Very stiff brown clayey silt, medium plastic (CI)		3	7	66	24				2.00	1.64	21.5		UU	2 ,3, 4	1.3	3.7
21.00	21.45	SPT13	29	29		- with traces of gravel, 20.0 to 24.0 m						35.2	23.9	11.3								
23.25	23.55	UDS8													2.04	1.66	23.3					
24.00	24.45	SPT14	15	15		- with garvel, 24.0 to 27.0 m		5	15	66	14											
26.25	26.55	UDS9													2.04	1.66	23.2	2.67				

Table 3: Liquefactin assessment using Borehole geotechnical data

Layer	Soil Description	Depth to Top of layer (m)	Layer Thickness (m)	FS using Idriss and Boulanger (2008) method	FS using Youd and Idriss (2001) [SPT approach]
1	Fill	0	1	NL	NL
2	Silty fine sand	1	2	0.38	0.43
3	Silty fine sand	3	1.5	0.42	0.47
4	Clayey silt	4.5	1.5	NL	NL
5	Clayey silt	6	1.5	NL	NL
6	Clayey silt	7.5	1.5	NL	NL
7	Clayey silt	9	1.5	NL	NL
8	Clayey silt	10.5	1.5	NL	NL
9	Clayey silt	12	0	NL	NL

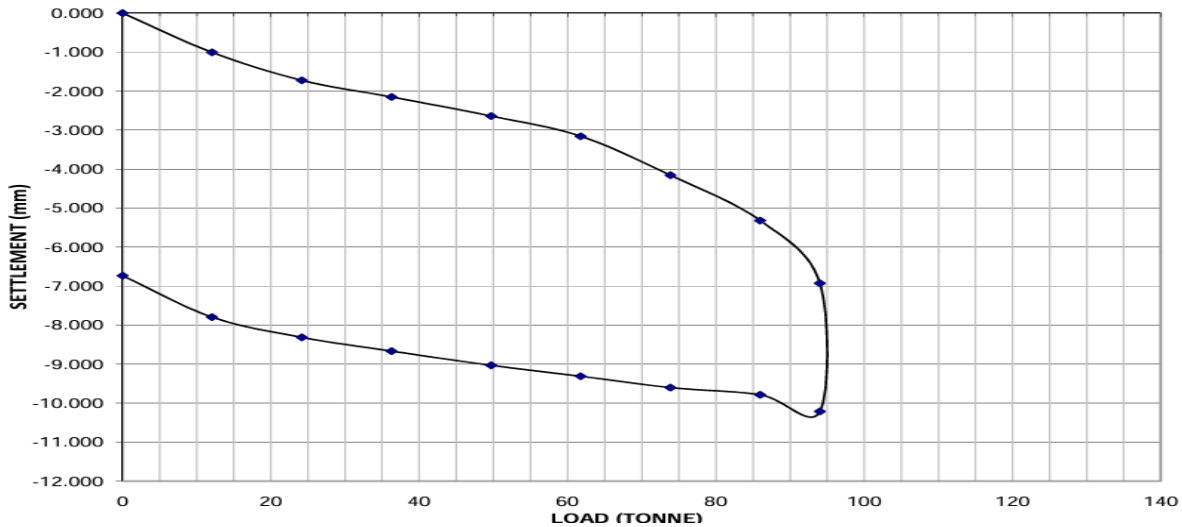
Table 4: Liquefactin assessment using crosshole seismic data

Layer	Soil Description	Depth to Top of layer (m)	Layer Thickness (m)	FS using Youd and Idriss (2001) [V_s approach]
1	Fill	0	1	NL
2	Silty fine sand	1	2	0.76
3	Silty fine sand	3	1.5	0.46
4	Clayey silt	4.5	1.5	NL
5	Clayey silt	6	1.5	NL
6	Clayey silt	7.5	1.5	NL
7	Sandy silt	9	1.5	NL
8	Silty fine sand	10.5	1.5	NL
9	Clayey silt	12	1.5	NL
10	Clayey silt	13.5	1.5	NL

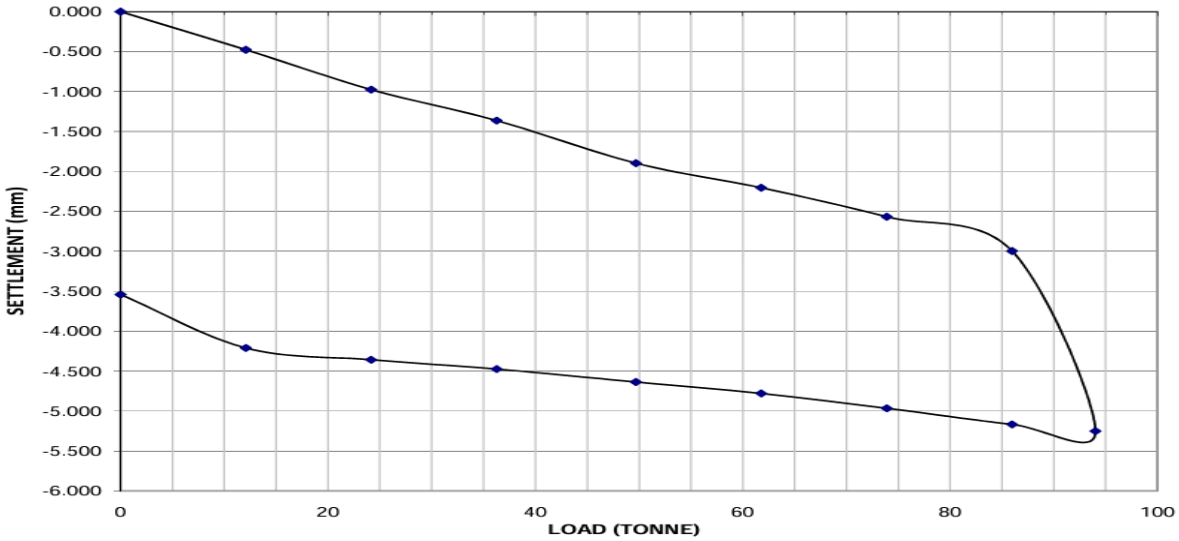
Tests available:

Routine Test: Routine tests were carried out, which achieved the required capacity as per IS 2911 Part 4. This is likely because all the piles selected for the routine test being good piles.

Graph 1: Load vs Load increment (Routine Load Test for Pile C-5)



Graph 2: Load vs Load increment (Routine Load Test for Pile I-16)



Pile Integrity Test: The graphs from the pile integrity test report were evaluated and it was found that many of them were inconclusive.

