Predicting foundation behavior: In-situ tests for a multi-storeyed tower on alluvial sands

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ABSTRACT

For design of heavily loaded foundations of tall multi-storeyed buildings and other structures, it has become imperative to make predictions of foundation settlement as close to the actual settlement as possible. Pressuremeter tests and footing load tests can help to validate the theoretical estimates and calibrate the design profile developed on the basis of a thorough geotechnical investigation. The paper presents analysis of the geotechnical investigation and footing load tests. Settlement predictions based on the geotechnical design profile has been compared to the actual values measured from the footing load test. Numerical simulation of the test conditions by finite element method to was used to validate the field results. The results of the field test are in good agreement with theoretical predictions, thus enhancing the reliability of foundation analysis.

Keywords: alluvial sands; geotechnical investigation; foundation behavior; pressuremeter test; footing load test; numerical simulation; validating predicted settlement

1 INTRODUCTION

With the advent of multi-storeyed buildings supported on alluvium in urban areas of north India, the need for realistic assessment of foundation behavior cannot be over-emphasized.

Geotechnical investigation, usually consisting of boreholes to required depth was supplemented by pressuremeter tests for prediction of foundation settlement. Footing load tests on large size foundations offer value-addition not only by way of being a prototype test but also provide a basis for checking out the validity of the theoretical prediction models.

The paper presents a case study of a geotechnical investigation for a 43-storeyed building with two basements in Noida, Uttar Pradesh, India. To assess settlement of foundations bearing on the alluvial sand, deep boreholes and pressuremeter tests were done. After excavation for the basement was done, a footing load test was performed.

2 SOIL CONDITIONS

2.1 Regional Geology

Regionally, the eastern half of Noida forms part of Ganga alluvial plain, whereas it's western part is in close proximity of Hindon and Yamuna rivers.

The area is in the Indo-Gangetic plains (Krishnan, 1986) and forms the part of Ganga-Yamuna doab. The eastern boundary is marked by Ganga River and Yamuna River defines the western boundary. It is an almost monotonous flat plain, dissected by drainage of different orders. Quaternary sediments occur in the area to substantial depth. The newer alluvium comprises primarily of loose to medium dense sands. The older alluvium of Upper Pliestocene age consists of medium dense to dense sands, silts and clays of low to medium plasticity.

2.2 Scope of Geotechnical Investigation

Three 41-43 storeyed towers are planned at the site. The scope of the geotechnical investigation for each tower included four boreholes to 40 to 80 m depth, pressuremeter tests in one borehole and one cross-hole seismic test.

After excavation to the founding level of 9 m depth, a RCC footing of size 2 m by 2 m was cast and load tested. The results were used for a better assessment of modulus of subgrade reaction.

The paper presents results of one 43-storeyed tower. Settlement predictions from borehole and pressuremeter data have been compared with footing load test results and numerical modeling.

2.3 Stratigraphy

Geotechnical investigation for the tower revealed that the soils at the site are alluvial in nature and primarily consist of fine sand with thin minor layers of sandy silt to the maximum explored depth of 80 m. Groundwater was met at 10.6-13.6 m depth during the period of the investigation. Typical data to about 35 m depth from two boreholes is presented on Fig. 1.

