International Journal of Science, Technology and Management (IJSTM) ISSN (online): 2231-775X
Volume 1, Issue 1, 2025

Geotechnical Investigation and Structural Design of a High-Rise Residential Building in Gurugram, India

Amandeep [1], Monu Kumar [2], Harish chawla [3] Department of Civil Engineering
BRCM College of Engineering & Technology, Bahal, India
[1]M. Tech Scholar, Department of Civil Engineering, BRCMCET, BAHAL
[2]Assistant Professor, Department of Civil Engineering, BRCMCET, BAHAL
[3]Assistant Professor, Department of Civil Engineering, BRCMCET, BAHAL

1.0 Abstract

This paper presents a site-specific geotechnical and structural evaluation for a proposed high-rise residential tower on a 28.82-acre plot in Gurugram, Haryana, located in seismic Zone V. The ground investigation program included fifteen boreholes extending to 40.45 m, Standard Penetration Tests (SPT) at 1.5 m intervals, and twenty-nine electronic Cone Penetration Tests (e-CPT).
Groundwater was recorded at depths between 7.4–9.0 m. Laboratory investigations, covering Atterberg limits, compaction, UCS, triaxle shear, and consolidation, revealed sandy silts in the upper 10 m, underlain by silty sands up to 28 m, and dense strata beyond. Liquefaction assessment indicated a minimum Factor of Safety of 0.86 at 3 m, increasing above 2.0 beyond 12 m. Field density testing confirmed compaction levels of 98–99%. Pile analysis for 600 mm diameter foundations showed lateral capacities ranging from 45 t at 20 m to 105 t at 40 m. Structural analysis of a 110.3 m tower in ETABS demonstrated maximum settlements below 25 mm and inter- storey drifts within IS 1893 limits. The findings emphasize the importance of integrating geotechnical characterization with structural modeling to ensure stability, serviceability, and seismic safety of high-rise developments in critical seismic zones.

2.0 Introduction

This research presents an integrated geotechnical and structural analysis for a high-rise residential development on a 28.82-acre site in Gurugram, Haryana, India. Subsurface exploration comprised fifteen boreholes drilled to 40.45 m, Standard Penetration Tests (SPT) at 1.5 m intervals, and twenty-nine electronic Cone Penetration Tests (e-CPT). Groundwater was encountered between 7.4–9.0 m. Laboratory testing, including Atterberg limits, compaction, UCS, triaxial shear, and consolidation, characterized sandy silts (0–10 m), silty sands (10–28 m), and dense strata below 28m. Liquefaction analysis indicated a Factor of Safety of 0.86 at 3 m, improving to >2.0 beyond 12m. Field density tests confirmed 98–99% relative compaction. Pile analysis for 600 mm diameter piles yielded lateral capacities ranging from 45 to 105 t between 20–40 m depths. Structural modelling of a 110.3 m tower in ETABS verified maximum settlements within 25 mm and inter- storey drifts within IS 1893 limits. The results highlight the critical role of integrating detailed geotechnical evaluation with structural modelling to ensure serviceability, safety, and seismic resilience of high-rise structures in Zone V regions.

2. Literature Review

Soil–Structure Interaction (SSI) is widely recognized as a controlling factor in the seismic behavior of tall structures. Early theoretical contributions by Wolf (1985) provided the basis for analyzing foundation dynamics, while Gazetas (1991) showed that SSI can shift natural frequencies and increase seismic displacements. Recent analyses, including Hulagabali et al. (2023), have confirmed that insufficient pile embedment amplifies structural drifts, underscoring the importance of reliable SSI modeling in high seismic zones such as Zone V.

The assessment of liquefaction remains central to seismic geotechnics. Penetration resistance–based correlations first proposed by Seed and Idriss (1971) underpin present-day design procedures and are embedded in IS 1893:2016. Evidence from the Bhuj earthquake (2001) demonstrated the destructive role of liquefaction in shallow foundations (Choudhury & Sitharam, 2004). Contemporary design practice relies on cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) frameworks expressed as factors of safety, which remain the most effective tools for evaluating liquefaction potential in sandy deposits.

The design of deep foundations has been strongly influenced by the work of Poulos and Davis (1980), particularly for predicting pile load–settlement response. Poulos (2017) further highlighted the efficiency of combined pile–raft foundations (CPRF), which balance load transfer between piles and raft. Case studies from international projects (Katzenbach & Leppla, 2024) and recent Indian experiments (Mittal, 2025) validate CPRF as a practical and resilient foundation system for high-rise construction in variable soils.

