Normal Project Flow

- Step 1: The client/owner defines the project scope and specific project requirements.

- Step 2: The architect in consultation with the owner and sometime with structural consultants decides the overall initial layout and the type of structures to suit the owners requirements.

- Step 3: Soil Investigations and arriving at optimum foundation solutions, through continuous interaction between Foundation and Structural Consultants.
Factors to consider

- How deep is good strata? → Sand is Good!
- How is water table situation?
  - What is the season when geotechnical investigation was done? (Moisture content effect, when clayey strata)
- Are there any special soil conditions?
  - Expansive, dispersive or soft clay?
  - Poorly graded soils? → Gravel mix deposits!
- What is the architectural plan and what are the expected loads on different columns?
  - Clubbing the columns into category A, B, C … based on the load ranges, before making decisions
  - Column spacing at different locations?
  - Special walls, enclosures or columns?
- Is there any variation in the strata across the building plan
  - Change in soil type
  - Inclines strata (Clays?)
  - Partial fill ground
  - ……?
- In case bearing capacity criteria prevails → Is it total stress or effective stress analysis possible in calculation?
- What are the neighboring structures and where is the line of property?
- What are the construction requirements and constraints?
- Despite all that, there is uncertainty at each level

What is the allowable bearing pressure for different foundations?
Alternative Foundation Systems for Buildings

- Strip Footing
- Spread Footing?
- Combined Footing?
- Raft with Basement?
- Piled Assisted Raft System?
- Raft with Ground improvement?

Strip Footing or Spread Footing?

- Loads are relatively small → (3 to 4 storey buildings)
- Ground is firm from shallow depth
- Columns loads are reasonable and well spaced
- Most preferred due to ease of construction
- Consider uniform depth as much as possible → vary the dimensions; but depth can change if needed
- Plan of utilities and finished level → minimum depth of foundation
- Comparison of field test data and laboratory test data → major discrepancy means lack of confidence in design parameters → find the reasons or conduct more tests
Strip Footing or Spread Footing?

- Allowable bearing pressure varies significantly based on the size and shape of foundation
  - 2x2 footing may have almost 2-times bearing pressure than 6x6 footing in some cases → Savings?
  - One bearing pressure for the whole building is not a good option, but one depth can be good for ease of construction
- Consider differential settlement between different columns: threshold limits to be checked
- Close spacing of footings is alarming to go for alternative foundation systems → Combined footing or Raft foundations

Foundation Systems for Taller Buildings

- Raft Foundation with more Basements
- Pile Foundation With Cap
- Pile Assisted Raft Foundation
- Raft Foundation with Ground Improvement
Raft Foundation with more Basements

- Advantage of Gross Bearing Pressure!
- Thumb Rules:
  - On an average per storey load is usually 1.5 tonnes and bulk density is slightly more than that
  - One storey per meter of basement depth → per basement three storey building with no bearing pressure requirement
  - Allowable bearing pressure increases with depth
  - Some bearing pressure means more storeys.
- Adjacent structures can put constraints

Piled-Raft Foundation

- Use of piles to reduce raft settlements and differential settlements
- Leads to considerable economy without compromising the safety and performance of the foundation.
- It makes use of both the raft and the piles, and is referred to here as a pile enhanced raft or a piled raft.
Piled-Raft Foundation

![Diagram of Piled-Raft Foundation]

- Soil
- Bearing stratum
- $d = 2r_0$
- $r_0$
- $L$

**Diagram:**
- Load-settlement curve with different curves for Raft only (settlement excessive) and Raft with pile designed for conventional safety factor.
- Curve 0: Raft only (settlement excessive)
- Curve 1: Raft with pile designed for conventional safety factor
- Curve 2: Raft with piles designed for lower safety factor
- Curve 3: Raft with piles designed for full utilization of capacity.
Design of Piled-Raft