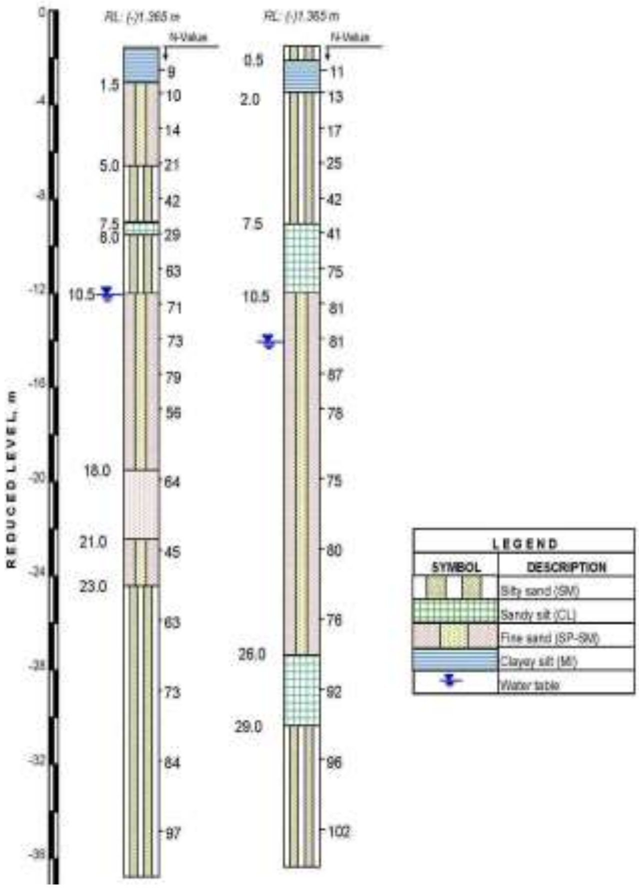

Fig. 1. Typical borehole data

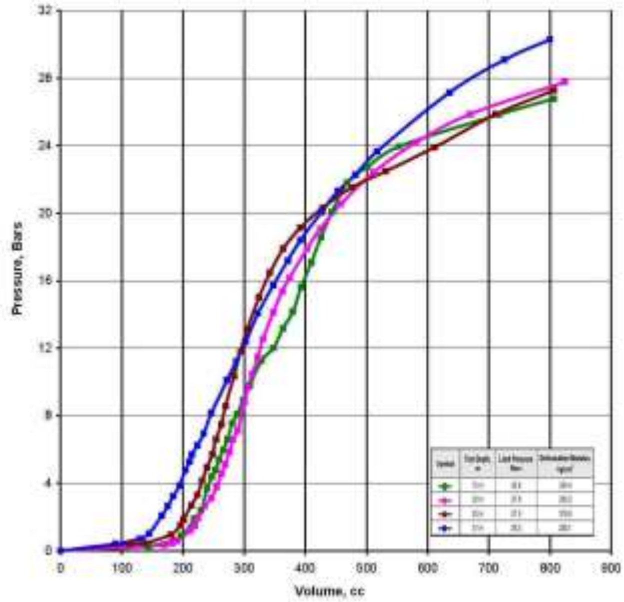

Fig. 2. Pressuremeter test results

3 DESIGN PROFILE

The field and laboratory test results are summarized on Fig. 3.

Table 1 presents the soil parameters were selected for the settlement analysis based on the field and laboratory test results obtained from the borings done on site.