Quality assurance during construction is equally important for long-term performance. The IS 2720 series specifies protocols for laboratory compaction and shear strength testing, as well as in-situ density checks. Achieving more than 95% of the maximum dry density (MDD) is widely regarded as necessary to control settlement (Sharma & Sivapullaiah, 2018). At the present project site, field density tests showed compaction of 98–99%, exceeding requirements and confirming effective ground preparation.

Past earthquakes in India further reinforce the need for such practices. The Bhuj earthquake of 2001 caused widespread damage to multi-storey buildings due to liquefaction-related foundation failures (Sitharam & Govindaraju, 2004; Choudhury, 2005). These lessons have driven code revisions and encouraged the adoption of advanced systems such as barrettes, diaphragm walls, and CPRF in the Delhi–NCR region (Kumar et al., 2020).

The literature establishes four pillars for designing high-rise structures in seismic regions: accurate SSI modelling, comprehensive liquefaction evaluation, optimized deep foundation systems, and strict construction quality control. These principles provide the framework for the present study, which integrates detailed site-specific investigations with structural modelling of a 110.3 m tower to ensure serviceability and seismic resilience in Zone V conditions.

3.0 Methodology

A comprehensive geotechnical and structural investigation was performed to characterize subsurface conditions, evaluate seismic susceptibility, and develop a safe foundation–superstructure system for the proposed 110.3 m residential tower. The methodology involved field exploration, laboratory testing, soil characterization, liquefaction analysis, pile foundation design, and structural modelling, all conducted in accordance with Indian Standards.

3.1 Field Exploration

Fifteen boreholes were drilled up to 40.45 m depth using rotary drilling equipment with bentonite slurry circulation to ensure borehole stability. Standard Penetration Tests (SPT) were carried out at 1.5 m intervals in line with IS 2131:1981, yielding N-values for assessing soil density and strength. In addition, twenty-nine electronic Cone Penetration Tests (e-CPTs) were conducted, providing continuous profiles of cone resistance (qc), sleeve friction (fs), and pore water pressure (u2). Groundwater was encountered at depths between 7.4 and 9.0 m below the surface.

Compaction was verified using Field Density Tests (FDTs) conducted by the sand replacement method (IS 2720 Part 28:1974) and the core cutter method (IS 2720 Part 29:1975). Results indicated 98–99% relative compaction, exceeding the minimum requirement of 95%.

3.2 Laboratory Testing

Disturbed and undisturbed samples obtained during drilling were tested as per IS 2720 series. Index properties such as Atterberg limits and grain size distribution were determined, while compaction tests (Modified Proctor) established Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). Strength parameters were derived from Unconfined Compressive Strength (UCS), direct shear, and consolidated undrained triaxial shear tests with pore pressure measurement. One-dimensional consolidation tests yielded settlement parameters (Cc, Cr, Cv).
Chemical tests confirmed acceptable levels of sulphates, chlorides, and organics, indicating no aggressive conditions for reinforced concrete.

3.3 Soil Stratigraphy

The soil profile indicated sandy silts up to 5 m, silty sands to 10 m, medium dense sands to 20 m, dense sands up to 30 m, and very dense sands with gravel beyond 30 m. This progression confirmed increasing stiffness and bearing capacity with depth.

Table 3.1: Soil Profile from Borehole and Laboratory Results

Depth Range (m)	Soil Type	PI (%)	γ (kN/m³)	Relative Density
0–5	Sandy Silt	12	18.1	Loose
5–10	Silty Sand	9	–	Medium
10–20	Medium Dense Sand	–	19.0	Medium Dense
20–30	Dense Sand	–	19.6	Dense
>30	Very Dense Sand/Gravel	–	–	Very Dense

3.4 Liquefaction Analysis

3.4.1 Pile Foundation Design

Foundation analysis was carried out as per IS 2911 (Part 1/Section 2):2010. 600 mm diameter bored cast-in-situ piles were analysed for lateral load capacity.

Table 3.2: Pile Lateral Capacity

Embedment Depth (m)	Diameter (mm)	Capacity (t)
20	600	45
40	600	105

Plot highlights rapid increase in lateral resistance with depth, reflecting the contribution of dense and very dense strata.

3.4.2 Structural Modeling

The structural analysis of the 110.3 m tower was conducted using ETABS and STAAD Pro. Design loads were considered in line with IS 875 (Parts 1–3), seismic forces per IS 1893:2016 (Zone V), reinforced concrete provisions as per IS 456:2000, and ductile detailing provisions in accordance with IS 13920:2016. Pile design was validated against IS 2911. Soil–structure interaction was included by modelling soil spring stiffness derived from the geotechnical parameters.