Table 5: Pile integrity reflectogram data

Sr No.	Reflectogram	Remark
I-2	18.0m; 23/11/2017 Amp:28 V: 3900m/s; I2; Stem may be of varying section	The reflectogram is not appropriate and not representing the shaft integrity. However it is still assumed to be acceptable.
M-2	19.0m; 23/11/2017 Amp:95 V: 3250m/s; M2; OK	Low velocity is considered probably to qualify the pile length. Shaft has shallow depth anomalies.
S-2	16.3m; 23/11/2017 Amp:15 V: 4300m/s; S2; OK	Shaft length is only 16.3 m and reflectogram is not strong and clear. However shaft is still considered as OK.
F-2	15.7m; 07-12-2017 V:4200m/s Amp:23; F2; OK	For 18 m long (design length) shaft, how 15.7 m long shaft can be acceptable
F-5	18.0m; 20-12-2017 V:3400m/s Amp:160; F5; OK	The velocity is very less and amplification is very high. Shaft reflectogram is also shows either necking or budging but results reported as ok.

For pile integrity testing report, different amplification levels are selected for each pile (it's like different zoom level for each picture) which is not usual and needed to be re verified. It seemed that it was carried out to identify the toe response but

neither toe response is obvious nor signals along the pile are meaningful which may provide different conclusion for shaft response.

Initial conclusions and recommendations:

Drawing upon the analysis of defects identified through visual inspection and the evaluation of existing geotechnical data, the following initial conclusions were formulated:

1. While construction record was already available it was not clear, why all the routine load tests were conducted on the piles which are free from any construction defect. It was possible to conduct the load tests on few of the piles having considerable anomalies i.e. shorter in length, pile having borehole collapse record etc. which would provide more insight of the defective piles. Presently none of the routine compressive load tests represent any defective pile. The routine load test program for compressive load only represents the half of the piles of the building. It only covers pile mark A to J and 1 to 17.

2. It was recommended to carry out additional routine tests on piles selected from the defective group, as well as from the remaining of the area spanning J to T. However, given the criticality of project completion timeline and the time-consuming nature of routine tests, high-strain dynamic load testing (HSDT) was proposed for selected piles under strict supervision of experts and all relevant parties**.**

Table 6: Piles selected for high-strain dynamic load testing

Sr No.	Colour Marked (Refer Layout)	Piles marked by location
1		H-11
2		P-14
3		D-12
4		S-5
5		P-5
6		K-17
7		A-2
8		O-17

3. It is strongly suggested to re-conduct the integrity testing at least on all the piles in question under strict supervision of expert and all parties involved. This will help to revalidate the proper pile length casted, shaft integrity and proper identification of the anomalies associated with the piles in the group.

4. The validation of pile load tests was recommended for the site by using PLAXIS3D and conventional t-z & q-z curves. These data will be further used for re-analyzing the entire pile group. Load data on the individual column supports are to be made available to quickly revisit and take decision regarding augmentation or modification in the layout of piles and raft.

5. Re-analysis considering the as-built pile conditions was to be put on hold until the results of HSDT and low strain pile integrity tests became available.

6. The outcomes of the newly recommended tests were critical for exploring remediation options, including:

    a. Leveraging the pile cap to compensate for the exclusion of the strength contribution from defective piles, where uncertainty existed in determining their load carrying capacity.

    b. Another option of design scenario where the pile cap shape and design can be modified considering the change in the pile alignment. In such case, the existence of some of the short-concrete piles may also be taken, depending on the results of HSDT, which is essential. However, in case of any uncertainty in fixing the capacity of short concrete piles, fresh pile casting is to be recommended adjacent to defective piles.

c. Third option was not to do any further testing but to cast additional piles adjacent to all defective piles and redesign layout of piles and raft.

7. Prior to discarding the piles only based on short concrete piles (over drilling during boring lead to sinking of the reinforcement cage) or eccentricities or lack of appropriate development length for reinforcement cage was not considered to be prudent approach and it was preferred to assess the pile capacities prior to discarding defective piles.

Project activities following Initial conclusions and recommendations:

1. Low strain pile integrity tests:

The test agency was instructed to perform tests on remaining piles to achieve 100% coverage. While it is not feasible to present all the test results here, an evaluation of the test results for piles in question is presented. (Refer table 7)

Table 7: Evaluation report of Pile integrity tests

Sr. no.	PIT on Group of Piles	Pile mark	Length as per PIT (m)	Date	Velocity (m/s)	Amplification	Comments
1	PIT report - 11 nos	B5	14	12/29/2017	4250	75	HSDT can be considered
2		C9	10	11/25/2017	4300	170	HSDT is recommended
3	PIT report - 12 nos	Q2	19.2	12/13/2017	3200	120	Impedence is not uniform
4		D1	12.5	12/11/2017	4000	33	Impedence is not uniform
5		D7	16.1	12/11/2017	4100	38	Impedence is not uniform
6	PIT report - 14 nos	C4	16.5	11/21/2017	4150	25	Clear reduction of impendence and could be necking.
7		B2	18	11/22/2017	3850	170	Impedence is not uniform
8	PIT report - 16 nos	F1	18.3	11/23/2017	3600	65	Impedence is not uniform
9		H1	19.8	11/23/2017	3250	75	Impedence is not uniform
10		J3	18	11/23/2017	4000	30	Strongly recommend to excavate this shaft up to 3 m and see the defect.
11		L2	16.5	11/23/2017	4000	55	Impedence is not uniform
12		N2	18.8	11/23/2017	3250	110	Seems defect at 3.5m
13		N3	17.4	11/23/2017	3900	12	Excavate upto 3m to detect the defect
14		T2	16.5	11/23/2017	4300	19	Impedence is not uniform at 6m depth
15	PIT report - 19 nos	B11	18	12/20/2017	3450	95	Impedance decrease at
16		B15	17.6	12/6/2017	4250	55	Integrity shall be conducted after removal of top weak concrete
17		B17	18.8	12/6/2017	3250	65	HSDT can be considered
18		C16	18.9	12/6/2017	2750	190	Poorly reported
19		M8	19.3	12/6/2017	2900	41	Poorly reported
20		P15	20.9	12/6/2017	3850	25	Seems poor pile head
21		S14	16.3	12/6/2017	3300	410	Defect is reported
22	PIT report - 26 nos	A8	16.5	12/5/2017	3500	95	Necking defects as reduction in impedance.
23		D10	18	12/5/2017	3550	130	Seems defect at 4.5m
24		I13	18	12/5/2017	3850	95	Impedence is not uniform at 6m depth
25		K15	18.3	12/5/2017	3600	260	Impedence is not uniform at 15m depth
26		L17	17.8	12/5/2017	3650	47	Impedence is not uniform
27	PIT report - 26 nos	A10	18.1	12/1/2017	3450	110	Poorly pile head
28		O9	17.9	12/1/2017	4300	97	Seems defect
29		O10	18	12/1/2017	3200	60	Impedence is not uniform
30		O11	17.7	12/1/2017	4200	65	Early toe response
31		O12	18	12/1/2017	3850	41	Seems defect
32		P11	15.7	12/1/2017	3900	110	Impedence is not uniform
33		Q11	18	12/1/2017	4200	13	Seems defect