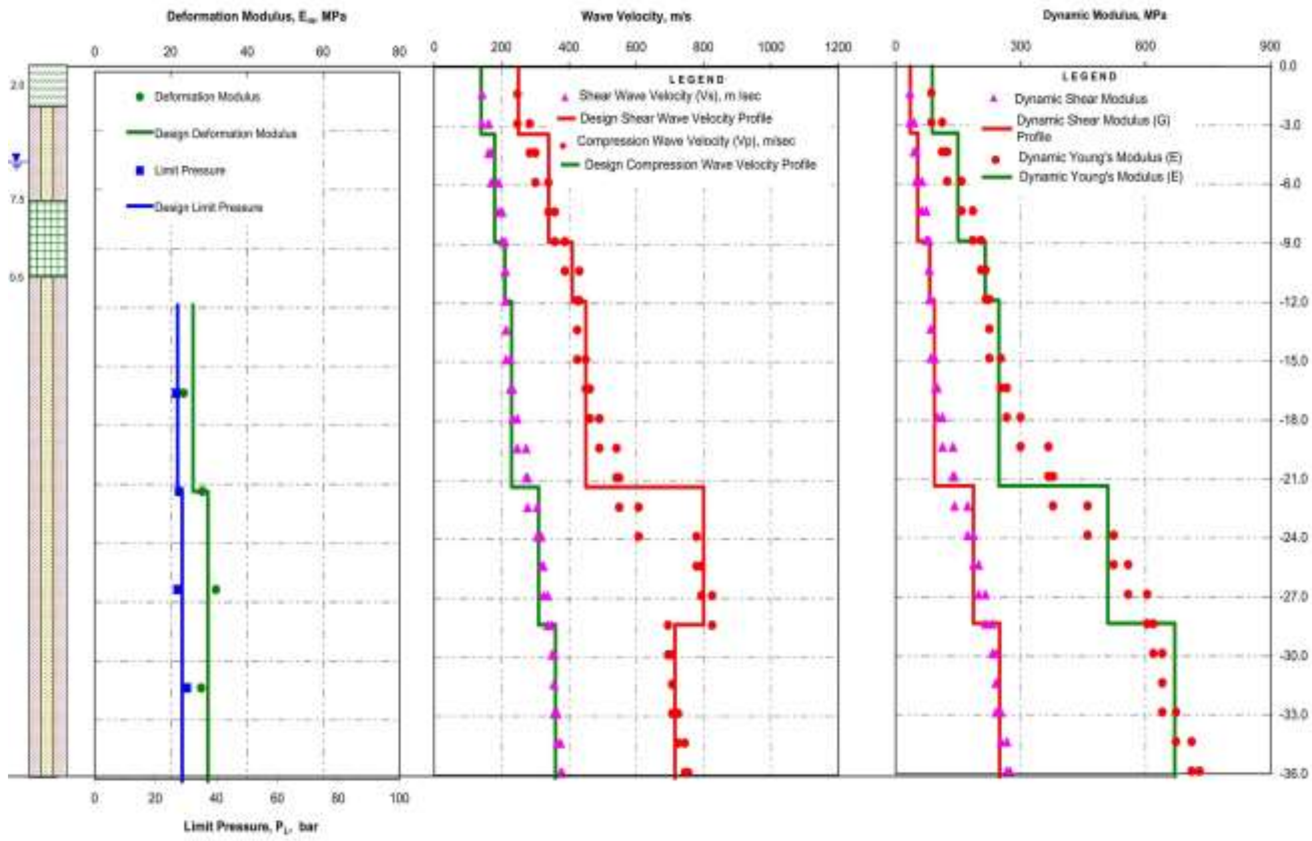

Fig. 2. Soil Parameters interpreted from geotechnical investigation

Table 1 Design Profile

Depth, m From	Depth, m To	N	γ	c	ϕ°	E	E_{PMT}	E_d
0.0	2	12	17.0	75	4	28		
2.0	7.5	20	17.5	0	30	44		53
7.5	10.5	26	17.5	90	4	100	240	82
10.5	20.0	30	18.5	0	31	250	259	93
20.0	27.0	35	19.0	0	31	290	298	187
27.0	35.0	82	19.2	0	32	290	298	250

where
γ = bulk density of soil, KN/m^3
c = cohesive intercept, kPa
ϕ = angle of internal friction, degrees
N = field SPT N-value
E = modulus of elasticity (static), MPa
E_{PMT} = deformation modulus (pressuremeter), MPa
E_d = dynamic Young's modulus (cross-hole seismic test), MPa

The E values selected for analysis was based on empirical correlations with SPT values.

Haberfield (2013) suggests computing the static E as the dynamic Young's modulus determined from cross-hole seismic test divided by a factor of 5.

The Japanese design standard suggests:

E= 2600 to 2900 N (kPa)

This correlation matches well with pressuremeter modulus as well as E assessed from footing load test.

4 SETTLEMENT ANLYSIS OF FOOTING

4.1 Approach

Settlement analysis has been done for a 2 m x 2 m size foundation by the following methods:

1. Classical approach - immediate settlement using elastic theory as given in IS: 8009 (Part 1)-1976.
2. Hough's curves (proposed by Hough. 1969) were used to estimate settlement.
3. Settlement analysis using pressuremeter data has been done using the design rules proposed by Clarke (1995).
4. Finite Element analysis using MIDAS GTS NX (3D) software.