The analysis results indicated maximum settlements of 25 mm, which is below the permissible 50 mm limit, and inter-storey drift ratios were within the IS 1893 limit of 0.004h. This confirms that the integrated geotechnical–structural approach satisfies both safety and serviceability requirements.

4.0 Results and Analysis

4.1 Results

The outcomes of the geotechnical and structural investigation are summarized under soil stratigraphy, in-situ testing, laboratory evaluation, liquefaction assessment, pile capacity, and structural response. Both tabulated data and graphical outputs are included for clarity.

Table 4.A Soil Stratigraphy and Index Properties

Depth Range (m)	Soil Type	PI (%)	γ (kN/m³)	SPT N-value
0–5	Sandy Silt	12	18.1	8–12
5–10	Silty Sand	9	-	12–15
10–20	Medium Dense Sand	-	19	15–22
20–30	Dense Sand	-	19.6	28–36
>30	Very Dense Sand/Gravel	-	-	>50

The soil becomes progressively denser with depth, with very dense sand and gravel layers beyond 30 m offering suitable conditions for pile foundations.

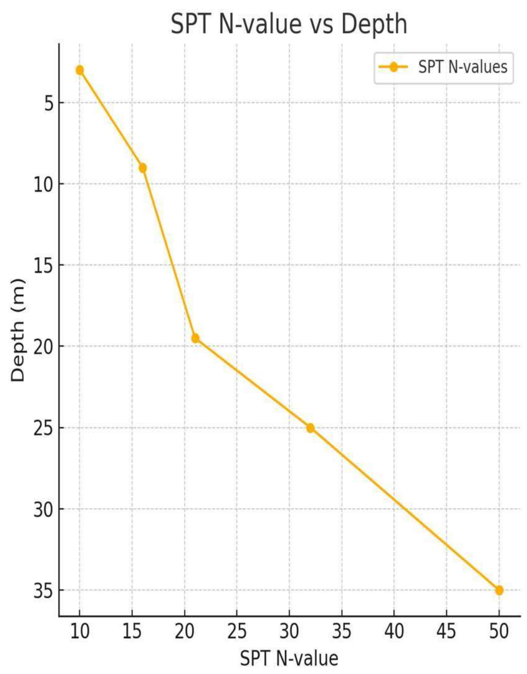


Figure 4.1: SPT N-value vs Depth

Table 4.B Cone Penetration Test (CPT) Results

Depth (m)	qc (MPa)	Friction Ratio (%)	Ic Value	Soil Behavior
0–5	3–5	3–4	>2.6	Sandy Silt
5–10	5–8	2–3	2.2–2.5	Silty Sand
10–20	8–15	1.5–2	2.0–2.2	Medium Sand
20–30	15–25	<2	<2.0	Dense Sand
>30	>25	<2	<1.8	Dense Sand/Gravel

CPT results confirm the soil transitions observed in boreholes, with resistance increasing sharply after 20 m.

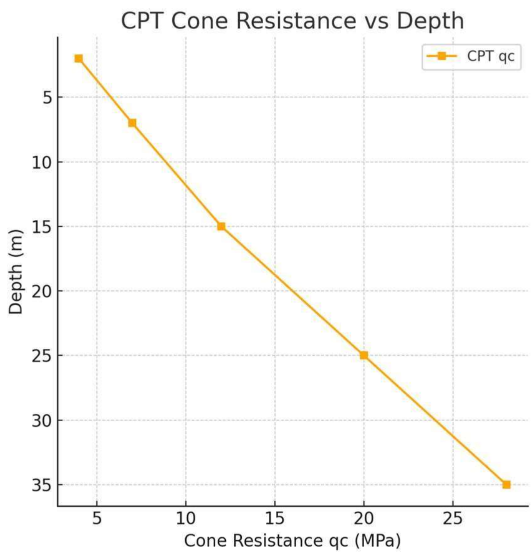


Figure 4.2: CPT Cone Resistance vs Depth

Table 4.C Liquefaction Assessment

Depth (m)	FS	Liquefaction Status
3	0.86	Susceptible
6	1.1	Marginal
9	1.55	Safe
>12	>2.0	Stable

Liquefaction analysis shows that the upper 6 m is vulnerable, while layers below 12 m are safe against seismic shaking.