- Design methods are available for vertical loads
- Lateral load response for piled raft is yet to be fully explored to develop design methods
  - Moments and static lateral forces are no problem, but seismic forces are of concern
  - There are some studies available on construction arrangements for reducing damage due to seismic forces
- Demands accuracy of pile load capacity
  - The savings from it is worth making the effort for more of initial and routine pile load tests at different locations on the site
- Strategy of pile locations to reduce differential settlements

Design Process for Piled-Raft

- Preliminary stage
  - Assess the feasibility of using a piled raft
  - Number of piles to satisfy design requirements

- Second stage
  - Assess where piles are required
  - General characteristics of the piles

- Final detailed design stage
  - Optimum number, location and configuration of the piles
  - Distributions of settlement, bending moment and shear in the raft
  - Pile loads and moments.

Pile Foundation with Cap

- Is it really required? The answer is?
  - Is there a rock strata at shallow depth? → Can it consider shallow foundation or ground improvement in that case?
  - Is group action required to consider this option?
  - Is estimation of pile capacity a concern? Is there major uncertainty about the strata?
  - Is project too small?
  - The raft is too small to worry about it?
  - Loads too heavy?
Raft with Ground improvement

- No extra basement and no piles!
- Can be highly cost effective in most cases
- Clayey strata below can be a problem, but solutions are:
  - Stone columns, Sand pile
  - Soil mixing, injection systems
  - Pre-loading, vacuum loading
- Sandy or Silty strata is easier to handle
  - Vibro-compaction
  - Dynamic compaction, vibro-replacement, vibro-concrete
- Check availability and economy

Foundation Engineering Practice - Interface between Structural and Foundation Engineers

<table>
<thead>
<tr>
<th>S.No</th>
<th>Best Practice (Mostly followed by developed world)</th>
<th>Most Situations in India at present</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>After Site Selection</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Contour Survey</td>
<td>Sometimes available</td>
</tr>
<tr>
<td>2</td>
<td>Geology of site by expert</td>
<td>By the Geotechnical Agency as part of the Geotechnical Investigation</td>
</tr>
<tr>
<td>3</td>
<td>Preliminary Geotechnical Investigation by an accredited Agency</td>
<td>Rarely Done</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
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<th>Best Practice (Mostly followed by developed world)</th>
<th>Most Situations in India at present</th>
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</thead>
<tbody>
<tr>
<td>4.</td>
<td>Project layout with location of important structures made available to Geotechnical consultant.</td>
<td>Generally not made available to Investigation Agency</td>
</tr>
</tbody>
</table>
| 5.   | **Scope of Detailed Geotechnical Investigation:**  
Geotechnical Consultant in Consultation with structural consultant and on the basis of structural details. | • Not the common practice.  
• Most often a bill of quantities and a standard set of laboratory tests are given to the agency by Architect/Structural Designer.  
• *Inappropriate* also because the laboratory tests are a function of the type of soil strata. |

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</table>
| 6.   | • Detailed Soil Investigation by an accredited and qualified investigation agency.  
• Investigations done under independent supervision by a qualified person. | • Lack of accreditation process.  
• Most investigation agencies are not accredited. They do not have trained manpower.  
• Mostly not supervised |
| 7.   | Investigation report by the agency giving the results of field and laboratory tests only. No Foundation Recommendations. | Report containing  
• Results of Field and Laboratory Tests  
• Recommendations for Foundations  
• Safe Bearing Capacity and Pile Capacities without having full details of the structures |

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### Geotechnical Engineering Practice Contd...

<table>
<thead>
<tr>
<th>S.No</th>
<th>Best Practice (Mostly followed by developed world)</th>
<th>Most Situations in India at present</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.</td>
<td>Interpretation of the results by a Specialist Foundation Consultant and recommendation for type of foundation and foundation design parameters.</td>
<td>Very rarely the case. Investigation Agency hardly has qualified and experienced Foundation Engineers.</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>S.No</th>
<th>Ideal/ International Practice</th>
<th>Most Situations in India at present</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.</td>
<td>Involvement of Foundation Consultant during execution, review of results of further tests. Ex. Pile Load Tests (Initial &amp; Routine)</td>
<td>Very Rare.</td>
</tr>
<tr>
<td>11.</td>
<td>Settlement Observations and information to Foundation Consultant.</td>
<td>Very Rare.</td>
</tr>
<tr>
<td>12.</td>
<td>Foundation Performance assessment and report by Foundation Consultant</td>
<td>Absent.</td>
</tr>
</tbody>
</table>
Extract from Eurocode 7, BS EN 1997-1:2004