The computed settlement has been compared with the footing load test results to assess of the expected foundation behavior vis à vis the measured values.

4.2 Computed Settlement

The settlement of a 2 m x 2 m size square footing bearing at 9 m depth at different loading intensities, computed on the basis of the conventional methods and pressuremeter are summarized in Table 2.

Table 2. Computed Settlement (2 x 2 m footing)

Applied Bearing Pressure, kPa	Elastic Theory	Hough's approach	Pressuremeter analysis
200	3.6	2.1	2.0
400	7.2	3.7	5.9
600	10.8	4.9	8.8

5 FOOTING LOAD TEST

A footing load test (FLT) was performed at 9 m depth using a 2 m x 2 m size test RCC footing (M-35 concrete grade) of 1 m thickness. The test procedure was in general accordance with IS: 1888-1982.

A photograph showing the test arrangement is presented on Fig. 3. A load frame arrangement was used to carry out the test. Eight (8) anchor piles were used to provide the reaction system. The top 6 m length of the reaction piles was filled with sand to avoid any interference within the footing influence zone.

Fig. 3. Set-up for footing load test

The footing was loaded by pushing up against the anchor arrangement using a 5000 kN capacity hydraulic jack. Four dial gauges were used to measure footing settlement with reference to a stable reference bar. The load was applied in 6 small increments of 400 kN each; up to a maximum loading intensity of 2400 kN.

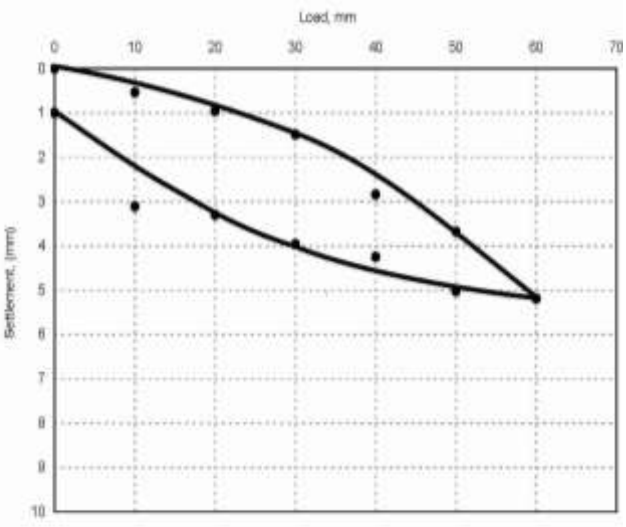

Fig. 4. Load-settlement curve - footing load test

For a loaded area of 4 m^2, this is equivalent to a maximum bearing pressure of 636 kPa exerted on the plate. Each load was held until the time rate of settlement became negligible (less than 0.02 mm per minute). The settlement of the footing at the maximum test load of 2400 kN was 5.1 mm. Figure 4 represents the load versus settlement graph obtained from the test.

The modulus of subgrade reaction interpreted from the test is 140 MN/m^3 and the E value is 250 MPa.

6 NUMERICAL SIMULATION

The footing load test was simulated using commercially available finite element software MIDAS GTS NX. A three dimensional model was selected for a better assessment of settlement. The footing size used was 2 m x 2 m bearing at 9 m depth.

The coordinate system used is the standard Cartesian coordinate system, where z-axis corresponds to the direction of depth and the x and y-axes correspond to the horizontal stretch of the ground. For the vertical boundaries at the nodes, the vertical displacement u_z is left free. The problem was modeled as a three-dimensional model considering uniformly distributed load being applied on the footing. Figure 5 illustrates the basic model used.