Table 7: Continued

Sr. no.	PIT on Group of Piles	Pile mark	Length as per PIT (m)	Date	Velocity (m/s)	Amplification	Comments
34	PIT report - 28 nos	S12	18	12/8/2017	3750	38	Seems defect
35		T13	18.1	12/8/2017	4000	19	Poorly reported
36		A11	16.5	12/11/2017	4000	140	Defect is reported
37		C12	14	12/11/2017	3350	160	Defect is reported
38		S11	19.6	12/11/2017	3900	95	Seems defect
39	PIT report - 34 nos	H9	18	12/20/2017	3650	55	Impedance decrease and defect
40		N8	18	12/20/2017	3350	150	Seems defect
41		S9	17.9	12/7/2017	4100	36	Seems defect
42		T16	18.1	12/7/2017	3900	21	Seems defect
43	PIT report - 35 nos	G1	11.9	12/25/2017	4250	75	Recommended for HSDT test.
44		G9	18	12/13/2017	4100	80	Seems defect
45		I12	13.8	12/25/2017	4250	41	Respone not clear, HSDT is recommended
46		K4	18.9	12/25/2017	3350	120	Seems defect
47		L7	17.3	12/20/2017	4300	80	Response not clear
48		M15	20	12/25/2017	3350	130	Seems defect
49		O16	18.4	12/13/2017	3600	50	What is the reason
50		P12	17.5	12/15/2017	4300	25	Not clear
51		S7	19.6	12/15/2017	3450	60	Not clear at 7m
52		T14	15.7	12/25/2017	4200	110	
53	PIT report - 35 nos	A2	18	11/25/2017	4200	250	Seems defective at 6.5 m
54		A6	16.5	11/25/2017	4000	191.7	Defective at 13.2m and 15m.
55		H3	18.4	11/25/2017	3750	140	Impedance is not uniform
56		M4	16	11/25/2017	4200	160	Seems defect
57		N1	12	11/25/2017	4250	49	HSDT is recommended
58		E8	18.9	11/27/2017	3850	140	Early toe response at 16m
59		F7	16.7	11/27/2017	4000	110	Early toe response at 16m
60		G8	18.1	12/17/2017	3750	147.4	Seems defect
61		H5	16.5	12/17/2017	4000	110	Seems defect
62	PIT report - 44 nos	C10	15.7	11/29/2017	3200	55	Toe response not clear
63		C14	18	11/29/2017	3900	60	Seems defect
64		D8	18	11/29/2017	3450	75	It looks like defect at 3m
65		F12	18	11/29/2017	4000	55	Is this not defect at 4m ?
66		H7	14	11/29/2017	4400	21	Toe response not clear,HSDT is
67		I8	18	11/29/2017	3900	26	Seems defect at 3.5m
68		J5	17.8	11/29/2017	3850	44	Seems defect at 3.5m
69		J13	18	11/29/2017	3500	19	Impedance is not uniform at 10.5m. It shows early toe response.
70		K5	18	11/29/2017	4000	85	Seems defect at 3 m
71		L15	18	11/30/2017	3500	33	Seems defect at 3.5m

Table 7: Continued

Sr. no.	PIT on Group of Piles	Pile mark	Length as per PIT (m)	Date	Velocity (m/s)	Amplification	Comments
72	PIT report - 15 nos	F2	15	12/7/2017	4200	55	Defect reported
73		F6	16	11/18/2017	3750	100	Defect reported
74		I2	14.7	23/11/2017	3900	105	Defect reported
75		K8	13	11/18/2017	4000	125	Defect reported, HSDT is recommended
76		D6	15.5	11/18/2017	3800	110	Defect reported
77		A16	15.7	11/19/2017	3600	105	Defect reported
78		D17	13	11/18/2017	3900	115	Defect reported
79	PIT report - 10 nos	E11	14.7	11/15/2017	3600	75	Defect reported, HSDT is recommended
80		E13	15	11/15/2017	3400	90	Defect reported
81		K10	13.8	11/15/2017	4000	105	Defect reported
82		M7	16.8	11/15/2017	3300	110	Defect reported
83		N10	14.8	11/15/2017	3500	85	Defect reported
84		O3	16	11/15/2017	3750	120	Defect reported
85	PIT report - 15 nos	P13	13	11/14/2017	4200	150	Defect reported, HSDT is recommended
86		R1	11.5	11/14/2017	4250	125	Defect reported
87		T15	16.5	11/14/2017	3850	110	Defect reported
88		A7	16	11/15/2017	3700	90	Defect reported

General observations (PIT Tests):

All the test results indicated that pile shaft exhibit uniform integrity, with wave speeds for the tested piles generally ranging from 3400m/sec to 4200m/sec, which may be classified as fair concrete quality. However, 34 piles showed an early toe response, warning further investigation.

2. High strain dynamic load testing:

A total of 8 HSDT tests were proposed in the initial conclusions report. These tests were conducted, and the results are summarized as below:

The obtained 8 nos. of HSDT test results suggest that pile offered sufficient resistance.

Table 8: (Summary of HSDT Tests)

Sr No.	Pile Location	Test Load (kN)	Observed Max capacity (kN)	HSDT-Net Settlement (mm)	HSDT- Total Settlement (mm)
1	D12	930	1260	1	2
2	A2	930	1450	5	3
3	K5	930	1030	1	2

Table 9: (Summary of HSDT Tests)

Sr No.	Pile Location	Test Load (kN)	Observed Max capacity (kN)	HSDT-Net Settlement (mm)	HSDT- Total Settlement (mm)
4	N2	930	1650	1	7
5	R3	930	1140	0.5	4
6	G1	--	--	--	--
7	H17	930	1050	0.3	2
8	D10	930	1610	0.5	2

3. As per PIT tests, 34 piles were identified as defective based on their early toe response. However, since pile integrity up to the point of toe response was found to be satisfactory, these piles could still be utilized. Pile shafts measuring 12-13 m or longer were expected to provide significant pile resistance. To identify the criticality of each pile, the forces on them were calculated using PLAXIS 3D and subsequently reviewed. The observed axial loads on these piles are tabulated (Table 10). Pile capacities were calculated based on the toe response lengths of the piles and compared with the actual calculated loads. It was found that 5 piles were getting marginally overloaded. Therefore, It was proposed to conduct additional HSDT on these 5 overloaded piles, with an additional 2 piles selected for confirmatory testing. Test results suggest that overloaded piles offered sufficient resistance (Table 11).

