ZABIULLAH KHAN (22PWCIV5814) Leader

MUBEEN UL HAQ (22PWCIV5878)

SECTION: U

Complex Engineering problem Foundation Engineering

SUBMITTED TO: Sir Dr. Shahid Ullah

DEPARTMENT: CIVIL ENGINEEERING

UNIVERSITY OF ENGINEERING & TECHNOLOGY PESHAWAR

Executive Summary

The two foundation alternatives for a twelve storey commercial building proposed on Warsak Road, Peshawar. The alternatives are: (i) a raft foundation located 5 m below natural ground level and (ii) a group of cast in-situ drilled piles. The design checks include bearing capacity, factor of safety, and settlement. The problem statement specifies a gross pressure of 180 kPa at raft base level and a maximum allowable settlement of 50 mm. The soil profile used in this report is based on the supplied CEP statement and Appendix-I.

The raft foundation satisfies the conventional undrained shear bearing-capacity requirement when checked at the founding level in the soft to medium clay. However, the raft fails the settlement criterion. The estimated total settlement is about 436 mm, which is much greater than the allowable settlement of 50 mm. The excessive settlement is mainly caused by the normally consolidated organic clay layer between 8 m and 15 m depth.

A pile foundation using 1.0 m diameter cast in-situ bored piles extending from the basement foundation level to about 25 m depth is therefore recommended. A layout of 120 piles is proposed. The allowable capacity per pile is approximately 3936 kN, while the working load per pile is approximately 2970 kN. The estimated pile group settlement is about 33 mm, which is less than the allowable value of 50 mm.

Item	Raft Foundation	Pile Foundation
Bearing capacity	Satisfactory for shear at founding level	Satisfactory
Estimated settlement	Approximately 436 mm	Approximately 33 mm
Allowable settlement	50 mm	50 mm
Decision	Not acceptable due to settlement	Acceptable and recommended

1. Introduction

Foundation design is controlled by two principal limit states: shear failure of the supporting soil and excessive settlement. In multi-storey buildings, both total settlement and differential settlement are important because excessive movement can damage structural and non-structural elements. In this project, a twelve storey commercial building is to be constructed on a site having clay and gravel strata. The presence of normally consolidated organic clay makes settlement analysis especially important.

The purpose of this report is to evaluate the suitability of a raft foundation and a pile foundation using rational engineering assumptions where input data are missing. Calculations are shown in a step-by-step academic format.

2. Project Data and Soil Profile

Parameter	Value adopted in report
Building type	Twelve storey commercial building
Location	Warsak Road, Peshawar
Raft founding depth, Df	5 m below natural ground level
Raft plan dimensions	30 m x 66 m (problem statement)
Raft area, A	1980 m2
Gross pressure at raft base	180 kPa
Required FOS for raft shear	3.0
Required FOS for pile end bearing	3.0
Required FOS for pile skin friction	2.5

Allowable settlement	50 mm

Depth below ground (m)	Soil description	Given data
0 to 5	Clay above/between basement level	Cu = 20 kPa near upper layer; water table at 1.5 m
5 to 8	Soft to medium normally consolidated clay	Cu = 80 kPa, Cc = 0.20, e0 = 0.70
8 to 15	Black organic normally consolidated clay	Cu = 40 kPa, Cc = 0.35, e0 = 1.00
15 to 21.3	Gravel	SPT N = refusal
21.3 to 25	Very stiff to hard clay	Cu = 200 kPa
Below 25	Gravel	SPT N = refusal

3. Design Assumptions

The following assumptions are adopted because some unit weights, elastic parameters, and pile installation details are not provided. The assumptions are reasonable for preliminary foundation engineering design and are kept conservative where the soil contains organic clay.

Property	Adopted value	Reason
Unit weight of soil above water table	18 kN/m3	Typical moist clay unit weight
Saturated unit weight of soft clay	19 kN/m3	Typical saturated clay unit weight
Saturated unit weight of organic clay	17 kN/m3	Organic clay commonly has lower unit weight
Saturated unit weight of gravel	20 kN/m3	Dense gravel/refusal layer
Unit weight of water	9.81 kN/m3	Standard value
Undrained bearing capacity factor, Nc	5.14	For phi = 0 clay condition
Shape factor for rectangular raft, sc	1 + 0.2B/L	Undrained rectangular footing approximation
Depth factor, dc	1 + 0.2Df/B	Undrained approximation
Pile diameter	1.0 m	Practical bored pile diameter for high-rise building
Pile toe depth	25 m below ground level	Pile carried through compressible layers to gravel/hard stratum
Concrete modulus for pile compression	25 GPa	Typical cast in-situ concrete modulus
Pile group arrangement	10 x 12 piles = 120 piles	Fits within raft footprint using practical spacing

4. Raft Foundation Design

4.1 Total Load and Contact Pressure

$$\text{Area of raft} = \text{B x L} = 30 \text{ x } 66 = 1980 \text{ m2}$$

$$\text{Total load, Q} = \text{qgross x A} = 180 \text{ x } 1980 = 356400 \text{ kN}$$

Therefore, the total dead and live load transferred to the foundation system is 356400 kN.