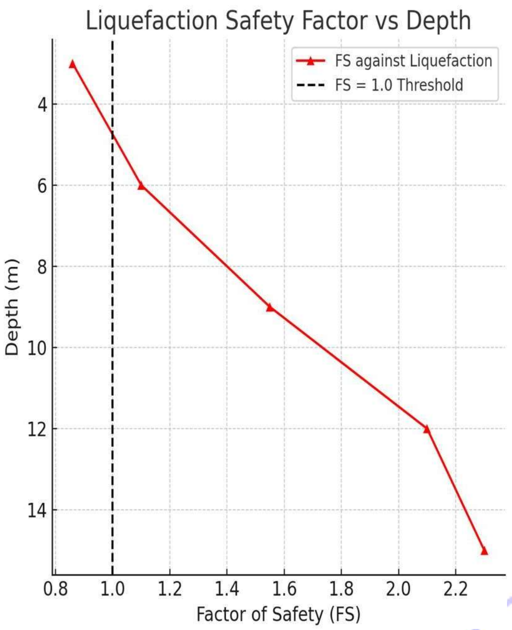
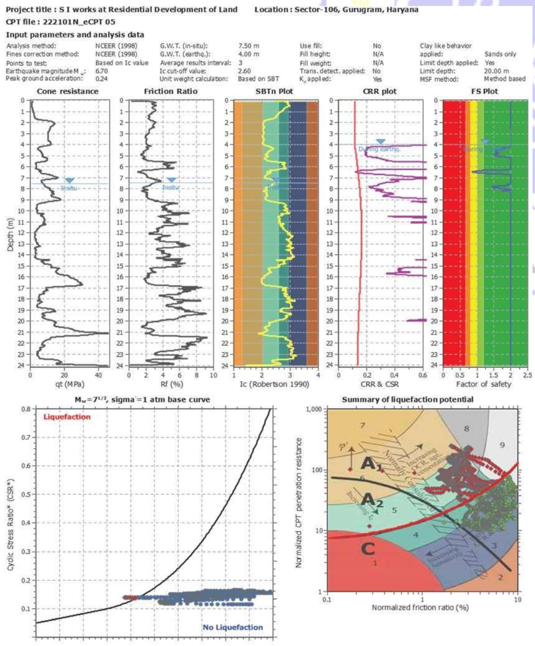


Figure 4.3: Liquefaction Safety Factor vs Depth



4.D Pile Foundation Performance

Embedment Depth (m)	Diameter (mm)	Capacity (t)
20	600	45
40	600	105

Pile resistance increases with embedment, with piles at 40 m providing more than twice the lateral resistance compared to 20 m.

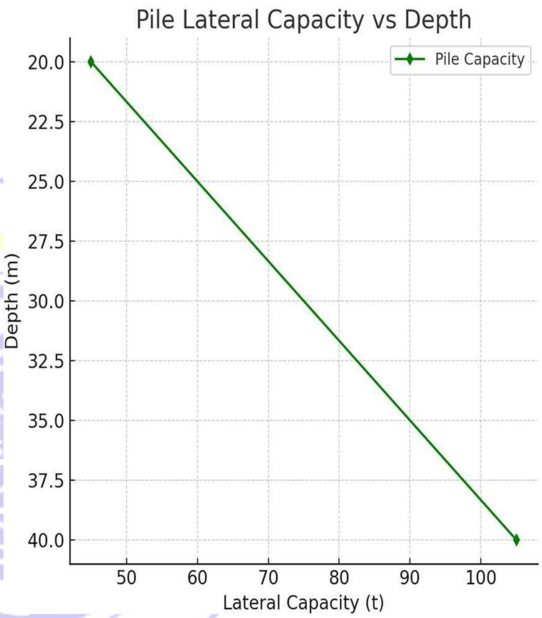


Figure 4: Pile Lateral Capacity vs Depth

5.1 Structural Modeling Results

Parameter	Result	IS Code Limit
Settlement	25 mm	50 mm (IS 800)
Drift Ratio	<0.004h	≤0.004h (IS 1893)
Fundamental Period	~3.2 s	-
Mode Shape	Sway	-

The structural model confirms settlements and drift ratios are within permissible limits, ensuring serviceability and seismic safety in Zone V.

5.0 Discussion

The findings of the investigation indicate that the site can safely accommodate a high-rise structure when deep pile foundations are used. Subsurface exploration shows a clear transition from relatively loose sandy silts in the upper five meters, with SPT N-values in the range of 8–12 and cone resistances of 3–5 MPa, to very dense sand and gravel deposits at depths greater than thirty meters, where N-values exceeded 50 and cone resistance was greater than 25 MPa.
Comparable soil sequences have been reported in other parts of Gurugram and along the Dwarka Expressway, where high-rise towers were also supported on piles terminating in dense strata beyond 25–30 m. The increase in stiffness with depth provides favourable conditions for settlement control and fulfils the requirements of IS 2911 for pile foundations.