Table 10: Axial load summary on 34 defective piles

Row	Column	Pile no.	Pile Coordinates		Pile length as per PIT (m)	Load [kN] from PLAXIS
			X	Y		
A	6	6	-4.92	18.13	16.5	481
A	8	8	-1.29	18.12	16.5	564
A	11	11	3.96	17.94	16.5	592
C	10	44	2.25	13.21	15.7	420
C	12	46	5.49	13.09	14	446
F	7	96	-3.41	7.09	16.7	390
H	7	130	-3.10	3.53	14	396
I	12	148	5.60	1.84	13.8	494
L	2	203	-13.18	-3.72	16.5	370
N	1	238	-15.20	-7.46	12	312
P	11	262	3.96	-10.87	15.7	488
S	14	320	9.28	-16.26	16.3	467
T	2	339	-13.20	-17.96	16.5	669
C	4	38	-8.86	13.04	16.5	353
H	9	128	0.41	3.62	--	406
A	7	7	-2.94	18.15	16	503
A	16	16	12.96	18.03	15.7	478
B	5	30	-6.81	15.64	14	340
C	9	43	0.38	13.19	10	427
D	6	63	-4.75	10.94	15.5	342
D	17	52	15.20	11.19	14	361

Table 10 (Continued)

Row	Column	Pile no.	Pile Coordinates		Pile length as per PIT (m)	Load [kN] from PLAXIS
			X	Y		
F	2	101	-13.50	7.22	15	302
F	6	97	-4.91	7.27	16	360
I	2	138	-13.31	1.76	14.7	325
K	8	178	-1.32	-1.68	13	404
E	11	79	4.35	8.98	14.7	495
E	13	81	7.48	8.86	15	432
K	10	180	2.03	-1.68	13.8	420
M	7	211	-3.22	-5.71	16.8	388
N	10	229	2.06	-7.42	14.8	419
O	3	241	-11.39	-9.30	16	413
P	13	260	7.39	-10.98	13	427
R	1	306	-15.14	-14.33	11.5	299
T	15	326	11.19	-18.08	16.5	371

Table 11: HSDT Test results on marginally overloaded defective piles

Sr No.	Pile Location	Length as per PIT	Test Load	Observed Capacity
1	C9	10 m	930 Kn	1663 Kn
2	E11	14.7 m	930 Kn	2188 Kn
3	K8	13 m	930 Kn	988 Kn
4	P13	13 m	930 Kn	1402 Kn
5	I12	13.8 m	930 Kn	1313 Kn
7	N1	12 m	930 Kn	1111 Kn
8	H7	14 m	930 Kn	1081 Kn

4. Validation of routine compression load test on pile

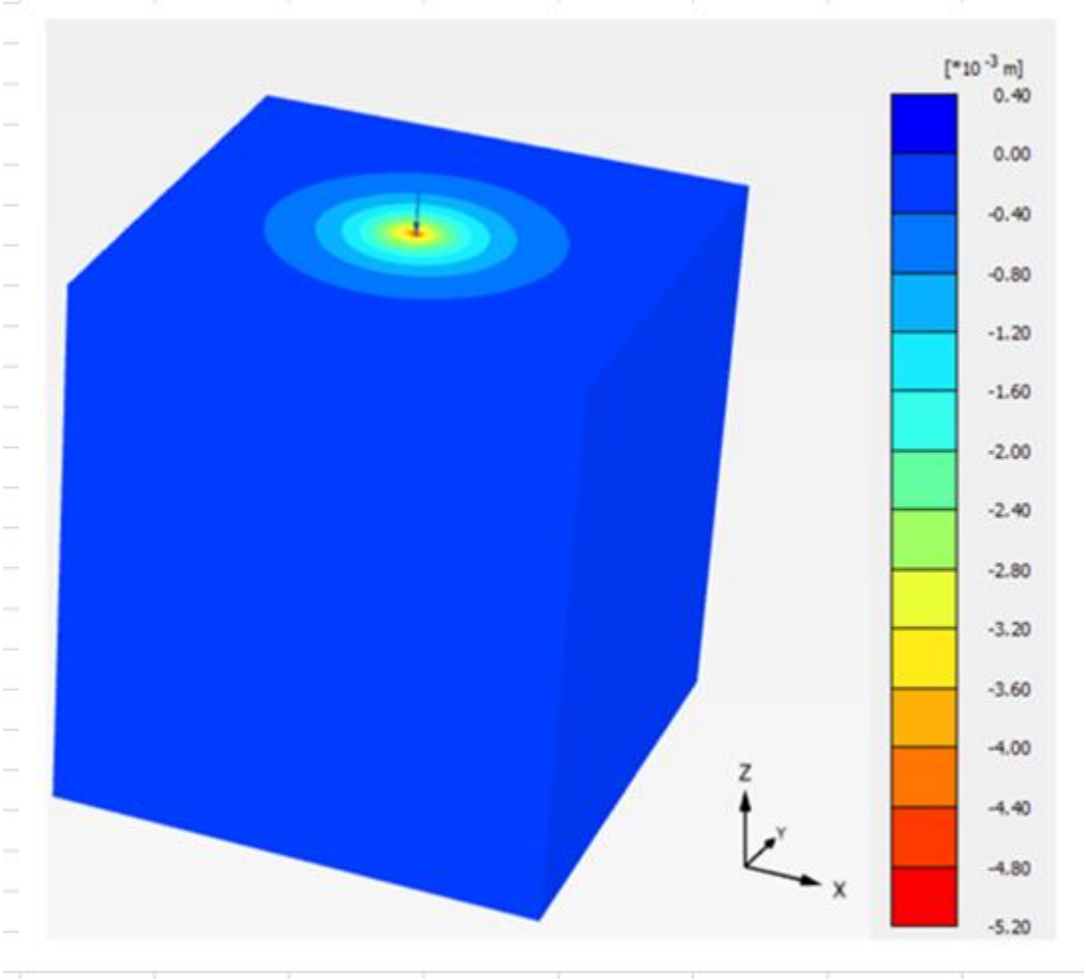


Figure - 2: Vertical deformation curve obtained in PLAXIS 3D for pile under vertical load of 930 Kn