The provisions of this standard (Eurocode 7) are based on the assumptions given below:

1. Data required for design are collected, recorded and interpreted by appropriately qualified personnel;

2. Structures are designed by appropriately qualified and experienced personnel;

3. Adequate continuity and communication exist between the personnel involved in data collection, design and construction;

4. Adequate supervision and quality control are provided in factories, in plants, and on site;

5. Execution is carried out according to the relevant standards and specifications by personnel having the appropriate skill and experience;

6. Construction materials and products are used as specified in this standard or in the relevant material or product specifications;
7. The structure will be adequately maintained to ensure its safety and serviceability for the designed service life;

8. The structure will be used for the purpose defined for the design.

9. These assumptions need to be considered both by the designer and the client. To prevent uncertainty, compliance with them should be documented, E.g. in the geotechnical design report.

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Eurocode 7 is the latest and best code of practise.

It helps in evolving Optimum Designs – Safety and Economy

Ensuring this standard will benefit India significantly

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QUALITY OF INVESTIGATION

- High quality is the very basis for excellence in practice.
- In spite of detailed standard specifications (IS-codes), the range of practices vary very widely in the country.
- For field investigations, most primitive to fairly sophisticated equipments are in use.
- Unfortunately, in majority of cases the practice is nearer to the primitive.
- Similarly laboratory testing practices vary widely, with little or no standardization.

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QUALITY OF INVESTIGATION

**India**

- Poor quality of the equipment.
- Shell & Auger, Wash
- Boring is also common
- SPT Equipment - manual operation
- Static cone penetration equipment with Mechanical cone.

**World Standard**

- Highly sophisticated and mechanised equipment.
- Continuous core sampling (in soils as well).
- SPT equipment with automatic hammer release.
- Static cone test with electric cone and piezocone (crucial for assessment of liquefaction)

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Non Standard Equipment
No safety measures

Global Standard

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Static Cone Penetration - Reaction with Sand bags

Crawler Mounted SCPT Equipment

Case Studies
Project: Summer Palms, Sector 4A, Bahadurgarh, Haryana

- 13 Towers with S+14 storeys

**Original Investigation:**

- 11 Boreholes
- Strata- Silty sand and sandy silt layers with water table at 2 m below GL.
- SPT N values – 2 to 10 up to 7 m below Ground Level
- Layers up to 7 m below ground level are prone to liquefaction.

**Supplementary Investigation:**

- 14 Static Cone penetration Tests (SCPT)
- 8 SCPTs using Mechanical Cone
- 6 SCPTs using Electric Cone with Pore Pressure sensors.

✓ Confirmation of weak strata up to 7 m below ground level.
Foundation Adopted:

- Vibrostone columns to mitigate liquefaction and improve soil stiffness
- 900 mm diameter Stone Columns installed at 2 m c/c spacing using bottom dry feed method
- Raft Foundation on improved ground at 2.7 m below finished ground level
- Verification with Footing load tests on vibro stone columns
  - 2 m x 2 m Footing (Single Column)
  - 4 m x 4 m Footing (4 columns)
- SCPT tests between columns after installation of stone columns.
  - Significant ground improvement

Results of 2 m x 2 m Footing Load Tests (Single Column)

Maximum Settlement is 16.75 mm at 22.5 t/m² Load intensity
Results of 4 m x 4 m Footing Load Tests (Group Column)