4.2 Net Foundation Pressure

For settlement and net bearing calculations, the pressure relieved by excavation to 5 m depth is deducted from the gross pressure.

$$q0 \text{ at } 5 \text{ m} = (1.5 \text{ x } 18) + (3.5 \text{ x } 19) = 27 + 66.5 = 93.5 \text{ kPa}$$

$$qnet = qgross - q0 = 180 - 93.5 = 86.5 \text{ kPa}$$

The net foundation pressure used for settlement analysis is therefore 86.5 kPa.

4.3 Undrained Bearing Capacity Check

For saturated clay under short-term undrained loading, phi = 0 and the net ultimate bearing capacity may be estimated by:

$$qnet,ult = Cu\ Nc\ sc\ dc$$

$$sc = 1 + 0.2(B/L) = 1 + 0.2(30/66) = 1.091$$

$$dc = 1 + 0.2(Df/B) = 1 + 0.2(5/30) = 1.033$$

$$qnet,ult = 80 \text{ x } 5.14 \text{ x } 1.091 \text{ x } 1.033 = 462.3 \text{ kPa}$$

$$qnet,allow = qnet,ult\ /\ FOS = 462.3\ /\ 3 = 154.1 \text{ kPa}$$

$$FOSactual = qnet,ult\ /\ qnet = 462.3\ /\ 86.5 = 5.34$$

Since the actual factor of safety against undrained shear failure is greater than 3.0, the raft is safe against conventional bearing-capacity failure at the founding level. However, the large stress bulb of the raft extends into the organic clay layer, so settlement must be checked carefully.

4.4 Stress Increase Below Raft by 2:1 Method

For consolidation settlement, the vertical stress increase at the center of each clay layer is estimated using the 2:1 method:

$$Delta\ sigma\_z = qnet\ (B\ L)\ /\ ((B + z)(L + z))$$

Layer	**Depth range below ground (m)**	**Mid-depth below base, z (m)**	**Delta sigma (kPa)**
Soft to medium clay	5 to 8	1.5	86.5(30x66)/((31.5)(67.5)) = 80.5
Organic clay	8 to 15	6.5	86.5(30x66)/((36.5)(72.5)) = 64.7

4.5 Initial Effective Overburden Stress

The water table is taken at 1.5 m depth. Effective overburden stress is calculated using total overburden stress minus pore-water pressure.

Layer	Mid-depth (m)	Total vertical stress (kPa)	Pore pressure (kPa)	Effective stress, sigma0 prime (kPa)
Soft to medium clay	6.5	1.5(18)+5.0(19)=122.0	9.81(6.5-1.5)=49.1	72.9
Organic clay	11.5	1.5(18)+6.5(19)+3.5(17)=210.0	9.81(11.5-1.5)=98.1	111.9

4.6 Consolidation Settlement of Raft

Both clay layers are described as normally consolidated clay (NCC), therefore primary consolidation settlement is calculated as:

$$Sc = (Cc\ H / (1 + e0))\ \log10((\text{sigma0 prime} + \text{Delta sigma}) / \text{sigma0 prime})$$

$$\text{Soft clay: } Sc1 = (0.20 \text{ x } 3)/(1 + 0.70)\ \log10((72.9 + 80.5)/72.9) = 0.114 \text{ m} = 114 \text{ mm}$$

$$\text{Organic clay: } Sc2 = (0.35 \text{ x } 7)/(1 + 1.00)\ \log10((111.9 + 64.7)/111.9) = 0.243 \text{ m} = 243 \text{ mm}$$

$$\text{Total consolidation settlement} = 114 + 243 = 357 \text{ mm}$$

The organic clay contributes the largest part of the settlement because it has high compression index and large thickness.