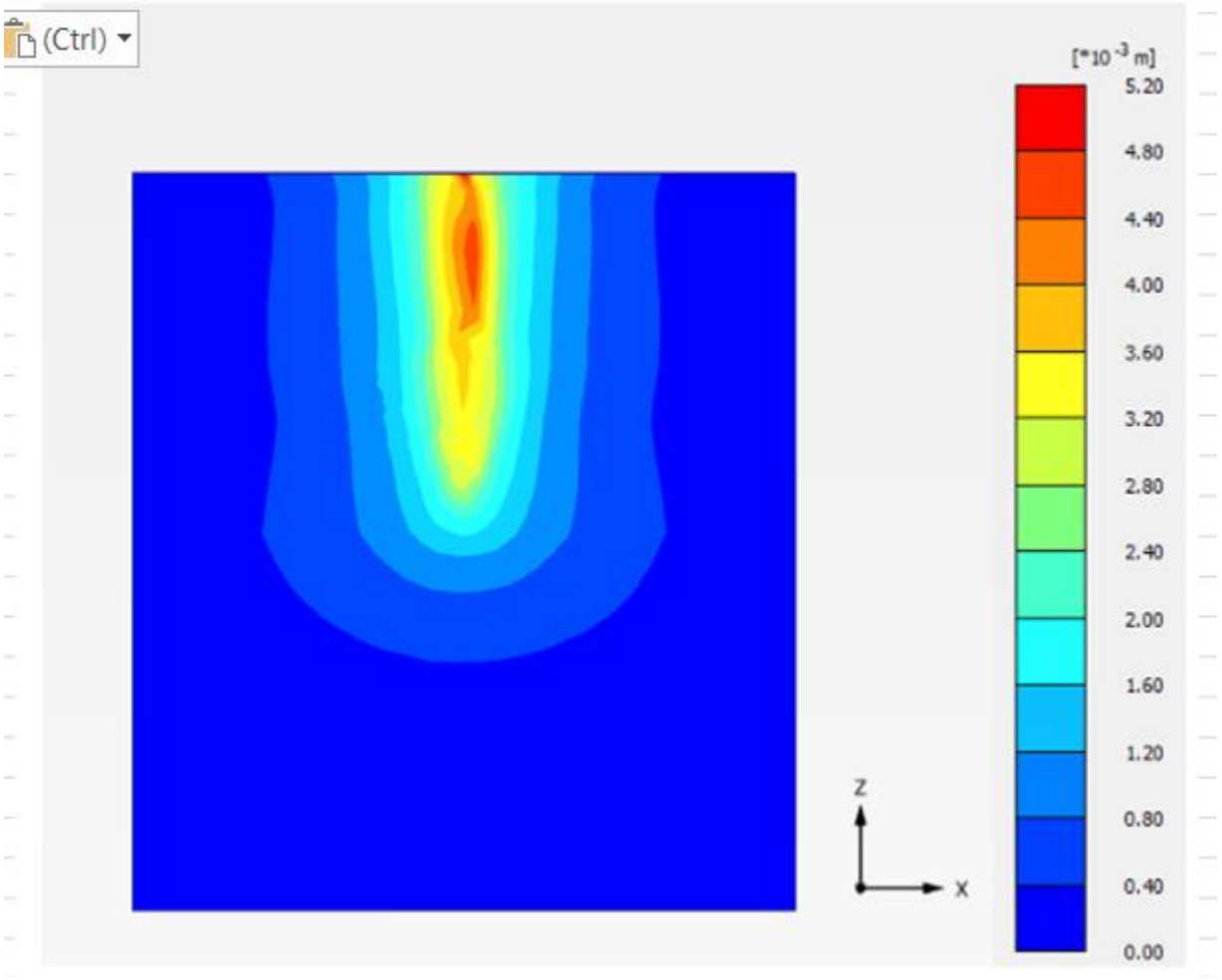


Figure - 3: Sectional view of vertical deformation curve obtained in PLAXIS 3D for pile under vertical load of 930 Kn

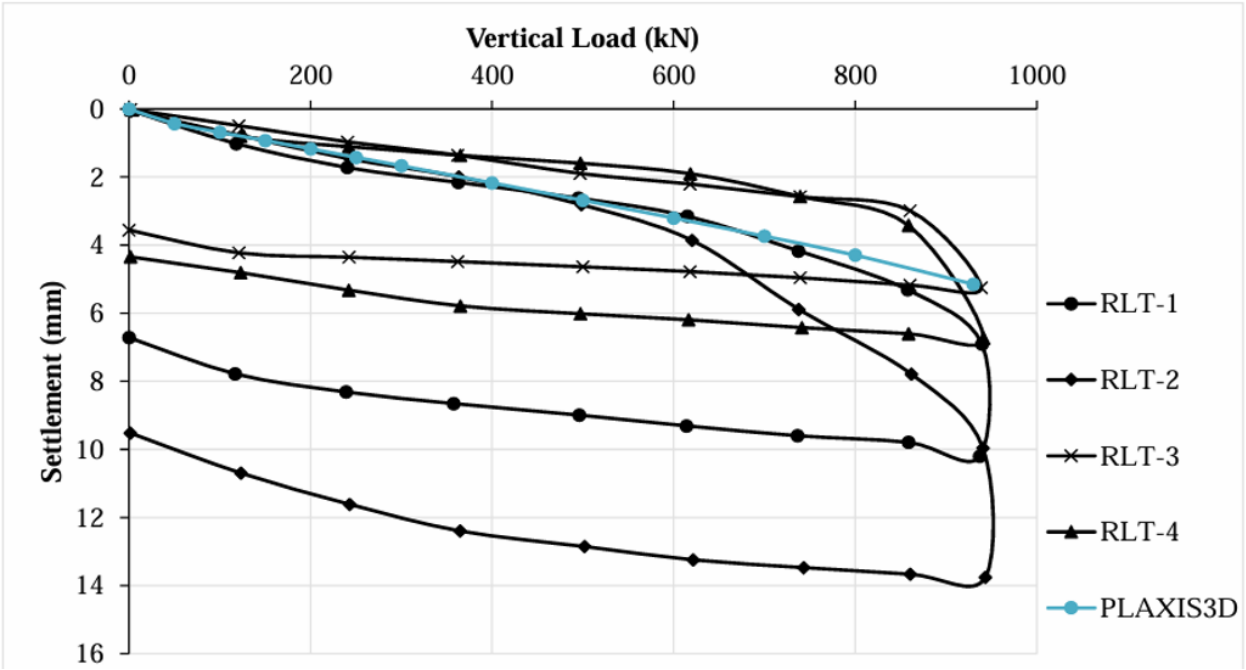


Figure - 4: Comparison of Load-Settlement curve for pile obtained through field load test and through PLAXIS 3D

1. **Analysis of Piles and Pile Cap:**

   A uniform model size of 200m x 200m x 50m is maintained for all the analysis. The column loads are applied as the point load on the pile cap. Following steps are followed while performing the analysis.