Liquefaction assessments, carried out using both SPT and CPT correlations, reveal that the near-surface sandy silt layers up to about 6 m are potentially unstable, with a factor of safety as low as 0.86 at 3 m depth. In contrast, soil layers below 12 m showed factors of safety greater than 2.0, confirming liquefaction resistance at design earthquake loading. This stratified behaviour is consistent with observations from previous seismic events. For example, in Bhuj (2001) severe foundation tilts occurred in buildings founded on loose sandy fills, whereas structures bearing on deeper dense strata were less affected. Similar trends were recorded in Niigata (1964) and Christchurch (2011), where shallow layers liquefied but deeper competent soils limited overall damage. By embedding piles into dense strata, the present design avoids reliance on the susceptible upper soils and thereby reduces the risk of deformation during earthquakes.

Analysis of pile performance shows lateral capacities of about 45 tonnes at 20 m and 105 tonnes at 40 m for 600 mm bored piles. These values increase with depth in response to the transition from medium dense to very dense granular layers. The capacities are consistent with measurements from other Indian high-rise projects, including those in Mumbai, and align with international practice where bored piles in dense sands typically mobilize capacities in excess of 100 t at similar depths. The results provide a margin of safety in line with IS 2911 provisions and compare well with recommendations in offshore foundation guidelines such as API RP 2A, which advocate similar safety factors.

Numerical modelling of the 110.3 m tower demonstrated satisfactory structural performance. The predicted settlement of 25 mm is within the 50 mm limit prescribed by IS 800 and IS 2950. Inter-storey drift ratios remained below 0.004h, complying with IS 1893:2016. The fundamental natural period of about 3.2 seconds corresponds well with empirical estimates for buildings of similar height and slenderness and is comparable with measured values in international studies of tall buildings in Seoul and Tokyo.
Importantly, by implementing ductile detailing in accordance with IS 13920, the design provides energy dissipation capacity that reduces the likelihood of brittle column or beam failures. This directly addresses shortcomings observed in Nepal (2015), where poor detailing led to excessive drift and partial collapse in many RC structures.

When compared with past earthquake case histories, the approach adopted here demonstrates resilience. Failures reported in Bhuj and Kobe were often linked to pile foundations terminating in liquefiable or weak strata, whereas the current design ensures that load transfer occurs in dense, non-liquefiable layers. Similarly, excessive deformation and lack of ductility that contributed to collapses in Nepal are avoided here through codal compliance and advanced numerical checks. From an international perspective, the integrated geotechnical–structural methodology used at this site is in line with strategies followed in high-seismicity regions such as Japan and California, where deep piles and ductile detailing are considered essential for tall buildings.

In summary, the combined results demonstrate that the use of deep piles founded in dense strata, coupled with liquefaction hazard mitigation and rigorous structural detailing, ensures compliance with Indian codes and parallels global best practice. The tower is expected to perform satisfactorily under both service and seismic loading conditions, offering a robust foundation–superstructure system for Zone V environments.

6.0 References

- Wolf, J. P. (1985). Dynamic soil–structure interaction. Englewood Cliffs, NJ: Prentice-Hall.
- Gazetas, G. (1991). Formulas and charts for impedances of surface and embedded foundations. Journal of Geotechnical Engineering, 117(9), 1363–1381. https://doi.org/10.1061/(ASCE)0733-9410(1991)117:9(1363)
- Seed, H. B., & Idriss, I. M. (1971). Simplified procedure for evaluating soil liquefaction potential. Journal of the Soil Mechanics and Foundations Division, 97(9), 1249–1273. https://doi.org/10.1061/JSFEAQ.0001662
- Poulos, H. G., & Davis, E. H. (1980). Pile foundation analysis and design. New York, NY: John Wiley & Sons.
- Poulos, H. G. (2017). Tall building foundation design: Research to practice. Innovative Infrastructure Solutions, 2(1), 1–20. https://doi.org/10.1007/s41062-016-0064-4
- Choudhury, D., & Sitharam, T. G. (2004). Seismic design considerations for soil–structure systems in India after the Bhuj earthquake. Current Science, 87(10), 1396–1400.
- Sitharam, T. G., & Govindaraju, L. (2004). Geotechnical aspects of Bhuj earthquake. Current Science, 86(3), 394–403.
- Bureau of Indian Standards. (2016). IS 1893 (Part 1): Criteria for earthquake resistant design of structures. New Delhi, India: BIS.