4.7 Immediate Settlement of Raft

Immediate settlement in saturated clay is estimated using elastic theory. Because elastic modulus values are not supplied, an equivalent undrained modulus of 33 MPa is adopted for the composite clay mass below the raft. This value is conservative for the soft and organic clay profile.

$$Si = qnet\ B\ (1 - nu2)\ Is / Eu$$

$$\text{Assume } nu = 0.45, Is = 1.10, Eu = 33000 \text{ kPa}$$

$$Si = 86.5 \text{ x } 30 \text{ x } (1 - 0.45\text{^}2) \text{ x } 1.10 / 33000 = 0.069 \text{ m} = 69 \text{ mm}$$

4.8 Total Settlement and Raft Decision

$$Stotal = Si + Sc = 69 + 357 = 426 \text{ mm}$$

Criterion	Calculated value	Allowable value	Status
Factor of safety against shear	5.34	3.0 minimum	Pass
Total settlement	426 mm	50 mm maximum	Fail

Although the raft foundation is safe against shear failure, it is not acceptable because the predicted settlement is much higher than 50 mm. The controlling failure mode is settlement, not bearing capacity.

5. Pile Foundation Design

5.1 Selection of Pile Type and Length

Cast in-situ drilled piles are selected to transfer most of the building load through the soft and organic clay layers into the dense gravel and very stiff to hard clay. The pile cap is assumed to be at the basement raft level, i.e., 5 m below ground level. Piles extend to 25 m depth, giving an effective embedded length of 20 m below pile cap level.

Pile parameter	Adopted value
Pile type	Cast in-situ bored pile
Pile diameter, D	1.0 m
Pile cap/foundation level	5 m below ground level
Pile toe depth	25 m below ground level
Effective pile length below cap	20 m
Pile base area, Ab	piD2/4 = 0.785 m2
Pile perimeter, p	piD = 3.142 m

5.2 Ultimate Skin Friction Capacity

For clay, the alpha method is used:

$$fs = \text{alpha Cu}$$

For the gravel layer where SPT refusal is reported, a conservative unit shaft resistance of 100 kPa is used. The pile segments below the pile cap are considered.

Layer along pile	Thickness (m)	Adopted unit skin friction (kPa)	Ultimate skin friction (kN)
Soft to medium clay, 5 to 8 m	3.0	alpha Cu = 0.60 x 80 = 48	3.142 x 3.0 x 48 = 452
Organic clay, 8 to 15 m	7.0	alpha Cu = 0.80 x 40 = 32	3.142 x 7.0 x 32 = 704
Gravel, 15 to 21.3 m	6.3	100	3.142 x 6.3 x 100 = 1979
Very stiff to hard clay, 21.3 to 25 m	3.7	alpha Cu = 0.35 x 200 = 70	3.142 x 3.7 x 70 = 814

$$\text{Qs,ult} = 452 + 704 + 1979 + 814 = 3949 \text{ kN}$$

$$\text{Qs,allow} = \text{Qs,ult} / 2.5 = 3949 / 2.5 = 1580 \text{ kN}$$

5.3 End Bearing Capacity

The pile toe is taken into dense gravel/refusal stratum at about 25 m depth. A conservative ultimate unit end bearing of 9000 kPa is adopted for preliminary design in the refusal layer.

$$\text{Qb,ult} = \text{qb,ult Ab} = 9000 \text{ x } 0.785 = 7069 \text{ kN}$$

$$\text{Qb,allow} = \text{Qb,ult} / 3 = 7069 / 3 = 2356 \text{ kN}$$

5.4 Allowable Capacity of One Pile

$$\text{Qallow,pile} = \text{Qs,allow} + \text{Qb,allow} = 1580 + 2356 = 3936 \text{ kN}$$

The allowable axial compression capacity of one 1.0 m diameter bored pile is therefore approximately 3936 kN.

5.5 Number of Piles Required

$$N_{required} = \text{Total load} / Q_{allow,pile} = 356400 / 3936 = 90.5 \text{ piles}$$

The theoretical minimum number of piles is 91. However, additional piles are required to allow for column layout, group action, construction tolerance, load eccentricity, and differential settlement control. A practical group of 120 piles is selected.

$$\text{Working load per pile} = 356400 / 120 = 2970 \text{ kN}$$

$$\text{Utilization ratio} = 2970 / 3936 = 0.75$$

The working load per pile is less than the allowable pile capacity, giving adequate reserve capacity.

5.6 Proposed Pile Layout

A 10 x 12 pile group is proposed under the building footprint. The spacing is selected as approximately 3D in the 30 m direction and about 5.5D to 5.7D in the 66 m direction depending on edge clearances and final column positions. This arrangement can be adjusted during detailed structural design to match the column grid.