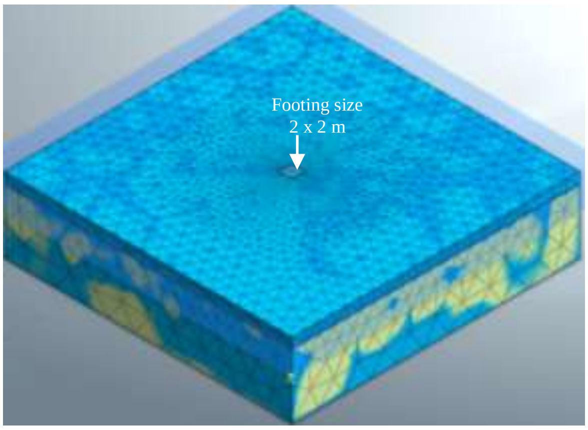

Fig. 5. Three dimensional finite element model

Mohr-Coulomb constitutive model was used to model the soil layers. The design profile as give in Table 2 was used. Typical settlement contours under pressure of 400 kPa is illustrated on Fig. 6.

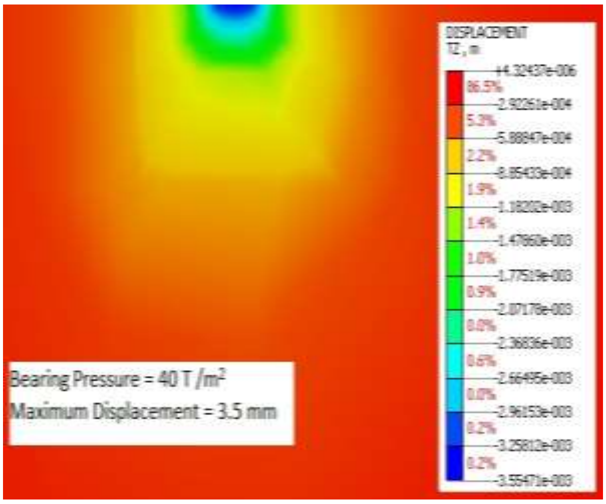

Fig. 6. Settlement contours from 3D finite element analysis (MIDAS)

Vertical settlements at centre of footing computed from the finite element modeling and that measured in footing load test are summarized in Table 3.

Table 3: Settlement (MIDAS 3D) and footing load test

Applied Bearing Pressure, kPa	Centre Settlement (MIDAS), mm	Settlement measured in FLT, mm
200	1.7	1.0
400	3.5	2.9
600	5.5	5.1

The settlement computed from the finite element analysis matches well with the settlement estimated from the footing load test.

7 COMPARISON OF VALUES

The results of field test are in good agreement with most theoretical predictions. While the Hough's approach and pressuremeter analysis compare well with the footing load test results, the elastic theory overestimates the settlement. Table 4 makes a comparison of the predicted values versus the measured settlement.

Table 4: Comparison of Estimated settlement with FLT

Applied Bearing Pressure	Ratio of computed settlement to that measured in footing load test			
	Elastic Theory	Hough	Pressure -meter	FEM
200	3.6	2.1	2.0	1.7
400	2.5	1.3	2.0	1.2
600	2.1	1.0	1.7	1.0

7 CONCLUDING REMARKS

Selection of realistic design parameters requires a thorough geotechnical investigation and in-situ testing to minimize uncertainties, empiricism, etc. Since foundation settlement predictions are only as good as our test data, the authors advocate use of footing load tests to calibrate the theoretical design profile against actual site performance. In alluvial deposits, tests such as pressuremeter and footing load tests are can effectively validate the design parameters for a performance based design of foundations.

REFERENCES

Krishnan, M.S. (1986), Geology of India & Burma, CBS Publishers, New Delhi.

IS: 8009 (Part 1)-1976 Reaffirmed 2003, Indian Standard Code of Practice for Calculation of Settlements of Foundations, Part 1, Shallow Foundations subjected to Symmetrical Static Vertical Loads, Bureau of Indian Standards, New Delhi

Hough, B.K. (1969), Basic Soils Engineering, Ronald Press, New York.

Clarke, BG (1995) Pressuremeters in Geotechnical design. Blackie Academic and Professional, London.

Geocode 21 (2002), Japanese foundation design guideline.

IS: 1888-1982, Reaffirmed 2002 Method of Load test on Soils (Second Revision), Bureau of Indian Standards, New Delhi