Maximum Settlement is 10.2 mm at 15 t/m² Load Intensity

- Soil Modulus of Improved ground (Es)
  From 4 m x 4 m Footing Load Tests = 400 kg/cm²
- For lower layers, Subgrade Modulus is obtained using correlation by Schultz and Muhs (1966).
  Range: Es = 300 kg/cm² (for N=10) to 800 kg/cm² (for N=50)
- Estimated settlements of Raft for S+14 storey towers is 66 mm to 75mm.
- Construction in progress
- Settlements being monitored.
N vs Es for Sands, After Schultz and Muhs (1966)

Pile Assisted Raft for a 51 Storey Tower at Gurgaon

- High rise tower with 51 storeys and 2 Basements.
- Strata: Predominantly Sandy Silt with water table 25 m below Ground level
- Founding Level: 12 m below Ground Level
- SPT N value is 35 & above below Founding level.
Preliminary Design proposed by a Structural Consultant:

- A Large Piled Raft of size 54 m x 68 m ($3672 \text{ m}^2$) with 600 mm dia bored piles of varying length
- Total number of piles = 345.
- Total Settlement of the Piled Raft is restricted to 50 mm

Additional Investigations were proposed by us with 2 additional boreholes, 50 m depth.

Fresh Assessment and Analysis led to a solution of reduced raft size and number of piles.
Revised Pile Assisted Raft Design based on Fresh Analysis:

- Raft Area = 1740 m$^2$ (Original 3672 m$^2$)
- Bored Piles of 600 mm diameter and 18 m long
- Total number of piles = 94 (Original 345)
- Settlements restricted to 50 mm (as desired by the client)

- Approximately 25 % of total load will be transferred to piles from raft.
- Initially load will be predominantly transferred to the piles.
- At maximum allowable settlement, the ultimate capacity of the piles will be fully mobilized.
  - Hence Piles are designed for ultimate capacity.
7th CARGO BERTH AT KANDLA PORT

- 65 m wide x 250 m long RCC Deck Structure supported on Bored Piles, 1.0 m dia @ 5 m c/c both ways.
- 190 m wide X 250 m long open stack area to store cargo up to loading Intensity of 200 KN/m2.
- Sand Drains and Preloading for Ground Improvement.
- Measurement of pore water pressures and lateral displacements.

CONSTRUCTION PROBLEMS

- The area in front of the structure has to be dredged after construction of the berthing structure.
  - Lateral instability of the soft clay layer and lateral forces on the piles.
- Inundation of the whole area during high tide.
  - Construction of RCC Piles is difficult.
- Large area behind the Berthing structure requires ground improvement by preloading with the soil fill upto 6m height.
  - Further instability due to lateral soil movement.
7th Cargo Berth (Contd.)

**LAYOUT OF CARGO BERTH**

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7th Cargo Berth (Contd.)

**TYPICAL SECTION OF CARGO BERTH**

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7th Cargo Berth (Contd.)

SLIP SURFACE

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7th Cargo Berth (Contd.)

SLIP FAILURE DURING CONSTRUCTION

- With 50% of the piles installed, a deep seated slip failure occurred.
- Damage to a large number of piles.
- Head displacement of 8 piles as high as 2.5 m which meant breakage of the piles.
- 80 piles had top displacement exceeding 30 cm.
- Theoretical analysis shows permissible displacements without structural damage as 30cm.

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REASONS FOR FAILURE

- Instability of the clay slope under the weight of the fill placed for making the construction possible.
- Lateral movement of the slope under the influence of the preloading:
  - The piezometers installed to observe the rate of consolidation did not function properly,
  - The settlement observation clearly indicated the lateral displacements which was not taken notice of,
  - The direct measurement of the lateral displacements using the slope indicator were not taken as the instrument (probe) was nonfunctional for one year.

REMEDIAL MEASURES

- Further fill to facilitate construction of piles was stopped.
- Further pile installation was done using end on method.
- Integrity tests were carried out on the displaced piles to find the extent of damage.
- About 80 replacement piles were installed adjacent to the displaced piles wherever displacement exceeded 30 cm.
- Connecting beams suitably designed to take care of the eccentricity.
A closer interaction between Structural Designers and Foundation Consultants would have avoided this type of problem and failure.

In most cases such an interaction will ensure safety, save time and money.