Layout item	Value
Number of piles across width	10
Number of piles along length	12
Total piles	120
Approximate spacing across 30 m direction	3.0D
Approximate spacing along 66 m direction	about 5.5D
Approximate working load per pile	2970 kN

5.7 Group Capacity Check

For bored piles bearing in a dense/refusal stratum, the group capacity is commonly checked as the lesser of the sum of individual pile capacities and the block capacity. For this preliminary design, the sum of individual allowable capacities is:

$$Q_{group,allow} = 120 \times 3936 = 472320 \text{ kN}$$

$$Q_{applied} = 356400 \text{ kN}$$

$$FOS_{reserve} = 472320 / 356400 = 1.33 \text{ relative to allowable design load}$$

The group allowable capacity exceeds the applied building load. A final detailed design should also check the actual column reactions, lateral loads, pile cap bending, and negative skin friction if long-term consolidation of upper clays is expected.

5.8 Pile Group Settlement

The pile settlement consists of elastic compression of the pile shaft, settlement at the pile toe, and group settlement of soil below the pile group. Since the pile toe is placed in gravel/refusal or very stiff material, group settlement is expected to be much smaller than raft settlement.

5.8.1 Elastic Compression of Pile

$$\text{delta\_p} = Q\ L\ /\ (Ap\ Ec)$$

$$Q = 2970\text{ kN}, L = 20\text{ m}, Ap = 0.785\text{ m2}, Ec = 25{,}000{,}000\text{ kPa}$$

$$\text{delta\_p} = (2970 \times 20)\ /\ (0.785 \times 25{,}000{,}000) = 0.0030\text{ m} = 3\text{ mm}$$

5.8.2 Toe and Group Settlement Estimate

For piles ending in dense gravel/refusal stratum, toe settlement at working load is assumed as 10 to 20 mm for preliminary design. A value of 15 mm is adopted. Additional group settlement in the hard bearing stratum is estimated as 15 mm. These values are consistent with a preliminary serviceability estimate for a pile group founded beyond the compressible organic layer.

$$\text{Stotal,pile group} = \text{pile compression} + \text{toe settlement} + \text{group settlement}$$

$$\text{Stotal,pile group} = 3 + 15 + 15 = 33\text{ mm}$$

Settlement component	Estimated value
Elastic compression of pile	3 mm
Toe settlement in dense/refusal stratum	15 mm
Group settlement below toe	15 mm
Total pile group settlement	33 mm

The estimated pile group settlement is less than the allowable settlement of 50 mm; therefore, the pile foundation satisfies the serviceability requirement.

6. Comparison of Foundation Alternatives

Design aspect	Raft foundation	Pile foundation
Main load transfer mechanism	Distributed pressure to upper clay layers	Load transferred to gravel/hard clay by shaft and end bearing
Bearing capacity	Passes conventional undrained check	Passes individual and group capacity checks
Settlement behavior	Very large due to organic clay	Small because piles bypass compressible layers
Estimated settlement	426 mm	33 mm
Construction complexity	Simpler excavation and raft casting	More complex drilling and quality control
Risk	High settlement risk	Lower settlement risk
Suitability	Not suitable	Suitable

7. Final Recommendation

The raft foundation should not be adopted for the proposed twelve storey commercial building because the estimated settlement is much greater than the allowable settlement of 50 mm. The soil profile contains a thick normally consolidated organic clay layer, which causes excessive consolidation settlement under the raft pressure.

The recommended foundation system is a group of cast in-situ drilled piles. The proposed preliminary design consists of 120 bored piles, each 1.0 m in diameter, extending to approximately 25 m depth. This design provides adequate axial capacity and limits the estimated pile group settlement to approximately 33 mm, which is within the allowable settlement limit of 50 mm.

8. References

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CE-430 Foundation Engineering Complex Engineering Problem statement and Appendix-I soil profile supplied by the course instructor.

Appendix A: Summary of Main Numerical Results

Quantity	Value
Raft area	1980 m2
Total load	356400 kN
Net raft pressure	86.5 kPa
Raft net ultimate bearing capacity	462.3 kPa
Raft allowable net bearing capacity	154.1 kPa
Raft actual FOS against shear	5.34
Raft consolidation settlement	357 mm
Raft immediate settlement	69 mm
Raft total settlement	426 mm
Pile diameter	1.0 m
Pile toe depth	25 m
Allowable capacity per pile	3936 kN
Selected number of piles	120
Working load per pile	2970 kN
Estimated pile group settlement	33 mm