   1. Development of soil model including the fill soil.
   2. Excavation the model for placing the pile cap.
   3. Introduction of piles to the soil model.
   4. Placing the pile cap.

A total of 340 piles are first modelled in PLAXIS3D and analyses are carried out. As piles cross marked are short concreted by more than 3 m , they are neglected in the model and fresh new adjacent piles are considered in the analysis. It was observed that the allowable axial load of 775 kN (considering 25% seismic demand) was not satisfied in 22 number of piles lying at the corner and edge location of cap. This is mainly due to the misaligned built-in piles. We performed extensive iterations and suggested a most optimum design solution that is 1.2m extension on the west side for adding 43 new piles (20 piles in west side of pile cap + 12 piles in east side + 11 piles in south east side) around the periphery of the building. In addition to that 8 new piles are proposed adjacent to existing piles.

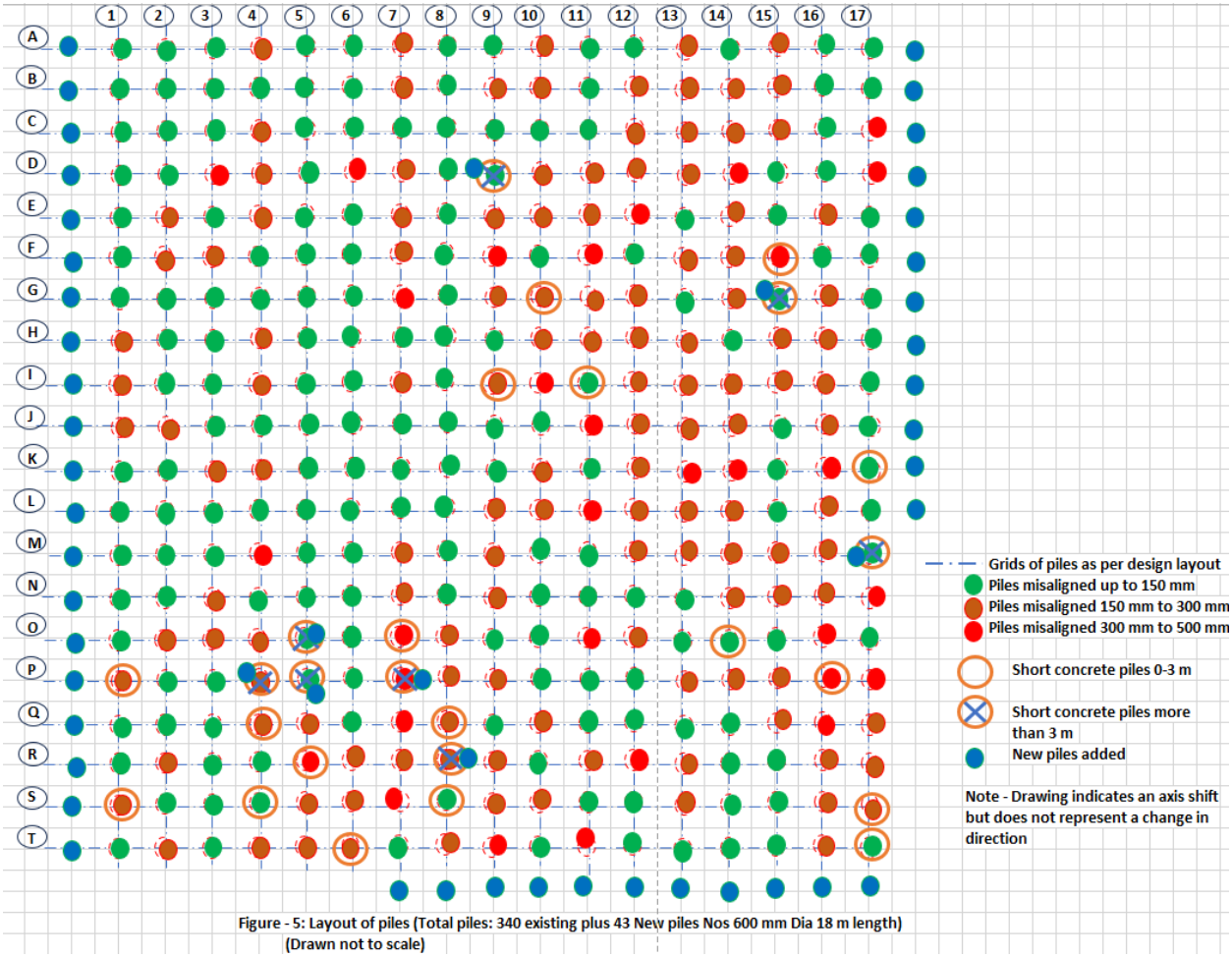


Figure - 5: Layout of piles (Total piles: 340 existing plus 43 New piles Nos 600 mm Dia 18 m length) (Drawn not to scale)

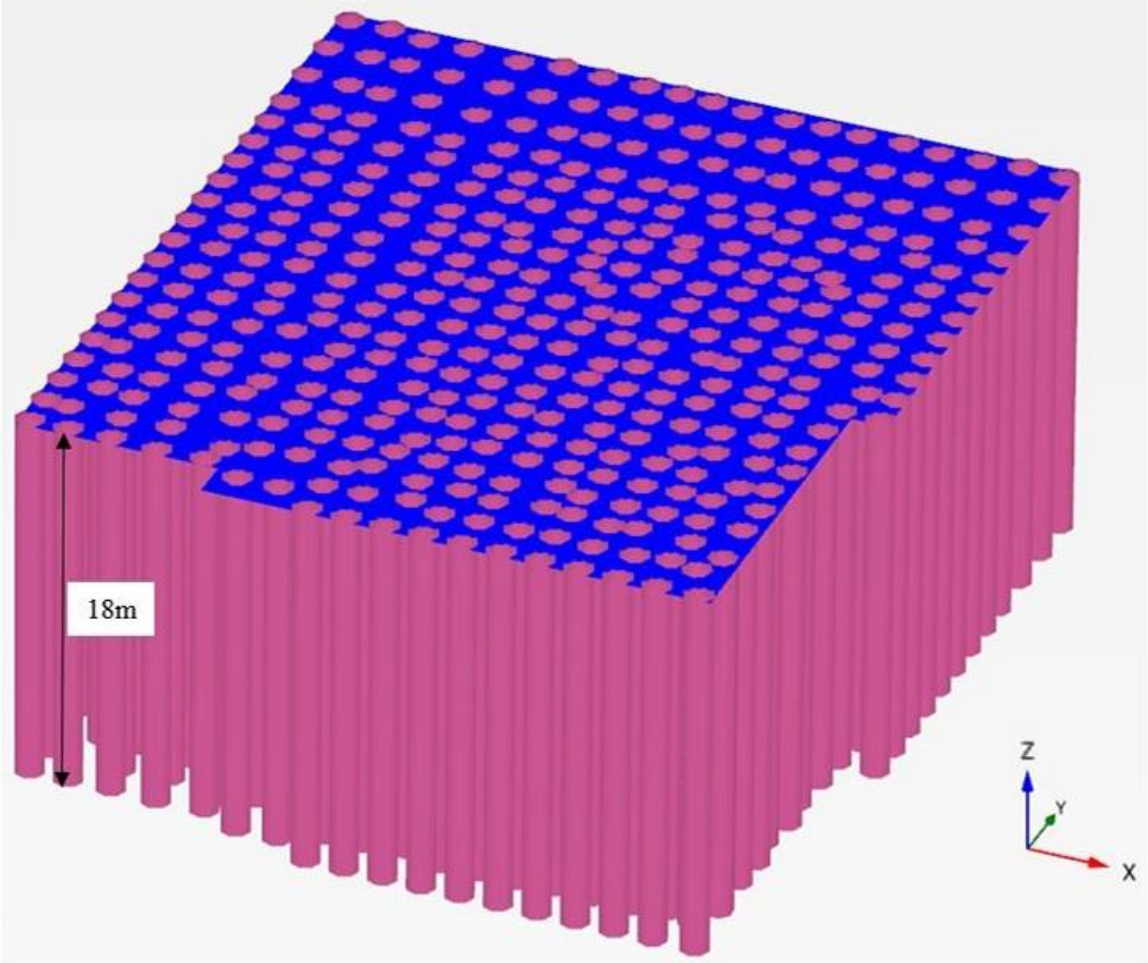


Figure 6: View of pile cap and piles in PC1 as modelled in PLAXIS3D

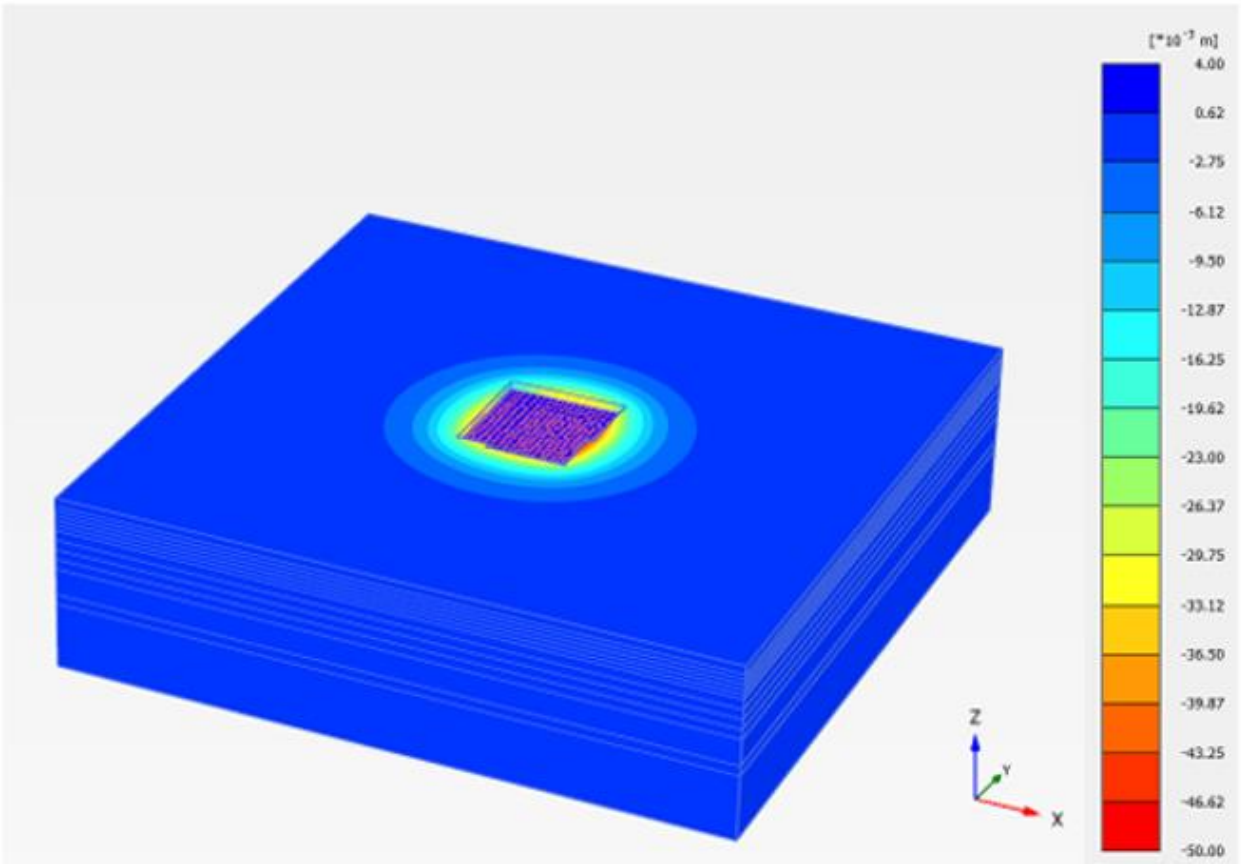


Figure - 7: Vertical deformation curve obtained under pile cap in PLAXIS 3D for building loads

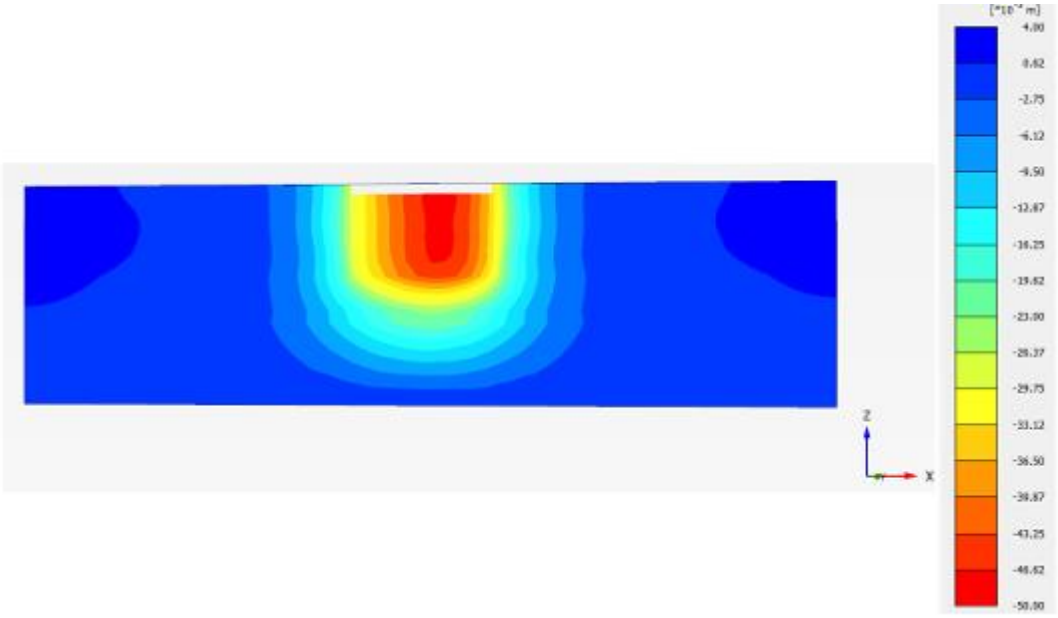


Figure - 8: Sectional view of vertical displacement under pile cap in PLAXIS 3D for building loads

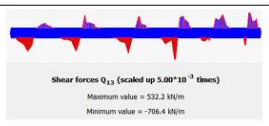
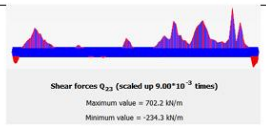
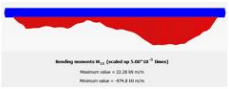
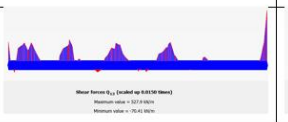
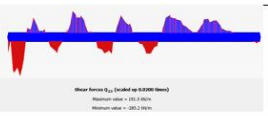
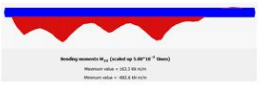
PC Number	Section	Shear force, (Q13) (kN)	Shear force, (Q23) (kN)	Bending moment, M11 (kN.m)	Bending moment, M22 (kN.m)
PC1	xx				
	yy				

Figure - 9: BMD and SFD for pile cap with the revised layout of Piles

Final conclusions:

1. The developed numerical model in PLAXIS3D was validated using field test results provided by the geotechnical agency for selected piles.

2. The results of the low-strain pile integrity tests results showed that pile shafts demonstrated uniform integrity within the acceptable limits, except for 34 piles. These piles were further analyzed for axial loads derived from the modelling of entire pile group. Axial loads were compared with the calculated capacities based on PIT test toe response shaft lengths. 5 piles were found to be marginally overloaded. HSDT load tests were conducted on these 5 piles, and the results validated them as safe.

3. As the piles selected for routine load tests conducted prior to the reporting of quality issues sufficiently representative of pie group, HSDT load tests were conducted on 7 selected piles. Results validated them as safe.

4. After multiple iterations of PLAXIS 3D analysis, the most optimal, feasible, and safe design layout required the addition of 43 new piles along the periphery of the as-built pile group. Additionally, 8 new piles were added adjacent to the 8 proposed cross-marked piles that were to discarded. Since the pile cap had not yet been cast, its thickness and reinforcement were designed based on the shear force and bending moment diagram for the augmented pile layout.

5. Although short concreted piles (0-2 m) were recommended to be developed under stringent site supervision, these piles were considered in the calculations with derated capacities equal to 50% of their actual capacity.

Remedial measures adopted:

1. Augmented layout of piles and pile cap was issued for construction.
2. Short-concreted piles (0-3 m) were excavated to the top of the concrete and developed to the desired level using reinforcement coupling and pipe shuttering.
3. Short-concreted piles more than 3 m were excluded from the strength contribution, these piles were to be kept buried in the ground without being connected to the pile cap.
4. Pile number D-15 showed possible defect at a depth of 2.5 m from the test level. It was excavated and exposed, with the poor loose concrete being chipped off. The pile was then repaired with reinforcement coupling and re-concreting.

Lessons learnt:

1. Poor construction practices, methods and a lack of stringent quality procedures led to defects in the pile's construction. Quality control is crucial for construction projects because it can lead to increased costs, extended project time line, and failure to meet the targeted production date.

2. The remedial measures aimed to utilize most of the as-built piles and provide solutions and recommendations promptly. Identifying and eliminating problems through sequential tests and analysis proved to be cost and time

effective approach. HSDT were quickly conducted without the need for any reaction arrangement. Each test required only one day to conduct one test. The entire defect analysis, along with tests and solutions, took three months time to complete.

Conflict Of Interest

No conflict of interest

Funding

No funding

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3. Identifying Defects in Deep Bored Piles - Case Studies from India by Sorabh Gupta (Vice President), Cengrs Geotechnica Pvt. Ltd., India, Email: sorabh@cengrs.com

4. Testing for Monitoring Pile Construction, Geosymposium 2008, Indian Geotechnical Society Delhi Chapter, pp 173-178

5. ASTM D4945-08, Standard Test Method for High-Strain Dynamic Testing of Piles

Biography

An accomplished Civil Engineer with over 25 years of expertise in leading engineering solutions for world-class industrial projects across diverse sectors, including chemical, oil & gas, FMCG, automotive, and power transmission industries. With a rich tenure at esteemed organizations like L&T EDRC, Mott MacDonald, and IPS, I have spearheaded the design and execution of complex technological structures and facilities. Currently serving in the Engineering Services Department at KEC International, I am dedicated to driving excellence in industrial engineering and innovation.